OPTO

SPIE Photonics West

Contents

Technical Abstract Summaries

Conferences + Courses: 23-28 January 2010
BiOS Exhibition: 23-24 January 2010
Photonics West Exhibition: 26-28 January 2010

The Moscone Center
San Francisco, California, USA

SPIE
Connecting minds. Advancing light.

Conference 7597: Physics and Simulation of Optoelectronic Devices XVIII

Monday-Thursday 25-28 January 2010 • Part of Proceedings of SPIE Vol. 7597

Physics and Simulation of Optoelectronic Devices XVIII

7597-01, Session 1

Microscopic theory and numerical simulation of quantum well solar cells

U. Aeberhard, Forschungszentrum Jülich GmbH (Germany)

With the increasing utilization of quantum confinement effects in photovoltaic devices through the use of low-dimensional structures such as quantum wells, wires or dots, microscopic theories start to be required for an accurate analysis and simulation of the device characteristics. These quantum photovoltaic devices are optoelectronic systems where optimization of both the

optical transitions and the transport properties are essential for an ideal device performance. One of the most advanced theoretical approaches able to describe both quantum optics and quantum transport in nanoscale devices is based on the Keldysh or non-equilibrium Green's function (NEGF) formalism. In the present paper, the NEGF approach is adapted to cover the photovoltaic regime of operation of bipolar quantum well diodes as prototypes of quantum photovoltaic devices. A microscopic theory is developed that describes the essential photovoltaic processes of photogeneration, carrier relaxation, radiative recombination and transport to carrier selective contacts. The theory is numerically implemented using band structure models ranging from single-band effective mass to multiband tight-binding approaches. Interactions with photons and phonons are described perturbatively via corresponding self-energies on the level of the self-consistent Born approximation. Carrier injection is considered through contact self energies representing open-system boundary conditions. The optical properties follow from the dielectric function derived within the same theoretical framework via the calculation of the transverse interband polarization function. To illustrate the capabilities of the approach, a variety of microscopic and macroscopic device properties is determined from the numerically computed Green's functions for different configurations of single and multiple quantum wells, such as the local density of states, charge carrier density, dark- and photocurrent as well as spectra for absorption and emission, besides key photovoltaic characteristics like I-V curves and quantum efficiency.

7597-02, Session 1

Modelling and performance of quantum well solar cells

P. Kailuweit, R. Kellenbenz, F. Dimroth, Fraunhofer-Institut für Solare Energiesysteme (Germany)

Embedding quantum wells into the depletion zone of the p-n-junction of a III/V solar cell offers an elegant way to optimize the cell performance by extending the absorption range of a solar cell beyond the bandgap of the host solar cell. A predictive theoretical modelling is an important prerequisite for solar cell design to save development cost and to understand the physical processes of such a solar cell. Such a model, based on a commercial TCAD system, will be presented for a quantum well solar cell. We calculated the external quantum efficiency of a GaAs solar cell with a stack of quantum wells embedded into it's intrinsic region. The model was then calibrated to the measurements of a real quantum well solar cell to determine material dependent fitting parameters. After this calibration the predictive capability of the model was proved by simulation of a different sample, leaving all fit parameters fix. Results of different parameter variations will be presented which reveal the physical behaviour of such a solar cell and define the frame conditions of quantum well solar cells for use in applications.

7597-03, Session 1

Zonal efficiency limit calculation for nanostructured solar cells

J. Kupec, ETH Zürich (Switzerland); S. Yu, B. Witzigmann, Univ. Kassel (Germany)

The famous Shockley-Queisser detailed balance calculation for determining the efficiency limit of a multi-junction solar cell with respect to the bandgap energies does not address the strong local deviations of the optical power absorption for the case of a nanostructured cell. Furthermore, the assumption of perfect absorption of all incident light exceeding the bandgap energies cannot be justified. We present a modified Shockley-Queisser efficiency limit calculation for nanostructured photovoltaic devices. It incorporates a rigorous wave optics calculation and spatially resolved generation of electron-hole pairs.

We apply this method to a single-junction and dual-junction InAs/InP nanowire array for the use in concentrator solar cells. We investigate the efficiency limits regarding the arrangement of the active regions within the wire. We evaluate the efficiency limit of various radial and axial junction designs and highlight the influence of the electromagnetic modal characteristics on the local generation rate as well as the interplay between nanowire geometry, arrangement of the active regions and the bandgap energies.

Our results indicate that in a nanowire array solar cell with low volume fill factor the efficiency limit can approach the values of planar thin-film devices. This observation indicates the occurrence of micro-concentration and underlines the necessity of a wave optics approach. The spatially and spectrally resolved analysis shows that generation on the surface of the nanowires is considerable particularly with regard to high energy photons. Therefore, it is necessary to efficiently extract those carriers for highest efficiency designs.

7597-04, Session 1

Higher limiting efficiencies for nanostructured solar cells

J. Adams, Imperial College London (United Kingdom); G. Hill, J. S. Roberts, The Univ. of Sheffield (United Kingdom); K. W. Barnham, N. J. Ekins-Daukes, Imperial College London (United Kingdom)

New higher limiting efficiencies have been predicted for solar cells with low-dimensional absorbers. The strain-balanced quantum well solar cell is a GaAs p-i-n cell containing compressively-strained InGaAs quantum well (QW) layers. At the operating bias, the predominant loss mechanism is via radiative recombination from the QWs, however it has been found that the QWs have a fundamental efficiency advantage over bulk material as they radiate anisotropically. The effects of quantum confinement and strain in the QWs lift the degeneracy of the heavy hole (HH) and light hole (LH) valence bands. The HH band couples to emission perpendicular to the QWs, and the LH band couples predominantly to emission in the plane of the QWs. In compressively-strained QWs, the HH transition becomes more probable, so radiative emission is suppressed in the plane of the QWs. Fundamentally, emission need only occur in the same direction as absorption, a situation which can be engineered by adjusting the energetic valence band alignment via strain. This leads to a higher detailed-balance limiting efficiency than in previous calculations where emission was assumed to be isotropic. We will present the results of detailed-balanced efficiency modelling in the radiative limit for isotropic and restricted emission, including the effects of back-reflectors such as the angularly-dependent distributed Bragg reflector. We will discuss what occurs for a more realistic scenario where radiative recombination is not

the only loss mechanism in the cell. We will also present experimental evidence indicating anisotropic emission in devices with highly-strained QWs.

7597-05, Session 1

FDTD simulation of metallic gratings for enhancement of electromagnetic field by surface plasmon resonance

H. P. Paudel, South Dakota State Univ. (United States); K. Bayat, Univ. of Waterloo (Canada); M. F. Baroughi, South Dakota State Univ. (United States); S. May, Univ. of South Dakota (United States); D. W. Galipeau, South Dakota State Univ. (United States)

Enhancement of electromagnetic field by engineered metallic nanostructure on the metal surface by exciting surface plasmon polaritons is investigated. We employed 3D Finite-Difference Time Domain (FDTD) method for simulation of gratings in visible and NIR radiations. Surface plasmon resonance has potential application in photonic circuit miniaturization, optical signal processing, optical signal switching, optical data storage, biosensors and absorption enhancement in solar cell. Electromagnetic near-field enhancement by two-dimensional array of metallic gratings on metal surface and their characterization by size, shape, period, lattice types, radiation angles and wavelength were not investigated previously. Rectangular and cylindrical protrusions of two dimensional gold (and silver) arrays in square and triangular lattice on gold (and silver) surface interfaced with dielectric material of refractive index 1.49 (PMMA) were simulated. We found that the cylindrical grating in square lattice has the maximum enhancement by 10 times and 50 times at sharp edges, which is predominantly due to excitation of surface plasmons by grating's localized plasmons. We showed that grating parameters such as grating period, aspect ratio and grating height can be tuned for excitation of surface plasmon polaritons for particular frequencies of interest. Results also showed that triangular lattice grating has the wider enhancement bandwidth than square lattice gratings and grating height is the most sensitive parameters of field enhancement. We got the identical result from another FDTD simulation tool 'Meep'. The same amount of enhancement is found when the measured reflectance is substituted in analytical expression of field enhancement derived from conservation of energy. The investigation explored the novel way of enhancing field above metal surface by tuning the geometric sizes of gratings.

7597-06, Session 2

Multi-exciton generation in solar cells (Keynote Presentation)

A. Zunger, National Renewable Energy Lab. (United States)

Abstract not yet in.

7597-07, Session 2

Vitual single-crystalline GaAs photovoltaics on flexible metal substrates

A. Freundlich, V. Selvamanickam, Univ. of Houston (United States)

Integration of III-V semiconductors with inexpensive flexible substrates is a desirable feature to many opto-electronic applications. In particular combining the unsurpassed performance of GaAs based multi-junction technologies with conventional roll to roll processing standards of thin film industry could lead to paradigm-shifting reduction of the cost of solar electricity.

Here we report the fabrication of single crystalline GaAs epilayers on thin (50 microns) flexible polycrystalline metallic substrates by molecular beam epitaxy (MBE). The flexible poly-crystalline Ni-based substrates were coated with an oxide-ceramic epitaxial buffer, adapted from a previously developed structure for high Tc superconductor wire technology, followed by a very thin (<50nm) Ge layer. Through a careful control of the growth sequence the self -annihilation of anti-phase boundaries was implemented within the first 100nm growth yielding a 2x4 RHEED diagram typical of a single domain (001) GaAs. Epilayers exhibited a specular morphology and high resolution X-ray diffraction analysis confirmed the single crystalline (001) nature of deposited GaAs film. Temperature dependent photoluminescence (PL) analysis revealed a strong PL in as-grown samples. The low temperature PL was found to be dominated with DA -eA like bands in the 1.4-1.5 eV range. The energy of the narrow excitonic emission detected in PL suggested the absence of any significant thermoelastic/lattice mismatch strain (<0.1%) in the epilayers.

Finally the presentation evaluates various defect tolerant device designs (i.e. quantum well solar cells) for the fabrication of high efficiency photovoltaics using the proposed approach and discusses preliminary device results.

7597-08, Session 2

A practical guide to photovoltaic solar cell design

D. Ding, S. R. Johnson, S. Wu, Arizona State Univ. (United States); S. Yu, Univ. of Arkansas (United States); Y. Zhang, Arizona State Univ. (United States)

Photovoltaic solar cell modeling is often approached in two different directions: i) numerical simulations based on drift-diffusion model and ii) theoretical analysis based on detailed balance models. Although commercial software packages such as Silvaco and Crosslight are available and widely used, it is not straightforward to extract device physics from these complicated numerical simulations. On the other hand, detailed balance models are quite capable of clarifying the fundamental limitations of ideal solar cells by neglecting many important loss mechanisms that occur in real devices. In this study the detailed balance model is extended to explicitly elucidate the impact of loss mechanisms and other aspects of real solar cells, including nonradiative recombination, photon recycling, spontaneous emission coupling, light scattering and trapping, and non-ideal absorbance and emittance. These calculations are summarized in graphical representations (or efficiency maps) that compare extracted power with six major losses: transmission, thermalization, spatial relaxation, Auger recombination, radiative recombination, and Shockley-Read-Hall recombination. By using this approach it is easy to understand practical design parameters such as bandgap energy, surface preparation, junction number, solar concentration, and material quality typically expressed as nonradiative lifetime. These efficiency maps provide a thorough understanding of the photovoltaic conversion process and an insightful and practical guide to solar cell design.

7597-09, Session 2

Modelling of dye sensitized solar cells using a finite element method

A. Gagliardi, M. Auf der Maur, D. Gentilini, A. Di Carlo, Univ. degli Studi di Roma Tor Vergata (Italy)

Dye sensitized solar cells (DSC) are an interesting alternative to conventional cells. The cell is divided in two regions, a mesoporous material made of titanium oxide and a liquid electrolyte. The oxide is covered by a monolayer of molecules. The functioning of the device is a sequence of steps where the electron excited into the dye propagates through the oxide up to the photo-anode. The regeneration of the dye is performed by the electrolyte. Today the development of DSCs in laboratories has reached a stage where detailed physical models may

contribute considerably to the optimization of these devices. In this work we present an electrical model to simulate DSCs based on a Finite Element Method as an extension of TiberCAD code. The CAD allows to calculate steady-state properties and ideal IV characteristics of the cell shaping 1,2 and 3D meshes of the device. The model handles all the charge carriers (cation, iodide, triiodide, electron) coupled to Poisson equation on the same footing within drift-diffusion equations. Recombination processes using mass law equation at the oxide/electrolyte interface and photogeneration of electrons in the oxide are included in the model. The aim of this work is to investigate the different performances of the cell by changing not only the topology of the oxide region, but also the position of the electrodes, cathode and photoanode, in order to optimize the cell characteristics.

7597-10, Session 3

Simulation and design of core-shell GaN nanowire LEDs

B. J. Connors, M. Povolotskyi, R. Hicks, B. Klein, Georgia Institute of Technology (United States)

The high crystalline quality, large junction surface area, and insensitivity to c-axis oriented polarization fields make core-shell doped GaN nanowire p-n junctions exciting prospects for use as LEDs. The LED external efficiency depends upon the spatial distribution of optical recombination within the device, which may be controlled through the use of radial heterojunctions, such as quantum wells and electron blocking layers. In this work, we explore the impact of an axially varying doping profile on the spatial distribution of optical recombination in a GaN nanowire LED.

The numerical simulation of the nanowire LED is carried out using the TiberCAD simulation package. This package provides a finite-element-based solution to the drift-diffusion model of a nanowire. Simulations of core-shell nanowire LEDs are performed with various doping profiles to produce variations in the optical recombination distribution throughout the device.

In a core-shell device with a uniformly doped n-type core, the current density tends to travel primarily along the core, as the mobility of electrons is much greater than that of holes in GaN devices. The optical recombination is concentrated beneath the p-contact, where most of the current crosses the p-n junction. By properly setting a tapered doping profile in the n-type core, it is possible to increase the uniformity of the optical recombination along the junction. In certain geometries this will increase the extraction efficiency of the nanowire LED.

7597-11, Session 3

Modelling of AlN/GaN superlattices for integration in near-UV distributed Bragg reflectors

A. Zorila, J. Jacquet, Supélec LMOPS (France); A. Ougazzaden, Georgia Institute of Technology (France); F. Genty, Supélec LMOPS (France)

One of the main problem for the realization of high reflectivity GaN-based Bragg mirrors operating in the UV and near-UV wavelength range is to limit the crack formation due to the lattice mismatch between the different nitride compounds while keeping a large refractive index contrast. In this system, the highest index contrast is obtain between AlN and GaN but these compounds exhibit a lattice mismatch as high as 2.4 %. Recent works have demonstrated that the introduction of several AlN/GaN superlattices (SLs) in a classical AlN/GaN quarterwavelength layers stacking strongly improved the crystalline quality and thus the optical properties of such a mirror. In this work, we have studied several AlN/GaN SLs for their use directly as low index material in a Bragg mirror. Such a configuration should allow to combine the limitation of cracks by SLs with the improvement of the index contrast. First, the band structure of different AlN/GaN SLs was modelled and gap energies lower than 3 eV could be found for several pseudo-alloys by choosing the right relative thicknesses of AlN and GaN. Then, the optical properties of the (AlN/GaN SLs)/GaN Bragg mirrors, centered at 400 nm and including these low gap SLs, were simulated showing that high reflectivities (>99%) can be waited from these structures with a relatively low number of pairs (< 20).

7597-12, Session 3

Optoelectronic and transport properties of nanocolumnar InGaN/GaN quantum disk LEDs

F. Sacconi, G. Penazzi, M. Auf der Maur, A. Pecchia, A. Di Carlo, Univ. degli Studi di Roma Tor Vergata (Italy)

Recent interest in III-nitride nanocolumn LEDs is due to their promising features, such as a nearly dislocation-free growth. Moreover, nanocolumns with a controlled variation of indium content in the active region, the InGaN quantum disk (QD), are believed to provide an high efficiency emission in the whole visible spectrum. In this work we use the multi-scale software tool TiberCAD [1] to study the transport and optical properties of a InGaN QD in a GaN nanocolumn p-i-n diode structure, both with a macroscopical and an atomistic approach. The aim of TiberCAD project is a device simulator able to treat several different physical problems at the relevant length scale, by applying each time the proper physical models, ranging from macroscopical to atomistic representations. TiberCAD simulator includes a mixed environment for FEM and atomistic calculations. In such an environment, it is possible to perform self-consistent FEM/tight-binding multiscale calculations.

First, the strain and the drift diffusion equations for charge transport are solved in the whole device, together with a k.p multiband approximation for the computation of the quantum states in the QD and its optical properties.

Then, in a multiscale paradigm, the atomistic structure of the active region is generated, based on geometry and mesh informations. Finally, the total (electric and polarization) potential is projected on the on-site elements of the sp3s*d5 empirical tight-binding (ETB) Hamiltonian. On the other hand, strain is included by applying displacements to the crystal lattice and by scaling the tight-binding parameters accordingly.

Quantum states, electron and hole densities, and optical recombination spectrum are computed within the InGaN QD by means of ETB calculations; ETB particle densities are then projected up to the macroscopic scale for a selfconsistent solution of the drift-diffusion equations.

[1] M. Auf der Maur, M. Povolotskyi, F. Sacconi, and A. Di Carlo, Superlatt. and Microstruct., 41, 5-6, (2007), p. 381-385

7597-13, Session 3

Numerical optimization of light-emitting diodes for high-efficiency operation

O. Heikkilä, J. Tulkki, Helsinki Univ. of Technology (Finland)

We investigate how efficient the LEDs can ultimately be, how the efficiency of LEDs is determined and how much of the efficiency is sacrificed when high optical intensities are sought for using extensive numerical simulations. The operation of LEDs is simulated using a model that accounts for the macroscopic carrier transport, photon extraction and heat exchange. The junction temperature is solved self consistently along with the carrier transport equations. The model is currently employed to simulate simple bulk AlGaAs-GaAs double heterostructure LEDs which are expected to be currently capable of the most efficient operation. The model is used to calculate e.g. the external quantum efficiency (EQE) and the wall plug efficiency to find the optimal operating range. Also comparative calculations are made using simplified analytical models. It will be shown that the optimal operating point is not necessarily found at the maximum of EQE because of the

contribution of lattice heat to the photon energy. Also the plausibility of electro-luminescent cooling in realistic LED structures is discussed. The efficiency droop limiting the high power operation is analyzed to find the underlying mechanisms in double heterojunction structures. The model is also used to predict a limiting current at which an insufficiently cooled LED becomes thermally unstable. Simple measures to increase the efficiency, reduce the power consumption and lower the junction temperature of LEDs are introduced based on the results, and experimental setups for measuring various material and device parameters are proposed.

7597-15, Session 4

Superconducting optoelectronics

I. Suemune, Hokkaido Univ. (Japan)

Optoelectonics is expanding its application fields, such as optical-fiber communications, displays, solid-state lightening and so on. Superconductivity has been regarded as a basic research field for some time but now it is also expanding the application fields to mass-transport, superconducting magnet for NMR and MRI, and highly sensitive SQUID magnetic-field sensors and so on. However up to very recently, the two fields have very few communications with each other. Now new trend is coming up: quantum information communication and processing. Several candidates have been proposed for quantum information processing of “Qubits”, and one prominent candidate is superconducting qubits. They have relatively long coherence time due to macroscopic quantum coherence and have an advantage for future solid-state integration. These “processing qubits” have to be converted into “messenger qubits” to form networks for quantum information. The latter will rely on the present optical-communication technology. For this purpose, development of the interface technologies for the alliance of photonics and superconductivity will open the new possibility. The authors have proposed a photon-emitting LED combined with superconducting electrodes, SQLED, which is expected to be a key device to interface the two fields. This device is also expected to generate on-demand entangled photon pairs. The main mechanism is based on the coherent spatial extension of the Cooper-pair states into the photon emitting active layer, which is expected to enhance the oscillator strength of the radiative recombination processes by the Cooper-pair involvement in the recombination processes. In this talk, the fundamental principle of the SQLED operations and new findings of LED light output enhancement and shortening of radiative recombination lifetimes will be presented together with its future prospect.

7597-16, Session 4

Properties of n-InAsSbP/n-InAs interface

B. A. Matveev, A. Ankundinov, N. Zotova, K. Sergey, T. L’vova, M. Remennyy, A. Rybal’chenko, N. Stus’, Ioffe Physico-Technical Institute (Russian Federation)

InAsSbP/InAs based heterostructures are quite commonly used for LEDs and photodiodes (PDs) operating in the mid-IR spectral range mostly at wavelengths around 3300 nm. The latter wavelength is important for optical analyzers of the C - H gases, e.g. of the methane gas or other hydrocarbons that have strong fundamental absorption band at 3300 nm. Band gap discontinuities at an InAsSbP/InAs interface are mentioned to affect the light source performance and particularly the stimulated emission at low temperatures. However no study of the band discontinuity values in the InAsSbP/InAs structure was undertaken so far. In this work we present experimental results permitting evaluation of the n-InAsSbP/n-InAs interface discontinuities and show their impact on the performance of double heterostructure n-InAsSbP/n-InAs/p-InAsSbP LEDs and photodiodes operating at room temperature at the wavelength of 3300 nm.

The report will focus on IR - image analysis, current - and capacity - voltage integral characteristics, scanning Kelvin probe microscopy (SKPM) measurements and surface potential distribution as a function of forward and reverse bias performed in flip-chip or (110) - cleaved devices. The above measurements together with surface photovoltage distribution analysis enabled us determining positions and values of the potential barriers in n-InAsSbP/n-InAs/p-InAsSbP heterostructures.

The obtained data will be discussed with the reference to designing mid-IR LEDs with uniform current/emission distribution over the active area and PDs with reduced capacity.

7597-17, Session 4

Band structure calculation of dilute-As GaNAs by first principle

X. Li, H. Tong, H. Zhao, N. Tansu, Lehigh Univ. (United States)

Nitride semiconductors play important roles for light-emitting diodes (LEDs) and lasers in visible spectrum. High-efficiency LEDs and low-threshold lasers based on InGaN quantum wells in green regime are challenging due to charge separation, high strain misfit dislocation, and possible large interband Auger recombination.

Here, we investigate the band structure of the dilute-As GaNAs alloys (0% up to 8% As) by employing First-Principle method, for exploring new active materials in visible spectrum. Significant studies have been carried out on understanding the band structures of dilute-nitride GaNAs (up to 5% N) for near IR emission. In contrast to that, very few studies have been carried out on analyzing the band structure of the dilute-As GaNAs alloy, thus its important parameter such as band offsets between individual conduction bands and/or valence bands at the gamma point of the Brillouin zone (BZ) remain unknown. The properties of the band structures for the GaNAs alloys have fundamental impacts on the development of these materials into advanced device applications. The band structures of the dilute-As GaNAs were calculated by the Density-Functional Theory that adopts the Generalized Gradient Approximation, and the calculation routine is along high-symmetrical k-points in the BZ. The incorporation of dilute-As into the GaNAs alloy leads to significant decrease in the bandgap of the material, which allows direct band gap transition covering from 2.8eV (As-content of 3%) down to 1.8eV (As-content of 7%). The First-Principle shows that the dilute-As GaNAs alloy as a candidate for excellent active material for LEDs and lasers in visible regime.

7597-18, Session 4

Lasing and gain characteristics in Ga(NAsP) heterostructures on Si

C. Lange, S. Chatterjee, W. W. Rühle, Philipps-Univ. Marburg (Germany); N. Koukourakis, N. Gerhardt, M. Hofmann, Ruhr-Univ. Bochum (Germany); S. Liebich, M. Zimprich, R. Fritz, B. Kunert, K. Volz, W. Stolz, Philipps-Univ. Marburg (Germany)

The creation of a direct band-gap material on silicon is envisioned to enable advanced optoelectronic integrated circuits with drastically improved performance combining the advantage of optical data processing with the well-established silicon processing technology. However, the realization of a laser diode based on Si remains a challenge to date due to the indirect nature of its band structure. One possible solution is the integration of standard direct band gap III/V laser material such as GaAs or InP on Si-substrates. Still, the large lattice mismatch of these materials to Si causes high densities of threading dislocations in the epitaxial films, preventing any long-term stable lasing operation of integrated III/V laser diodes. In order to avoid dislocation formation, the novel direct band gap Ga(NAsP)/GaP-material system has been introduced which exhibits lasing up to room temperature for epitaxial growth on GaP-substrates for both optical and electrical injection.

Here, we investigate the gain and lasing characteristics of a Ga(NAsP)/(BGa)(AsP) multiple quantum-well laser structure grown by metal-organic vapour-phase epitaxy on an exactly-oriented (001) Si substrate. We observe lasing action after pulsed optical excitation for various samples.

Return to Contents

The emission power shows a clear threshold behaviour as function of excitation density at temperatures ranging from 10 K up to 125 K. Clear mode spectra are observed and an analysis with the Hakki-Paoli method yields a lower limit for maximal modal gain of 5 cm-1.

7597-19, Session 4

Influence of disorder on photoluminescence dynamics of Ga(AsBi)

A. Chernikov, S. Chatterjee, C. Bückers, S. W. Koch, Philipps-Univ. Marburg (Germany); S. Imhoff, A. Thränhardt, Technische Univ. Chemnitz (Germany); X. Lu, The Univ. of British Columbia (Canada); T. Tiedje, Univ. of Victoria (Canada); S. Johnson, Arizona State Univ. (United States)

The design new long wavelength material on GaAs substrates with the ability to produce telecom or even longer wavelengths on GaAs substrates is a major task in todays development of novel alloyed semiconductor materials. Recently, dilute Ga(AsBi) has been proposed as a potential candidate for an such an emitter material due to its giant bandgap bowing.

Here, we present time-resolved photoluminescence experiments on a 30nm Ga(AsBi) epilayers as function of excitation flux and lattice temperature. The sample contains a Bi fraction of about 4.5% and was grown by molecular beam epitaxy on semi-insulating 100 GaAs substrate. A 80MHz, 100fs Ti:sapphire oscillator centred at 1.55eV and 1.35eV is used for excitation above and below the GaAs substrate band gap energy; a standard spectrometer and streak-camera setup with a water-cooled S1 cathode yielding a time-resolution of 2ps is used for detection. The peak of the near band edge emission shifts from 1.13eV to 1.23eV as the excitation flux is increased beam more than two orders of magnitude at a lattice temperature of 10K. This blue shift is a clear sign of disorder present in the system. This is also supported by the low-energy tail of the emission spectrum which is spectrally more flat than the high-energy flank. The decay times increase across the emission band indicating a complex interplay between carrier relaxation and recombination. A pronounced S-shape is found for the emission peak as function of lattice temperature yielding a disorder potential of several 10's of meV.

7597-20, Session 5

Carrier dynamics in ZnMgO studied by time-resolved photoluminescence

A. Chernikov, M. Koch, S. Chatterjee, K. Volz, B. Pasenow, S. W. Koch, Philipps-Univ. Marburg (Germany); P. J. Klar, M. Eickhoff, B. K. Meyer, Justus-Liebig-Univ. Giessen (Germany); B. Laumer, T. A. Wassner, M. Stutzmann, Technische Univ. München (Germany)

A major step towards the development of ZnO-based UV emitters is the development of quantum well structures. Typically, Zn1-xMgxO is used as barrier material due to its similar in-plane lattice parameter and considerable band offsets. Here, we investigate the properties of different wurtzite Zn1-xMgxO epilayers with varying Mg contents. All samples were grown by plasma-assisted molecular beam epitaxy on c-plane sapphire substrates, using a MgO/ZnMgO buffer .

We perform time-resolved photoluminescence experiments as function of excitation flux and lattice temperature. A frequency-tripled 80MHz, 100fs Ti:sapphire oscillator centred at 4.3eV is used for excitation; a standard streak camera setup yielding a time-resolution of 800fs is used for detection.

The peak of the near band edge emission shifts from 3.38eV to 4.05eV as the Mg concentration is increased from x=0 to x=0.35 at a lattice temperature of 10K. The decay times increase by more than one order of magnitude as the Mg concentration increases indicating stronger localization. This is further supported by an increase of the respective spectral linewidths.

Typically, a series of phonon replica is observed for all samples. At low temperatures, the sample with x=0 (clearly) shows replica of the near band-edge emission while the replica signatures from bound excitons become more important as the Mg concentration is increased.

The bound excitons are ionized as the lattice temperature is increased revealing the zero phonon line as well as phonon replica associated with the free exciton emission line similar to the well-known ZnO material system.

7597-21, Session 5

Frequency modulation response of two-section quantum cascade lasers

E. Luzhansky, F. Choa, Univ. of Maryland Baltimore County (United States)

Abstract: we describe the theory of frequency modulation (FM) response of Quantum Cascade Lasers (DFB QCL). It includes cascading effect on QCL's maximum modulation frequency. Theory is enhanced with description of FM response of two section Distributed Feedback Laser (DFB) QCL. It is shown, that, in contrast to laser diodes, the FM response of two section QCLs is independent of the optical power. It can be optimized by correlation of two sections' effective lengths and by controlling the relative difference of their linewidth enhancement factors, . Utilization of model for the single section DFB QCL and agreement with previous results is shown as well.

7597-22, Session 5

Physical-random number generation using laser diodes' inherent noises

H. Nishimura, K. Doi, T. Ushiki, T. Sato, M. Ohkawa, Y. Odaira, Niigata Univ. (Japan)

Random numbers can be classified as either pseudo- or physical-random in character. This work demonstrates how laser diodes' inherent noise can be exploited for use in generating physical-random numbers in the field of cryptography.

Pseudo-random numbers' periodicity renders them inappropriate for use in cryptographic applications, but, naturally-generated, physical-random numbers have no calculable periodicity, thereby making them ideally-suited to the task. Laser diodes naturally produce a wideband "noise" signal that is believed to have tremendous capacity and great promise, for the rapid generation of physical-random numbers for use in cryptographic applications.

Because the character and shape of the laser diode's oscillation exert tremendous influence on the intensity and frequency noises, we need to determine which noise is best suited for the generation of fast physical-random numbers. To do this, we worked to identify the frequency noises by observing the transmitted light intensity through the frequency reference, and generated the physical-random numbers using an analog-digital (A/D) converter that produces, for example, 8-digits binary numbers from the detected laser intensity.

In the initial stages of the experiment, we measured a laser diode's output, at a fast photo detector and generated physical-random numbers using laser diode's intensity noises. We then identified and evaluated the binary-number-line's statistical properties. Because the frequency noise has higher frequency components than the intensity noise has, our preliminary result shows that fast physical-random numbers are obtainable, using the laser diode's frequency noise characteristic.

7597-23, Session 5

Complex low energy gain switching pulse processing using a highly nonlinear optical loop mirror

C. de Dios Fernandez, H. R. Lamela, Univ. Carlos III de Madrid (Spain)

When it comes to obtaining short optical pulses from diode lasers, Gain Switching (GS) shows as a direct and straightforward technique. It is a compact source for frequency tunable, high repetition rate, low-cost optical pulses in the picosecond range that can be applied to Commercial Off the Shelf (COST) diode lasers. Pulses from GS are widely used nowadays [1][2]. However, their application in new fields is at times limited. The pulses obtained have low power, an asymmetric shape and frequently present a trailing substructure that forms pedestals [3]. Depending on the laser technology considered, Fabry-Perot lasers, DFB [4] or VCSELs [5], the pulses generated vary from hundreds of picosecond to tens of picoseconds. Thus, improving the quality of GS pulses, due to their complex structure, low power and long temporal width, is a challenging task.

Nonlinear Optical Loop Mirrors (NOLM) are interferometric nonlinear devices based on an optical fiber Sagnac configuration, which are extensively used as part of optical communication systems [6] and as pulse compression and shaping devices. They are versatile and several studies have proposed different designs for these loops [7][8]. Hence, they make good candidates for the improvements of GS sources. However, as nonlinear devices, they exhibit a power dependant behavior. Then, the performance of NOLM is sensitive to the characteristics of the input pulse train. Also, long loops and high input energies are often needed to obtain compression or reshaping of the pulses. As a result, the capabilities of NOLMs cannot be used directly on low quality pulses, such as those obtained from GS diode lasers, without preprocessing stages [9].

In this work, we study the improvement of complex low quality pulses obtained from GS sources using a compact Highly Nonlinear Optical Loop Mirror (HNOLM) based on a high speed Nonlinear Semiconductor Optical Amplifier (NLSOA) and a Microstructured Optical Fiber (MOF). The loop is compact, containing 20 m of optical fiber and does not require any intermediate stage to process the pulses. The capability of the HNOLM to improve the pulse characteristics has been studied for several input energies in this work. Finally, the pulse quality has been evaluated too using the temporal pulse width, spectral width, pulse shape, pedestals height and pedestal width. Results show that HNOLM provides direct compression and pulse shaping for picosecond complex pulses obtained from a DFB COTS laser operating within the 1550 nm window.

References:

[1] H. Shams, A. Kaszubowska-Anandarajah, P. Perry, and L. Barry, “Demonstration and optimization of an optical impulse radio ultrawideband distribution system using a gain-switched laser transmitter,” Journal of Optical Networking, vol. 8, no. 2, pp. 179-187, 2008.

[2] H Liu, C. Gao, J. Tao, W. Zhao, and Y. Wang, “Compact tunable high power picosecond source based on Yb-doped fiber amplification of gain switch laser diode,” Optics Express, vol. 16, no. 11, 2008.

[3] P. Vasil’ev, I.H. White, and J. Gowar, “Fast phenomena in semiconductor lasers,” Rep. Prog. Phys., vol. 63, 2000.

[4] K. Otsubo et al., “Uncooled 25 Gbis/s direct modulation of semi-isulating buried-heterostuctured 1.3 um AlGaInAs quantum-well DFB lasers”,” Electronics Letters, vol. 44, pp. 631-633, 2008.

[5] M. Nakazawa, H. Hasegawa and Y. Oikawa, Student Member, IEEE “10-GHz 8.7-ps Pulse Generation From a Single-Mode Gain-Switched AlGaAs VCSEL at 850 nm” IEEE Photonics Technology Letters, vol. 19, no. 16, 2007.

[6] S. Boscolo, S. K. Turitsyn, and K. J. Blow, “Nonlinear loop mirror-based all-optical signal processing in fiber-optic communications,” Optical Fiber Technology, vol. 14, pp. 299-316, March 2008.

[7] S. Takamatsu, H. Watanabe, T. Matsuyama, H. Horinaka and K. Wada, “Pulse-shaping of gain-switched pulse from multimode laser diode using fiber Sagnac interferometer,” Optics Express, vol. 16, no. 24, 2008.

[8] K. Smith, E.J. Greer, N.J. Doran, D.M. Bird, and K.H. Cameron, “Pulse amplification and shaping using a nonlinear loop mirror that incorporates a saturable gain,” Optics Express, vol. 17, no. 6, pp. 408-410, March 1992.

[9] Y. J. Chai, I. Y. Khrushchev, R. V. Penty, and I. H. White, “Interferometric Noise Suppression by Means of Dispersion-Imbalanced Loop Mirror Over a Wavelength Range of 28 nm,” IEEE Photonic Technology Letters, vol. 14, no. 3, 2002.

7597-24, Session 6

Quantum design and experimental realization of high-power VECSELs

S. W. Koch, Philipps Univ. Marburg (Germany)

Our micsrocsopic quantum theory is used to design VECSELs for special emission wavelengths and/or high power output. The main ingredients of the quantum design scheme are reviewed and examples of realized structures and experimental results are shown.

This work is done in collaboration with J.V. Moloney, J. Hader, Y. Kaneda et al. Tucson, W. Stolz, B. Kunert, S. Chatterjee, et al., Marburg

7597-25, Session 6

Cavity design and heat management in vertical-external-cavity surface-emitting lasers (VECSELs)

T. Lu, Y. Kaneda, M. J. Yarborough, College of Optical Sciences, The Univ. of Arizona (United States); J. Hader, Nonlinear Control Strategies, Inc. (United States); J. V. Moloney, College of Optical Sciences, The Univ. of Arizona (United States) and Nonlinear Control Strategies (United States); A. Chernikov, M. Koch, B. Kunert, W. Stolz, S. Chatterjee, C. Bückers, S. W. Koch, Philipps-Univ. Marburg (Germany)

Vertical-External-Cavity Surface-Emitting Lasers (VECSELs) or semiconductor disk lasers in the infrared spectral range display a highly desirable combination of high output power, good efficiency, and good beam quality out of a small package. Additionally, high-speed frequency-doubled semiconductor disk lasers have been realized covering large parts of the visible spectrum, e.g., for full-color laser projection or as laser guide-star systems. The realization of high-power devices such as the latter requires a careful interplay between cavity design and heat management.

We experimentally investigate a model high-power device. A 1040nm VECSEL is realized using the semiconductor chip and a spherical output coupler in a linear cavity design. First, the performance is investigated as function of the reflectance of the output coupler. Next, we investigate the influence of the pump spot profile on the lasers parameters. It is investigated by varying the pump optics and their geometry, e.g., angle under which the pump is incident and role of aberrations such as defocus or tilt, such that the performance is optimized.

Different heat spreading and heat removal concepts in materials such as copper and diamond are compared. The respective performance is monitored under comparable high power pumping and cavity conditions by recording the spectrally resolved emission and the input-output characteristics. Finally, different cavity geometries, their respective impact on the mode size at the active region and the consequences for power scalability are discussed.

7597-26, Session 6

Ultrafast circular polarization oscillations in spin-polarized vertical-cavity surface-emitting laser devices

N. C. Gerhardt, M. Li, H. Jaehme, H. Soldat, M. R. Hofmann, Ruhr-Univ. Bochum (Germany); T. Ackemann, Univ. of Strathclyde (United Kingdom)

The combination of spin injection with optical amplification in spin-lasers offers new encouraging possibilities for future devices. Here we investigate the room temperature spin, carrier and polarization dynamics of electrically pumped vertical-cavity surface-emitting lasers (VCSELs) on a picosecond time scale, after injection of a small degree of spin polarization for the electron band population. For this purpose, we apply a hybrid excitation technique combining continuous-wave unpolarized electrical and picosecond spin-polarized optical excitation of a commercial VCSEL device. The experimental results demonstrate ultrafast circular polarization oscillations due to spin injection with an oscillation frequency of 11.6 GHz. The polarization dynamics are faster than the intensity dynamics due to the relaxation oscillations. Even more interesting, the circular polarization oscillations persist for more than 5 ns after spin injection, which is much longer than the spin-relaxation time in this device. We compare the experimental results with theoretical calculations on the basis of rate equation models for spin-polarized lasers in order to analyze the complex interplay between birefringence, spin- and carrier relaxation as a reason for the long persisting circular polarization oscillations in spin-VCSELs. A detailed understanding of the spin-dynamic mechanism of the polarization oscillations offers the possibility for independent polarization and intensity modulation in future spin-VCSEL devices.

7597-27, Session 6

Electro-optically modulated VCSELs and RCLEDs

J. A. Lott, V. A. Shchukin, N. N. Ledentsov, VI Systems GmbH (Germany); T. D. Germann, A. Strittmatter, A. Mutig, D. Bimberg, Technische Univ. Berlin (Germany)

We present the design, simulation, operating principles, growth, fabrication, and measured performance results of 850 nm-range electro-optically modulated (EOM) vertical cavity surface emitting lasers (VCSELs) and resonant cavity light emitting diodes (RCLEDs). The device structures are grown in a well-controlled single monolithic epitaxial growth step by both molecular beam epitaxy and metal-organic vapor phase epitaxy and are produced via standard large-volume micrometer-scale-device processing techniques. Finally we discuss how to use this innovative approach for the realization of high speed (> 10 Gb/s) optical signal modulation to enable the next generation of low cost and extremely reliable short-reach optical data communication systems.

7597-28, Session 7

Micro-diffraction lenses with subwavelength structures designed by the genetic algorithm

T. Shirakawa, Univ. of Tokyo (Japan); K. L. Ishikawa, RIKEN (Japan); S. Suzuki, Y. Yamada, Ricoh Co., Ltd. (Japan); H. Takahashi, Univ. of Tokyo (Japan)

Recent progress of nanotechnology has enabled the fabrication of diffractive optical elements (DOEs) with subwavelength structures (SWSs). However SWS DOEs can be designed neither by scalar diffraction theory nor by Fourier optics. To solve this difficulty, we have recently developed a design method based on the finite-difference time-domain (FDTD) method and the genetic algorithm (GA), called the GA-FDTD method. In this study, we present the design of SWS micro diffraction lenses with a 4 µm radius.

Maxwell's equations are solved by the FDTD for a system with axial symmetry with the perfectly matched layer absorbing boundary condition. The relief structure and height of the lens are optimized with the GA using binary coding. In consideration of actual fabricability, the grating width is 100 nm at least and the aspect ratio is 5 at most.

The optimized structure has more than twice as high focusing ability at a wavelength of 660 nm as that previously reported based on the binarization of the Fresnel lens, and turns out to be robust against fabrication error. Its grating height (400 nm) is different from that of the Fresnel lens (576 nm), and the relation between the widths of neighboring gratings cannot be expressed in a simple way. Furthermore, we have successfully designed a lens with equal focal length at three different wavelengths (660, 532, and 445 nm). The structures, which are not intuitive, are hard to deduce from experiences. These results indicate the effectiveness of the GA-FDTD method in the design of SWS DOEs.

7597-29, Session 7

LED integrated optical encoder

L. Acevedo, M. P. Y. Desmulliez, Heriot-Watt Univ. (United Kingdom)

The incoherent wave front emitted from a LED can be modelled by analysing the diffraction produced by a 4 micron period grating attached to the refractive glass sitting on top of the LED. Such a configuration is used for optical encoding application [reference needed, paper by John Carr, ESTC 2008.

In our application, the 460 microns diameter LED with an epitaxy thickness of 3.066 um is used within a monolithically integrated optical encoder. The incident light source from the LED is impinging onto the index grating manufactured at the surface of the substrate of the LED and further transmitted to a scale grating with a diffraction order of +1 and -1. Surfaces to determine the incidence irradiance (power/unit-area) impinging into the photodetector placed 1 mm away, the emitted divergence radiance per solid angle (power/steradian), and the diffractive flux allow us to compare these optical outputs with those obtained experimentally. Experimental data have been obtained by recording the power incident on the tip of a 8 um core optical fiber as it scans across the LED. Moreover, the theoretical model and the measured Lambertian beam are compared to the output parameters of the LED (2013 Farfield LED) as shown in Figures (1,2) and simulated source in Figures (3, 4, 5) below.

The simulating environment determines the behaviour of the rays of the light source in a Lambertian wavefront profile. It also predicts the Talbot effect produced by the grating when the light is propagated to the gratings of the optical encoder. Therefore by analysing the geometric configuration of the system such as the gratings period and pitch, the distance between LED and photodetectors, can be optimised to reduce optical crosstalk and increase output throughput

References

Optical Encoder Readhead Chip 078-1-4244-2814-4/08/$25.00@2008 IEEE

7597-30, Session 7

Study of propagation modes of bent waveguides and micro-ring resonators by means of the aperiodic Fourier modal method

D. Bucci, B. Martin, A. Morand, Institut de Microélectronique Électromagnétisme et Photonique (France)

In the last years, several numerical methods have been studied and applied to the analysis of high index contrast bent waveguides.

Very often, the problem is treated by using a conformal mapping, which

translates the bending into an equivalent index profile.

In this article, we will discuss the implementation of a full vectorial 2D mode solver by means of the Aperiodic Fourier Modal Method, developed directly in cylindrical coordinates.

In the first part of our work, we will develop a shorthand notation and the mathematical rules useful to describe the problem in a matrix form. The search of propagation modes is then reconducted to the search of eigenvectors of a matrix. We will at first test our formulation in 1D with results given by the conformal mapping technique.

In a second time, we will use the complete 2D solver to the determination of the resonance frequencies and quality factors of micro-ring resonators made on silicon surrounded by silica. These characteristics are related to the real and imaginary part of the propagation constants. By comparison with 3D-FDTD analysis, we will show how our implementation can be used to accurately describe the behavior of micro-rings having a bending radius as low as 1 µm. This technique is general and can be applied on micro-rings having an arbitrary cross-section and a quality factor comprised between 100 and 10000.

Perspectives of this work include the study of the propagation, as well as the coupling between micro-ring resonators and waveguides.

7597-32, Session 7

Three-dimensional meshfree numerical method for optical structures

F. Alharbi, King Abdulaziz City for Science and Technology (Saudi Arabia) and IBM Almaden Research Ctr. (United States); J. C. Scott, IBM Almaden Research Ctr. (United States)

A new and efficient three dimensional multi-domain spectral method formulation is developed to simulate and analyze optical structures. The formulation is meshfree and functional expansion based where the unknown physical quantities are approximated by expansions by preselected basis sets. The expansion coefficients are satisfying the governing equations. This is the fundamental difference between spectral methods and the conventional finite difference and finite element methods, where the unknown quantities are approximated by their values at meshing points.

To enhance the performance of the method, the computational window is divided into domains where the structural functions are smooth. This allows avoiding the errors that are caused by the Gibbs phenomenon, which is associated with discontinuities. For bounded domains, Chebyshev polynomials and Fourier series are used and predefined exponential basis sets are used for half-bounded ones.

The formulation is very flexible where multiple coupled physical quantities can be obtained simultaneously. For example, in the case of electromagnetic field, the three electric field components are solved concurrently. Also, the boundary conditions are considered analytically without any approximation. Additionally and as common for spectral methods, the method is very accurate and fast. This is mainly because the approximation by expansion reduces the numerical time and memory requirements.

The method is used to study wave propagation and scattering and modal behavior of many optical structures. To demonstrate the validity and the accuracy of the presented method, it is compared with various published methods, where many optical structures are studied.

7597-33, Session 7

Synthesis of titanium indiffused LiNbO3 waveguides with desired modal fields

E. K. Sharma, Univ. of Delhi (India); G. J. Saxena, Univ of Delhi (India)

In this paper we report a procedure based on variational approximation, to obtain the refractive index profile and in turn the process parameters for fabrication of waveguide from the desired modal field. It has been shown that the best variational separable field for a channel waveguide corresponds to the solution of two equivalent planar waveguides in the x and y directions. We show that for a desired modal field X(x)Y(y), one can obtain the refractive index profile parameters , h and w. We have illustrated the use of the procedure in the design of waveguides for optimum coupling efficiency between a fiber and waveguide. Assuming the separable channel waveguide field it is possible to extract the optimal modal field parameters and hence, the refractive index profile parameters, for maximum coupling efficiency which in turn define the process parameters or fabrication conditions of the waveguide such as temperature and time of diffusion, width and thickness of the titanium strip. For a given strip width, each profile width w corresponds to a fixed profile depth h. In an attempt to maximize coupling efficiency along the x-direction to unity by appropriate choice of X(x) for a typical communication fiber, we realized that the corresponding w resulted in an h which reduced efficiency in the y-direction to a very small value. Hence, it was necessary to compromise on the choice of X(x); we restricted the choice so as to obtain an efficiency of above 90% in the x-direction. With this choice it is possible to find an appropriate h and n for maximum coupling efficiency. Once the three parameters h, w and are known, the strip thickness, time and temperature can be defined. The results have been validated by comparison with those obtained by simulation on the BPM CAD simulator.

7597-34, Session 8

InAs quantum dot-based devices for ultrafast photonic signal processing

O. Wada, Kobe Univ. (Japan)

This paper discusses first the quantum dot (QD) growth technique based on molecular beam epitaxy (MBE), and then describes their application to photonic devices for ultrafast telecommunications such as SOAs and all-optical switches. An important issue in QD-SOAs is the polarization sensitivity which is primarily caused by the flattened shape of QDs. We have introduced our unique approach of columnar dot technique in which a number of QD layers are closely stacked to form a better geometrical isotropy. By optimizing the geometry and strain in InAs/InGaAs/InP QD system, polarization-insensitive SOA performance has been demonstrated for the first time at 1.55 mm. We also propose an alternative approach of using remotely stacked QD layers and demonstrate basic polarization-insensitive characteristics. As for all-optical switches, recent result of vertical structure QD-based all-optical switches is described. This switching device has a vertical cavity composed of a pair of asymmetric distributed Bragg reflectors (DBRs) incorporating a QD nonlinear medium. Through optimizing the design and fabrication of vertical structure all-optical devices, optical reflection-type switch response with a time constant as fast as 23 ps has been demonstrated. We thus illustrate the unique prospects of QD-based devices to future photonic communication and signal processing systems.

7597-35, Session 8

Thermal crosstalk reduction in IR thermo-electric photodetectors by lock-in method: 4D numerical simulations and experimental verification

W. Vandermeiren, J. Stiens, C. De Tandt, Vrije Univ. Brussel (Belgium); G. Shkerdin, V. Kotov, Institute of Radio Engineering and Electronics (Russian Federation); G. Borghs, IMEC (Belgium); P. Muys, Lambda Research Optics Europe (Belgium); R. Vounckx, Vrije Univ. Brussel (Belgium)

Laser induced temperature distributions inside doped semiconductor materials are used to derive laser beam profiles by means of the thermo-

electric Seebeck effect. Thermal diffusion will lead to a discrepancy between the optical intensity profile of the laser beam and the measured temperature distribution inside the semiconductor. An advanced numerical 4D finite element model describing the laser induced spatial temperature distribution in function of time in a layered GaAs based structure was developed in Comsol Multiphysics. Non-linearities as the temperature dependence of the absorption coefficient, the thermal conductivity and the Seebeck coefficient were taken into account. This model was used to investigate the optical chopper frequency dependence on the spatial thermal crosstalk level and the responsivity near the illuminated surface of the detector structure. It was shown that the frequency dependent crosstalk level can be reduced significantly by applying short chopping periods with respect to the thermal diffusion time constant. The thermal crosstalk is reduced to -10dB and -20dB for the first and second neighboring pixel respectively for a lockin frequency of 300 Hz. Experimental results of the spatial thermal crosstalk level and the responsivity were compared with simulations and satisfactory agreements between both were achieved. High power CO_2 laser profile measurements obtained with our thermoelectric detector and a commercially available Primes detector were compared.

7597-37, Session 8

Ultrafast compact silicon-based ring resonator modulators using metal-insulator switching of vanadium dioxide

J. Nag, J. D. Ryckman, R. F. Haglund, Jr., S. M. Weiss, Vanderbilt Univ. (United States)

We describe an optical modulator based on a silicon ring resonator coated with vanadium-dioxide (VO_2) motivated by the need for compact silicon-compatible optical switches operating at THz speeds. VO_2 is a functional oxide undergoing metal-insulator transition (MIT) near 67C, accompanied by huge changes in electrical resistivity and near-infrared transmission. The MIT can be induced thermally, optically (by ultra-fast laser excitation in less than 100fs), and possibly with electric field. The ability to optically induce an ultrafast phase change in VO_2 presents an excellent opportunity to realize high speed all-optical modulation in compact device structures. During transition, the large change in the refractive index (~1.96-3.25) in the near infrared, renders VO_2 appropriate for integration with silicon-based ring resonators at telecommunication frequencies. VO_2 is easily deposited on silicon and its ultrafast switching properties can be used to tune the effective index of ring resonators instead of depending on the weak electro-optic properties of silicon. The VO_2-silicon ring resonator is thus expected to operate at speeds up to 10 THz utilizing low Q-factor, with shorter cavity lifetimes, thus enabling faster, more robust device response while maintaining compact device size. We are carrying out a proof-of-concept study using double-layer e-beam lithography to make ring resonator structures on SOI substrates with rings varying in diameter from 2- 22 um coupled to 98um-long nanotapered waveguide at a separation of 200nm. The rings will be coated with 50nm of VO_2 by pulsed laser deposition. Our FDTD simulation results predict large modulation effects by switching the VO_2 thermally.

7597-76, Session 8

Finite difference time domain analysis of ultra-broadband enhanced absorption of silicon surface with nanostructures

H. Wang, C. Chen, J. Wu, National Chung Cheng Univ. (Taiwan); S. Feng, National Univ. of Kaohsiung (Taiwan); S. Liu, National Chung Cheng Univ. (Taiwan)

We investigate the ultra-broadband enhanced absorption properties in a wavelength range of 0.3~1.2 μm for silicon surface with nanostructures by using finite difference time domain (FDTD) algorithm. Three different types of surface structures including cone-like, air-hole, and inverted Pyramids structures are simulated. We demonstrate absorptance enhancement of silicon surface with varying different geometric arrangements, structure sizes, and shapes. The best enhancement structure is cone-like type which can suppress the reflection of surface about 2.5%. We design a special arrangement for air-hole type surface that can increase the absorption of solar surface about 65%. In the inverted Pyramids structures, we find the U shape of structure will increase the absorption efficiency due to a gradual change of refractive index. The physics of such remarkable absorption for the structured silicon surfaces are discussed as well.

7597-40, Session 9

Random lasing in nanocrystalline ZnO powders

H. Kalt, J. Fallert, R. Dietz, J. Sartor, D. Schneider, C. F. Klingshirn, Univ. Karlsruhe (Germany)

We study the properties of random lasing modes in nanocrystalline ZnO powders by spatially resolved high-excitation photoluminescence spectroscopy. Both localized and extended modes are observed in the same spatial region of the powder. We find that the localized modes appear at much lower optical gain than the extended ones as predicted by theory.

7597-41, Session 9

Control random laser modes by local pumping

H. Cao, Yale Univ. (United States)

A difficulty concerning the practical application of random lasers is the lack of precise control over lasing mode properties. We show that the lasing modes can be modified by inhomogeneous pumping of random media. The spatial inhomogeneity of gain causes dramatic and complicated changes of the lasing modes even in the absence of gain saturation. Some lasing modes disappear, while new modes are created at various frequencies.

7597-42, Session 9

Visible-wavelength random lasing of (Zn,Cd,Mg)O quantum well structures

S. Kalusniak, S. Sadofev, J. Puls, H. Wuensche, F. Henneberger, Humboldt-Univ. zu Berlin (Germany)

Semiconductor lasers operating in the visible wavelength range have been a subject of extensive research during the past years. Ternary ZnCdO is a material with considerable potential in this regard, as it can cover in principle band-gaps from the ultraviolet to the near infrared spectral range.

We have systematically fabricated (Zn,Cd)O/ZnO single and multiple quantum well structures and elucidated their optical properties. In the low-density excitation regime, huge polarization-induced electric fields of some 108 V/m are signified by a strong red shift of the photoluminescence band with increasing well width as well as an increase of the lifetime from the ps- to the µs-time scale. Effective screening of these fields occurs already at moderate optical excitation in the 10 kW/cm² range and recovers practically the bare quantum-confined transition energies and short lifetimes. In the same excitation range laser action of specially designed multiple quantum well structures is observed. The low-temperature lasing threshold is only 25 kW/cm² and increases moderately up to room temperature (150 kW/cm²). The emission wavelength is systematically tuneable by structure design. The longest lasing wavelength achieved so far is 510 nm at room temperature.

The laser action can be achieved without preparation of an optical cavity. Both spectral position and separation of the lasing modes are determined by the geometrical shape of excitation area and vary with the excitation power. A theoretical model assuming weak scattering reproduces the experimental finding reasonably well. For specially prepared micro-resonators, narrowing of the mode band and mode selection is demonstrated.

7597-43, Session 10

Lasing osicllation in a single quantum dot nanocavity system under strong/weak coupling regime

Y. Arakawa, M. Nomura, S. Iwamoto, Y. Ota, N. Kumagai, The Univ. of Tokyo (Japan)

We dicuss recent advances in light-matter interaction in a single quantum dot embedded with photonic crystal nanocavity. We have successfully demonstrated a transition from strong coupling regime to lasing oscillation by the single dot gain.

7597-44, Session 10

Radiative efficiency of MOCVD grown quantum dot lasers

L. J. Mawst, G. Tsvid, P. Dudley, J. Kirch, J. H. Park, Univ. of Wisconsin-Madison (United States)

Quantum dot lasers have been reported by MBE growth with high performance, although previous reports indicate that the overall radiative efficiency (i.e. Jspon/Jtotal) from such structures is surprisingly low (5-25%). Here, we study the gain and radiative efficiency of MOCVD grown InGaAs quantum dot lasers. Single-pass, multi-segmented amplified spontaneous emission measurements are used to obtain the gain, absorption, and spontaneous emission spectra in real units. Integration of the calibrated spontaneous emission spectra then allows for determining the overall radiative efficiency, which gives important insights into the role which nonradiative recombination plays in the active region under study. We use single pass, multi-segmented edge-emitting in which electrically isolated segments allow to vary the length of a pumped region. In this study we used 8 section devices (the size of a segment is 50x300 µm) with only the first 5 segments used for varying the pump length. The remaining unpumped segments and scribed back facet minimize round trip feedback. Measured gain spectra for different pump currents allow for extraction of the peak gain vs. current density, which is fitted to a logarithmic dependence and directly compared to conventional cavity length analysis, (CLA). The extracted spontaneous emission spectrum is calibrated and integrated over all frequencies and modes to obtain total spontaneous radiation current density and radiative efficiency. We find radiative efficiency values of approximately 25% at RT for 5 stack QD active regions. By contrast, high performance InGaAs QW lasers exhibit radiative efficiency ~50% at RT.

7597-45, Session 10

Inhomogeneous quantum dot gain medium for improved spatial coherence in wide-aperture semiconductor lasers

J. Mukherjee, Tyndall National Institute (Ireland); J. G. McInerney, Univ. College Cork (Ireland)

Scaling the brightness (spatial coherence) along with output power has been a long-standing problem for semiconductor lasers. The difficulty arises due to complex spatio-temporal modal filamentation associated with light-matter interaction in the non-linear semiconductor lasing medium. We have done a detailed theoretical study of spatio-temporal dynamics in wide aperture semiconductor lasers in order to identify factors limiting spatial coherence in the high power regime, thereby finding routes to scale the brightness using the unique properties of quantum confined active regions. In this context, we have developed a detailed opto-electro-thermal model, based on Maxwell-Bloch formalism, to describe frequency-, carrier- and temperature-dependent gain and dispersion. First a steady-state electro-thermal model is developed to simulate the current and heat spreading in the laser. The thermal model is then used in conjunction with the Maxwell-Bloch based dynamical model to obtain pump-dependent modal intensity structure and spatial frequency spectral characteristics. Effects of both homogeneous and inhomogeneous gain broadening are analysed. It is shown, via linear stability analysis and high resolution space-time adaptive FEM simulations that crystal growth induced inhomogeneous gain broadening in quantum dot lasers enhances spatial coherence and leads to suppressed filamentation and stable far-fields in both thermal and non-thermal regimes even when the phase-amplitude coupling is comparable to that in quantum well gain medium. Strong spatial-mode competition in the inhomogeneously broadened gain medium under cw operation is also highlighted.

7597-46, Session 10

Bipolar self-consistent optoelectronic model for quantum dot lasers

A. Martín-Mínguez, H. Odriozola, I. Esquivias, J. M. G. Tijero, Univ. Politécnica de Madrid (Spain); E. Pavelescu, J. P. Reithmaier, Univ. Kassel (Germany)

We present a simulator for Quantum Dot (QD) laser diodes. The simulator solves the complete bipolar semiconductor equations for the heterostructure. The special features of QD active layers are included through a multi-population non-equilibrium QD model. The interactions between the bulk material and Wetting Layer (WL), and between WL and each QD level and size are considered in terms of carrier capture/escape processes. The model includes inhomogeneous broadening due to the different QD size, homogeneous broadening in the gain, Shockley-Read-Hall, spontaneous and Auger recombination terms for bulk, WL and QD carriers.

The simulator is applied to 920 nm and 1060 nm lasers based on InGaAs/(Al)GaAs.

The influence of theoretical parameters, such as the homogeneous and inhomogeneous broadening, recombination parameters, capture times, band-offset, on the laser performance is analyzed. It is found that the maximum achievable gain depends on the symmetry of the QD electron and hole densities, which in turn depends on the band alignment. The simulation results are compared with experiments in broad area QD lasers. A high contribution of the bulk and/or WL non-radiative recombination terms has to be assumed to obtain a good agreement between the experimental and simulated threshold current densities and slope efficiencies. The measured temperature dependence of the emission wavelength for devices with different cavity lengths is reproduced in the simulations.

7597-47, Session 10

Bandwidth improvement by manipulating the high-frequency roll-off of an injection-locked QD laser operating at 1310 nm

N. A. Naderi, M. C. Pochet, The Univ. of New Mexico (United States); V. Kovanis, Air Force Research Lab. (United States); L. F. Lester, The Univ. of New Mexico (United States)

The high-speed modulation characteristics of an injection-locked quantum dot Fabry-Perot semiconductor laser operating at 1310-nm under strong injection are investigated experimentally with a focus on the enhancement of the modulation bandwidth. The coupled system consists of a small-signal modulated quantum dot slave injected-locked by a CW DFB laser as the master. At particular injection strengths and frequency detuning levels between the master and slave laser, a unique modulation response is observed that differs from the typical modulation response observed in injection-locked systems. This unique response is characterized by a rapid low-frequency rise along with a 20 dB per decade high-frequency roll-off (typically 40 dB per decade) that enhances the 3-dB bandwidth of the locked system at the expense of losing modulation efficiency of about 20 dB at frequencies below 1 GHz. Such behavior has been previously observed both experimentally and theoretically in the high-frequency response characteristic of an injection-locked system using an externally-modulated master; however, the results shown here differ in that the slave laser is directly-modulated. The benefit of the observed response is that it takes advantage of the enhancement of the resonance frequency achieved through injection-locking without experiencing the low frequency dip that significantly limits the useful bandwidth in the conventional injection-locked response. The second benefit of this unique response is the improvement in the high frequency roll-off that extends the bandwidth. Finally a bandwidth improvement of ~7 times compared to the free-running slave laser has been achieved.

7597-48, Session 11

Modeling of photonic-crystal-based high-power high-brightness semiconductor lasers

V. Shchukin, PBC Lasers GmbH (Germany); V. Kalosha, N. Ledentsov, D. Bimberg, Technical University of Berlin (Germany)

Modeling of semiconductor lasers based on multilayer epitaxial structures with ultrabroad vertical and ultrabroad lateral waveguides (WGs) suggests unique possibilities to fabricate high power high brightness lasers. Ultrabroad WGs are extremely advantageous as they allow extracting high power from a single chip, keeping low beam divergence and reducing undesirable non-linear effects in the gain medium, while one must ensure single mode lasing from a broad WG. Novel concepts addressing this challenge have been developed including vertical photonic crystal formed by epitaxial multilayer structure, lateral photonic crystal fabricated by multistripe processing with selective pumping of stripes, tilted wave laser based on phase matching effects in the propagation of optical modes in coupled resonators. The results have been employed in the fabrication of practical semiconductor lasers. Experimental results on high brightness lasers are presented [1] for the wavelength regions of 635-660 nm, 850 nm, 980 nm, and 1060 nm.

[1] Dieter Bimberg et al, Photonics West 2010, OE120

7597-49, Session 11

Applying the joint Wigner time-frequency distribution to characterization of ultra-short optical pulses in the actively mode-locked semiconductor laser with an external single-mode fiber cavity

A. S. Shcherbakov, P. Moreno Zarate, National Institute for Astrophysics, Optics and Electronics (Mexico); J. Campos Acosta, Consejo Superior de Investigaciones Científicas (Spain); Y. V. I. Il'n, I. S. Tarasov, A.F. Ioffe Physical-Technical Institute (Russian Federation)

An attempt is made to develop an approach to characterization of high-repetition-frequency trains including low-power picosecond optical pulses with an internal frequency modulation in both time and frequency domains in the case of exploiting semiconductor lasers matched effectively by an external single-mode fiber cavity. For these lasers, we analyze non-conventional regimes of the active mode-locking, which are connected with injecting various modulating signals and appearing specific composite states of a multi-pulse active mode-locking. Then, our approach uses the joint Wigner time-frequency distributions, which can be found due to involving the recently developed interferometric technique. In so doing, the modified scanning Michelson interferometer was exploited for shaping the field-strength auto-correlation functions peculiar to the above-mentioned types of light radiation. Theoretically, the Wigner distribution has an infinite resolution in time due to absence of averaging over any finite time interval. Moreover, for any finite lag length, it has an infinite frequency resolution. Together with this, the Wigner distribution being quadratic in nature is able to introduce various cross terms for a multi-component signal. For our analysis and creating the Wigner distributions, the data of experiments carried out with the InGaAsP/InP-heterolasers, operating at a wavelength of 1300 nm, had been used. When the optical signal consisted of contiguous ultra-short pulses with the repetition frequency up to 1.5 GHz, due to operating the semiconductor lasers in various active mode-locking regimes, typical pulse train-average auto-correlation functions had been characterized by temporal widths of about 3-15 ps. Additionally, stability of the chosen active mode-locking regimes had been followed and estimated.

7597-50, Session 11

Stability analysis of (Al,In)GaN laser diodes in an external cavity

U. T. Schwarz, Fraunhofer-Institut für Angewandte Festkörperphysik (Germany); H. Braun, Regensburg Univ. (Germany); C. Raab, A. Able, F. Lison, Toptica Photonics AG (Germany)

We investigate experimentally and theoretically the spectral and dynamic properties of grating stabilized external cavity diode lasers (ECDL) with blue to UV (Al,In)GaN laser diodes. Operation in a single longitudinal mode of the external resonator results in extremely narrow linewidth and large coherence length. The frequency-selective feedback allows tuning of the laser wavelength and locking to an external reference. Here, a Littrow design is used for the grating stabilized ECDL employing commercial (Al,In)GaN laser diodes. The behaviour of the blue and UV laser diodes in combination with the grating is markedly different from red and IR laser diodes in an identical setup.

We use the rate equation model as described by Lang and Kobayashi to simulate the dynamics of the laser diode in a cavity with external feedback. This model provides linewidth and sidemode suppression.

Coherence collapse and the chaotic regime of laser dynamics are also well described. We take the input parameters from other measurements of (Al,In)GaN laser diodes, in particular optical gain, antiguiding factor, mirror reflectivity, carrier density, and carrier lifetime from Hakki-Paoli and streak camera measurements which were carried out in our laboratory. For comparison with red and IR laser diodes, we rely on parameter sets from literature.

The model reproduces the measured behaviour of the (Al,In)GaN ECDL extremely well. The dependency of the width of stability plateaus on injection current is in agreement with the experimental observation. Our preliminary result is that the Lang-Kobayashi model describes grating-stabilized ECDL in the blue and UV region as well as for red and IR ECDL. The experimentally observed difference between blue/UV and red/IR ECDL in terms of stability is reproduced by the simulation.

7597-51, Session 11

Semiconductor laser oscillation-frequency stabilization using the Faraday effect

H. Arai, A. Sato, A. Sato, K. Nakano, T. Sato, M. Ohkawa, Niigata Univ. (Japan)

The semiconductor lasers in use today are on one hand, prized, and highly praised, for their small size, light weight, longevity and energy-efficiency, -and on the other, criticized for their susceptibility to frequency-fluctuations brought about by changes in temperature and drive current. Once this “wrinkle” is ironed out, semiconductor lasers will become the default light-sources, for satellites’ onboard interferometers.

Our studies have been directed at stabilizing oscillation to the atomic absorption line frequency reference, and using negative electrical feedback to the injection current. Frequency stabilization is accomplished, by either; a) applying direct modulation to the semiconductor laser’s drive current, or b) modulating the reference frequency, to obtain the error signal needed for stabilization. In this instance, Faraday effect-based stabilization was used. This indirect oscillation frequency stabilization has no discernable effect on spectra width, but, stability was no better than that observed in the system using the direct modulation.

When we compared Faraday effect- and direct modulation methods of stabilization, in order to uncover the root-cause of the discrepancy, sensors picked up system noise, the source of which was heat generated by the heavy current applied to a magnetic coil used to apply the Faraday effect. We also substituted a permanent magnet for the electromagnet.

7597-52, Session 11

Accurate source simulation in modern optical modeling and analysis software

D. A. Jacobsen, E. R. Freniere, M. Gauvin, Lambda Research Corp. (United States)

Modern optical modeling and analysis programs allow users to create and analyze accurate optical and opto-mechanical systems in the software environment prior to building actual hardware based systems. The resultant accuracy of these models depends on the accuracy of the components that make up the model including the light source characteristics, surface and material properties, and the model geometry. In this paper we will consider factors that lead to improved modeling of the light source such as spectral and angular properties, the spatial distribution of light within the source, and the interaction of the light with the structure of the source. These factors are extremely important for near field modeling, especially for fiber and light pipe coupling. Several options will be discussed including simple source models such as point sources, ray files, surface properties that define optical parameters such as spectral and angular distribution, and detailed 3D solid models of the source. Simulated results for spectrum, angular, and spatial distribution will be compared to actual measurements for a variety of source types. Discussion will also include the appropriateness of each modeling approach with respect to different applications.

7597-67, Poster Session

Blue-emitting ZnSe random laser

T. Takahashi, T. Nakamura, S. Adachi, Gunma University (Japan)

In contrast to the conventional semiconductor diode lasers, semiconductor random lasers can emit light without having Fabry-Perot resonators. Random laser action is known to be caused by strong multiple scattering of the emitted lights and light amplification in the disordered gain medium. Random laser shows unique characteristics, such as low threshold, spatial emission, and high coherency. It is clear that it is very important to develop random lasers emitting in the visible spectral region. However, most of the semiconductor random lasers (e.g., ZnO and GaN lasers) emit light in the near-UV region. ZnSe has an excitonic band gap of ~2.7 eV at room temperature and is, therefore, a promising material for realizing random laser in the visible spectral region. In this work, we report lasing action and characteristics of a blue-emitting ZnSe random laser at room temperature. Below the threshold excitation, we observe only a broad spontaneous emission peaking at ~470 nm. Above the threshold, several discrete lasing lines are observed to grow at the center of the spontaneous emission (~475 nm). The lasing line width is less than 0.4 nm which is found to be about 40 times smaller than the spontaneous emission.

7597-68, Poster Session

All optical logic gates using active plasmonic device block

G. Oh, Chung-Ang Univ. (Korea, Republic of); D. Kim, Korea Photonics Technology Institute (Korea, Republic of); H. Kim, Y. Choi, Chung-Ang Univ. (Korea, Republic of)

Optical logic gates are essential requirement for achieving optical signal processing and optical computing systems. Though intensity-dependent all optical logic gates such as Mach-Zehnder interferometers and distributed-Bragg gratings have been researched, these methods based on nonlinear planer waveguide devices have disadvantages in size, switching time, and energy loss. In this work, we propose a novel all optical logic gates based on active plasmonics that may control the electron-photon coupling through an external effect. The phenomenon of surface plasmon resonance is basically appeared on attenuated total reflection mirror block. Under this resonance condition, the incident light gets highly absorbed and loses a fair amount of its energy, resulting surface plasmon polaritons wave (SPW) at the metal surface. The SPW is the propagation of the bound oscillation resulted by the electron-photon coupling, and can be controlled by external light. In this paper, we study a simple block for all-optical logic gate by using active plasmonics with specific metal layer configuration such as photonic crystal. In our structure, it is possible to control the propagating light in the prism by an external light under resonance condition. We also optimize this configuration by finite-difference time-domain method for metal layer configuration. Finally, we consider an optical NAND-gate using active plasmonics based on double device block. More detailed results and discussions will be presented.

7597-69, Poster Session

Formulation of differential transfer matrix method in cylindrical geometry

M. Jiani, M. Vesal, S. Khorasani, B. Rashidian, Sharif Univ. of Technology (Iran, Islamic Republic of)

Transfer and scattering matrix methods are widely in use for description of the propagation of waves in multilayered media. When the profile of refractive index is continuous, however, a modified formulation of transfer matrices does exist, which provides a complete analytical solution of the wave phenomena in such structures. For this purpose, we have previously formulated and reported the Differential Transfer Matrix

Method (DTMM) [1-4].

Previously reported variations of the so-called DTMM had been limited to Cartesian geometry where layered media form one-dimensional structures and plane waves are used as basis functions. In this work, we extend the formalism to cylindrical geometry with radial symmetry, in which Bessel functions need to be employed as basis functions. Hence, complete analytical formulation of the DTMM under radial and axial symmetry is described and derived.

[1] S. Khorasani, and K. Mehrany, "Analytical Solution of Wave Equation for Arbitrary Non-homogeneous Media," Proceedings of SPIE, vol. 4772, pp. 25-36, Seattle (2002).

[2] S. Khorasani, and K. Mehrany, "Differential Transfer Matrix Method for Solution of One-dimensional Linear Non-homogeneous Optical Structures," Journal of Optical Society of America B, vol. 20, no. 1, pp. 91-96 (2003).

[3] K. Mehrany, and S. Khorasani, "Analytical Solution of Non-homogeneous Anisotropic Wave Equation Based on Differential Transfer Matrices," Journal of Optics A: Pure and Applied Optics, vol. 4, no. 6, pp. 524-635 (2002).

[4] S. Khorasani, and A. Adibi, "Analytical Solution of Linear Ordinary Differential Equations by Differential Transfer Matrix Method," Electronic Journal of Differential Equations, vol. 2003, no. 79, pp. 1-18 (2003).

7597-70, Poster Session

Passive fiber rings as a basic part of fiber optic sensors

J. Látal, P. Koudelka, P. ?i?ka, F. Hanáček, J. Skapa, V. Va?inek, Technical Univ. of Ostrava (Czech Republic)

With increasing demands for measurement accuracy of optical attenuation within fiber optic sensors and for increasing of the dynamic range new measuring methods are searched. One of them is based on passive positive feedback of active circuit, when rises fiber optical oscillator controlled by magnitude of attenuation of optical fiber in the feedback. The same team of authors designed and simulated a different type of fiber optic oscillator, where the feedback loop is formed by a serial sorting of erbium doped fiber and single mode fiber. Closed oscillating circuit is than composed by two asymmetric couplers, conventional single mode optical fiber and amplifying fiber. Oscillator operates at a wavelength of 1550 nm and uses composition of lights in the asymmetric coupler outgoing from the DFB laser modulated by fixed frequency and incoming from the feedback loop. The second asymmetric coupler provides output from oscillator. The light on the second coupler output is analyzed by frequency analyzer. Frequency spectrum of outgoing signal is changed with attenuation and with change of optical path of single mode fiber in the feedback. In this paper the results of the measurements during temperature change for different excitation frequencies of DFB laser will be presented.

7597-71, Poster Session

A ridge waveguide quantum well AlGaAs/GaAs laser design

M. Nazari, Sharif Univ. of Technology (Iran, Islamic Republic of)

An advanced structure of laser diodes has been designed using the simulation software.Simulation results suggest that the thicknesses of SCH layers, inner cladding and outer cladding layers should be changed in order to give low loss, narrow far-field divergence angle and high confinement factor. The Thickness of the etch stop layer is optimized to give the required effective lateral refractive index. At the end the channel width and ridge width are also optimized to obtaine single lateral mode. The emission wavelength of the SQW laser was 850 .The aim of our study was three folds: (1) to provide the comprehensive analysis and calculations to design a ridge waveguide laser. In the simulations, the thicknesses of SCH layers, inner cladding layers and outer cladding layers are varied in order to observe variations of far-field divergence and the total confinement factor as functions of layer thicknesses. Comparison among loss, narrow far-field divergence and high confinement factor are made to optimize layer thicknesses, (2) The thickness of an etch stop layer is optimized to achieve the required lateral effective refractive index difference, and also the far-field divergence of the ridge waveguide laser, (3) the channel width and ridge width are designed to maintain single lateral mode and low loss by using the three layer dielectric slab waveguide calculations.

The details of simulation using WAVEGUIDE software are provided in the following figures. Also there is a summary of the designed laser:

Confinement factor ( ): 0.01297672 , far field Divergence angle : 26

In ridge region: 3.372425 , in wing regions: 3.37020

Conclusion:

It is believed that our study might provide an accurate analytical approach to design ridge waveguide lasers. The width of the ridge region is obtained by calculation for single-lateral-TE-mode operation and we have 3.47 micrometers for it which only mode can propagate which satisfies the minimum requirement for a perfect laser. The present results are also useful for the design of other equivalent lasers.

7597-72, Poster Session

Optical cloak based on Schwarzschild geometry

S. Khorasani, Sharif Univ. of Technology (Iran, Islamic Republic of)

It is known that the curved space in the presence of curved geometry behaves as an equivalent anisotropic medium with different constitutive equations. This fact forms the approach to design of optical cloacking metamaterials [1], where approximate cloacks have been designed and implemented.

In this paper, we show that the eigenpolarizations of the concerned equivalent medium can be exactly solved, leading to a pseudo-isotropic [2] description of curved space with two refractive index eigenvalues and opposite signs, which correspond to forward and backward travel in time. We demonstrate the applicability of this method to Schawrzschild metric (which is the only exact solution of field equations under spherical symmetry) and derive exact form of refractive index for the corresponding system. We discuss the subtle optical anisotropy of space around a spherically symmetric, non-rotating blackhole singularity in terms of elegant closed form expressions, and for the first time, we show that the refractive index in such a pseudo-isotropic system would be a function of coordinates as well as the direction of propagation.

This would establish a rigorous method for design of a mathematically exact optical blackhole, with zero reflection for the incoming wavefront.

[1] D. Schurig, J. B. Pendry, and D. R. Smith, "Calculation of material properties and ray tracing in transformation media," Optics Express 14(21), pp. 9794-9804 (2006).

[2] S. Khorasani, "Generalized conditions for the existence of optical axes," J. Opt. A: Pure Appl. Opt., vol. 3, pp. 144-145 (2001).

7597-73, Poster Session

Modelling of magnetoconcentration effect in thin-layer p-n structure

B. S. Sokolovsky, Ivan Franko National Univ. of L'viv (Ukraine)

The report presents results of modelling of the magnetoconcentration effect (MCE) in planar thin-layer p-n structure whose lightly doped base regions have the thicknesses comparable with the diffusion lengths of non-equilibrium carriers. Electric current is assumed to flow in the direction parallel to metallurgical edge of the p-n structure and magnetic field is applied at right angle to the structure's surfaces. Electric and magnetic fields of such an orientation give rise to appearance of the

Lorentz force which causes spatial redistribution of carrier concentration in quasi-neutral regions of the p-n structure. For the Boltzmann statistics of carriers it has been obtained boundary conditions for the non-equilibrium carrier concentrations at the edges of space charge region what allows to consider MCE in both base layers as two self-matched effects. By means of both analytical and numerical calculations it has been analyzed features of the coordinate dependences of carrier concentration in the quasi-neutral base regions, as well as the total conductivity changes and current-voltage characteristics. The calculations have been carried out on the example of both non-illuminated and illuminated p-n structure based on HgCdTe solid solution. Possible practical applications of thin-layer p-n structures operated in the conditions of MCE are discussed.

7597-74, Poster Session

Role of electron blocking layer in III-nitride laser diodes and light-emitting diodes

Y. Kuo, J. Chang, M. Chen, National Changhua Univ. of Education (Taiwan)

A high energy band-gap electron blocking layer (EBL) just behind the active region is conventionally used in the nitride-based laser diodes (LDs) and light-emitting diodes (LEDs) to improve the confinement capability of electrons within the quantum wells. Nevertheless, the EBL may also act as a potential barrier for the holes and cause non-uniform distribution of holes among different quantum wells. Quite recently, Han et al. (Appl. Phys. Lett. 94, 231123, 2009) reported that, because of the blocking effect for holes, the InGaN LED device without an EBL layer has slighter efficiency droop and higher light output at high level of current injection when compared to the LED device with an EBL layer. This result seems to disobey the original intention of the usage of EBL. Our previous studies indicated that the utilization of EBL is essential for the InGaN laser diodes. However, our recent research showed that the optical properties of the InGaN LEDs deteriorate when they are with an EBL layer for some specific situations. In this work, the optical properties of the InGaN LDs and LEDs are explored numerically with the LASTIP simulation program and APSYS simulation program, respectively. Specifically, the energy band diagrams, radiative and SRH recombination rates, distribution of electrons and holes in the active region, and electron overflow are studied. The effect of EBL on the optical properties of the InGaN LDs and LEDs will then be concluded.

7597-75, Poster Session

Numerical simulation on high-efficiency GaInP/GaAs/InGaAs triple-junction solar cells

S. Chang, M. Tsai, S. Yen, S. Chang, Y. Kuo, National Changhua Univ. of Education (Taiwan)

The GaInP/GaAs/InGaAs triple-junction solar cell is one of the strong candidates for terrestrial and space applications. One of the most important advantages of this solar cell is the comparable short-circuit currents among the GaInP, GaAs, and InGaAs cells, which leads to relatively high sunlight-to-energy conversion efficiency. In this paper, the high-efficiency GaInP/GaAs/InGaAs triple-junction solar cells are investigated numerically by using the APSYS (Advanced Physical Model of Semiconductor Devices) simulation program. The solar cell structure used as a reference was based on a published article by Geisz et al. (Appl. Phys. Lett. 91, 023502, 2007). Note that the bandgap energies of the semiconductor materials under study are 1.8 eV for Ga0.5In0.5P, 1.4 eV for GaAs, and 1.0 eV for In0.3Ga0.7As. To increase the sunlight-to-energy conversion efficiency, matching of the short-circuit currents is attempted by adjusting the thickness of each cell. Since the high concentration solar cell system has the potential for growing demand and low-cost products, the characteristics of the GaInP/GaAs/InGaAs triple-junction solar cells at high concentration are also investigated in this study. Specifically, the open-circuit voltage, short-circuit current, and sunlight-to-energy conversion efficiency at different concentration factors are compared and analyzed. Then, according to the simulation result, the appropriate solar cell structure which possesses high sunlight-to-energy conversion efficiency is proposed.

7597-77, Poster Session

Study on temperature characteristic of green photodetector on Si substrate

X. Fu, Tianjin Polytechnic Univ. (China)

Photodetector is an optical receiver which transforms the energy of radiation (such as infrared, visible light or ultraviolet) into the electrical signal that is convenient for measurement. These detectors are widely used in various domains, such as biology, medical treatment, communication, finance, aviation, etc. The development of PN junction semiconductor photodetector is based both on the principle of internal photoelectric effect and on the theory of PN junction. In the paper, a silicon PN junction photodetector is developed on the basis of n-type single-crystal (100) silicon substrate. The optimum process parameter, such as junction area (Aj) and junction depth (xj) of PN junction, thickness of anti-reflection layer and so on, was determined by the measurement and property analysis of the detector. The properties of this semiconductor photodetctor depend on the temperature to certain extent, because characteristics of semiconductor are affected by temperature. We emphasize on the study on temperature characteristic of the photodetector: Firstly, the temperature behavior of dark current at zero bias voltage and wide temperature range was investigated. Results show that dark current increases exponentially with temperature. Secondly, the temperature behavior of photo current at zero bias voltage and wide temperature range was studied. The temperature characteristic is analysesed in the theory and optimized. Consequently, the prospect for the application of the detectors is cheerful.

7597-78, Poster Session

Modeling and simulation of AlGaAs/GaAs QW-DBR dual junction photovoltaic devices

H. Fardi, Univ. of Colorado Denver (United States); B. Van Zeghbroeck, Univ. of Colorado at Boulder (United States)

This paper investigates the validation and design of a new high efficiency photovoltaic cell through modeling and simulation.

Based on an initial analysis, in an ideal device structure, an efficiency as high as 46% can be achieved by combining a standard single-crystalline cell with a GaAs/AlGaAs multi-QW structure enclosed in a separate light-confining structure such AlGaAs/GaAs DBR. The assumption is that all the incident radiation with photon energy beyond the bandgap was absorbed in each region. In addition, we added the fact that a quantum-well structure can have a 300mV larger open circuit voltage than a bulk semiconductor device. As we know QW devices provide a somewhat higher power generation compared to their bulk p-n diode counter part and more importantly, they have a built-in trade-off between photocurrent and open circuit voltage.

We will present simulation model and material parameters by modeling and simulations of structures specifically designed to accurately determine the loss mechanisms such as the non-radiative recombination and loss of photons from the light trapping structure. The structures will be simulated using SimWindows, a program developed originally for studying lasers. It solves the non-isothermal drift-diffusion equations coupled with Stratton's energy balance equations which model the hot electron effects in embedded single QW GaAs/AlGaAs photodiodes . The model consists of a relatively large number non-linear and tightly coupled partial differential equations, and uses several position-dependent material and transport parameters that makes it very robust. The electrical device equations are solved by direct Newton-Raphson's method and the energy balance equations are solved by Gummel's de-coupled method . In addition it includes optical absorption, while a broad spectrum light input can be supplied to properly simulate the solar

spectrum.

A possible practical implementation is proposed where two key features are the use of a transparent contact between the two cells such as ITO and the wafer bonding of the two cells. The thin QW cell is separated from its substrate after wafer bonding, so that the wafer can be reused, thereby reducing the overall material cost.

This paper presents the validation and design of a AlGaAs/GaAs QW-DBR-Bulk daul junction phtotvotaic cell. As one decreases the number of quantum wells, the photocurrent reduces while the open circuit voltage increases . This reduction is primarily due to the reduced absorption of the incident photons with a photon energy close to the bandgap of the material as the absorption coefficient approaches zero at the bandgap energy. This analysis predict a maximum conversion efficiency of 26% for the crystalline cell, which is somewhat larger than experimental results since it does not include shadowing effects, reflection and recombination of minority carriers. In addition, the theoretical model and simulation results demonstrate from the combination of a bulk AlGaAs cell with a bandgap of 1.8eV and DBR ITO cell, an increase in the total efficiency by 12%, while using a QW cell with efficient light trapping adds another 8% for a total efficiency of 46%.

7597-79, Poster Session

Precise frequency stabilization technique for 850-nm vertical cavity surface emitting lasers by controlling their optical beat frequency

W. Sasaki, T. Ohhara, T. Yoshimi, Doshisha Univ. (Japan)

We have demonstrated a compact and precise frequency stabilization technique for commercially available 5mW, 850nm vertical cavity surface emitting laser (VCSEL) based on optical beat frequency control between two sets of frequency stabilized VCSEL's using Fabry-Perrot cavities as frequency standard, which were quite similarly fabricated with each other. Recently VCSEL has been widely prevailed for uses of low cost and small sized sensors, since it may afford low power operations and manufacturing costs in comparison with edge emitting type Fabry-Perrot laser diodes. Therefore, a highly versatile and inexpensive frequency stabilized coherent light source which can be mass producible will be available if the frequency stabilization for this type of VCSEL's is carried out. Generally, it has been commonly accepted that a satisfactory degree of coherence may be easily obtained from VCSEL's without any additional frequency stabilization technique since highly reflective coatings are to be put on their laser cavity edges. Nevertheless, some VCSEL devices, especially inexpensive type commercial products show multi-mode behaviors along with polarization instabilities. In the present work, as a simple and inexpensive approach to commercially available VCSEL devices, we have achieved a frequency stabilization scheme using two sets of quite similarly fabricated VCSEL's frequency stabilization systems with Fabry-Perrot cavity. The error signal was derived by optical beat frequency detection from these two sets of VCSEL's. Thus, the lasing frequencis of the VCSEL's were locked to each other by negative feedback for their injection current so that the variation in the optical beat frequency should be minimized. As a result, we have successfully suppressed the amount of frequency fluctuations in the free-running VCSEL of as much as 2GHz to be within a few tens MHz at measuring time of more than 1 min., that is, the attained Allan variance is within the order of 10^-9.

7597-80, Poster Session

Linewidth reduction of a 30mW-405nm GaN violet laser diode by optical-electrical double feedback method

K. Mizutani, T. Kuromori, W. Sasaki, Doshisha Univ. (Japan)

We have demonstrated a compact and efficient frequency stabilization system based on Pound-Drever-Hall method,along with optical feedback. For the long-term frequency stabilization, frequency of a 30mW 405nm GaN violet laser diode (LD)was stabilized to a reference confocal Fabry-Perot cavity (CFP cavity) by negative electrical feedback to the injection current of the LD based on Pound-Drever-Hall technique. Moreover, by employing optical feedback from another tilted CFP cavity along with electrical feedback, the residual frequency noise has been efficiently suppressed. The achieved power spectral density of frequency fluctuation under the controlled condition was within the order of 10^-8 [Hz2/Hz] within the Fourier frequency of a few tens kHz. The reduced linewidth under the double feedback condition is estimated to be narrower than at least 100 kHz, which seems to be the resolution limit of our measurement. The minimum square root of the Allan variance was within 10^-12 at the integration time of about 0.1 sec under the controlled condition.

7597-81, Poster Session

Calibrating procedures for LED simulation: tolerance, S/N ratio, and detector

C. Ou, Hsiuping Institute of Technology (Taiwan)

There is no doubt optical simulation is now becomes one of most important activities for both academic research and industrial application. However, it is surprising that few optical engineers pay attention on the calibration procedures before doing any simulation, since most people understand the importance of the calibration on experiment apparatus and instruments. In this article, we demonstrate and discuss the necessary calibration procedure for LED unit simulation. There seven calibration that one should undertake for LED simulation. The far field Lambertian emitting test is to exam the rays initialization and the sensitivity of the far field angular detector, the spectrum and color coordinate test is to verify the capabilities of the color mixing and the prediction of the color coordinates. As for the uniform scattering test along with the energy balancing test, is to study the accurate on the scattering mechanism modeling. Since the total reflection play an important role in LED package, the precision on the calculation of critical angle, Brewster angle and the Fresnel loss are crucial. Finally, a cross polarizer test with different angle is to verify the capabilities for polarization ray tracing with polarized components. Key points for these calibration tests are discussed in details. Major simulation softwares are implementing to clarify the possible lapse of numerical results on non-imaging system.

7597-82, Poster Session

Celestial calculation for the ground solar energy device

C. Ou, Hsiuping Institute of Technology (Taiwan)

Determination on the optimized setup parameters for the solar cell/heating device is critical. Factors for the optimization are the orbital parameters, seasonal climate and the surrounding of the system within the specific longitude and Latitude. In this article, a straightforward approach is to treat the sun rays as a set of emitting rays in a circular aperture that come from the celestial sphere. Such simplification did not consider the fact that the sun is an object with finite angular in the celestial coordinate, and a modified approach is to provide the finite angle effects by the scatter model. By doing this, one can use the simulate scattering of the sun radiations into a specified circular cone, which is centered in the specular direction. By taking this approach, the simulated rays, which surrounding the ecliptic, can illuminate toward directly to the solar cell/heating system After integrating the illuminated energy, the construction parameters of the solar energy system then can be optimized. One can build the energy storage device in this model. The procedures then can calculate the overall efficiency of the system in the very easy way. The weather conditions can be implementing by using the scattering model between the ground plane and the solar positions. However, difficulties will be occurs on the determinations of the scattering coefficients.

7597-83, Poster Session

Study of beam propagation in finite photonic crystals

A. Khavasi, K. Mehrany, M. Miri, A. Kazemi, S. Khorasani, Sharif Univ. of Technology (Iran, Islamic Republic of)

For in-band applications of photonic crystals (PC) the main questions are: How does a beam propagate inside the PC? What is the propagation direction of the beam? To answer these questions we should notice that in practice, PCs are finite. In a finite PC multiple reflections of the beam and the reactive power near the PC's interface due to the existence of evanescent wave, affect the beam propagation inside the PC. We can eradicate multiple reflections by using antireflection coatings and/or shaping PC's geometry. Hence, having known the direction followed by the first beam inside the PC rather than multiple reflected beams, the above questions are answered.

Many authors simply use band structure of infinite PC to predict the beam's direction in a finite PC. It is known that, in an infinite PC the propagation direction of a monochromatic wave packet is proportional to the normal to isofrequency dispersion diagrams. In this approach the propagating Bloch mode is only considered and evanescent Bloch waves near the boundaries of PC are neglected. The validity of this approximation for high frequencies has been questioned by Felbacq et. al. and instead a dressed (by evanescent waves) transfer matrix has been suggested [1]. In this work we delve into this subject more precisely, to evaluate that which of two approaches is more viable. For dealing with a finite size PC we use a rigorous grating based approach which is known as Legendre polynomial expansion method (LPEM) [2]. We consider a PC with finite number of layer as a stack of grating layers and study beam propagation inside it. We show through some numerical examples that the direction obtained by conventional band structure is more accurate than that of dressed transfer matrix of Felbacq et. al. We also demonstrate that this approximation can be improved by taking the effect of evanescent Bloch modes into consideration. The effect of these modes leads to a constant shift of beam's center inside and far enough from the PC's interface.

References:

[1] D. Felbacq and R. Smaâli, " Bloch Modes Dressed by EvanescentWaves and the Generalized Goos-Haenchen Effect in Photonic Crystal", Phys. Rev. Lett. 92, 193902 (2004).

[2] A. Khavasi, A. K. Jahromi and K. Mehrany, " Longitudinal Legendre polynomial expansion of electromagnetic fields for analysis of arbitrary-shaped gratings", J. Opt. Soc. Am. A, 25, 1564-1573 (2008).

7597-84, Poster Session

Plasma phase separation in superconduct crystal

N. P. Netesova, Lomonosov Moscow State Univ. (Russian Federation)

By means of the inharmonious oscillation model the superconducting crystal is considered consisting of two subsystems, the phase transition temperature depends on a square plasma frequency. Just plasma fluctuations in two subsystems 1 and 2 at certain parities can initiate phase transition. Conductivity electron can create in a crystal area of other instable phase and stabilize its localization. Free electrons couple to lower system energy. For this purpose it is necessary, that electron energy in a local phase was essentially much less, than in an initial phase. It is necessary to satisfy condition 11= 12, where 12 is interaction energy in an initial phase, 11 is interaction energy in the local again formed phase. In high-temperature superconductors spontaneous division into two phases: superconducting and isolating was revealed. Stratification on two phases in superconducting crystals has been confirmed experimentally. Substantive provisions of phase stratification theory in our approach are interpreted within the plasma mechanism superconductivity. From the plasma mechanism of superconductivity follows superconducting crystals exist at room temperature. There are superconductors with temperatures of phase transition above a room temperature.

7597-85, Poster Session

VCSEL's frequency stabilization of an external cavity diode laser: countermeasures against atmospheric-temperature variations

M. Motojima, K. Doi, T. Sato, M. Ohkawa, T. Suzuki, Niigata Univ. (Japan)

External cavity diode lasers (ECDL) are presently experiencing a surge in popularity, as laser light-sources for advanced optical measurement systems. While these devices normally require external optical-output control, we simplified the setup, a bit, by adding a second external cavity. This technique boasts the added advantage of having a narrower oscillation-linewidth than would be achievable, using a single optical feedback. Because laser's driving-current and an atmospheric temperature directly impact the ECDL's oscillation frequency, during the frequency stabilization, it was necessary, in this instance, to construct the smaller ECDL system, which we mounted on a Super-Invar board, to minimize the influence of thermal expansion.

We introduced the vertical cavity surface emitting laser (VCSEL) as the laser diode in tour external cavity system. The VCSEL has low threshold current, single-longitudinal-mode operation, a circular output beam, wafer-scale integration and less mode hopping characteristics by the temperature change than the other semiconductor lasers. Because VCSELs are now commercially available, and the ECDL systems using them are expected to improve their frequency stability, we have replaced a Fabry-Perot type laser diode with a VCSEL, and examined its oscillation-frequency stability. Therefore we were able to expect that the VCSELs with our double optical feedback system have good oscillation frequency stability. The obtained VCSEL's oscillation-frequency stability, i.e., the square root of Allan variance was 4×10-10, at averaging time =1 sec.

7597-86, Poster Session

Analysis and characterization of the small-signal modulation of a vertical external cavity surface emitting laser

N. B. Terry, M. Walton, R. G. Bedford, Air Force Research Lab. (United States)

The small signal modulation of a vertical external cavity surface emitting laser (VECSEL) is examined. The modulation transfer function (MTF) of the cavity is measured for multiple photon lifetimes operating between Class A and Class B regimes, where the photon and carrier lifetimes are of the same order. Three coupled ordinary differential equations with similarities to an electrically-injected quantum-well laser with a separate confinement heterostructure are used to mathematically describe the time-dependant VECSEL response. We present a series of measurements that provide many important laser parameters such as internal device losses and differential gain. The VECSEL operating in this regime is an overdamped oscillator and has free-running characteristics that are not unlike quantum-dot and quantum-cascade lasers.

7597-53, Session 12

Optical components for very short reach applications at 40 Gb/s and beyond

N. N. Ledentsov, J. A. Lott, V. A. Shchukin, VI Systems GmbH (Germany); A. Mutig, T. D. Germann, S. A. Blokhin, A. M.

Nadtochiy, L. Y. Karachinsky, D. Bimberg, Technische Univ. Berlin (Germany)

Just as the density of transistors on a chip about doubles with each new generation within a period of two years, processor bandwidth also about doubles. Consequently the speed of input-output (I/O) devices must grow and today we find processor I/O approaching or slightly surpassing 10 Gb/s per channel for 100G Ethernet server applications. Similarly, Storage Area Networks will soon be supported by Fibre Channel FC16G transceivers operating at the newly standardized serial signaling rate of 14 Gbaud.

Further upgrades will require on-board links at 25, 28 and 40 Gbaud, speeds that are barely feasible with copper cabling, even for very short reach distances. Thus the role of optical interconnects will increase dramatically as the data transfer rate increases. Furthermore, an increased bandwidth demand necessitates an equal or even greater demand for low cost and highly power efficient micro-laser and -detector components along with their associated driver and transimpedance amplifier integrated circuits (ICs) to maintain an overall competitive systems cost.

In this talk a summary is given on recent achievements in vertical cavity surface-emitting lasers (VCSELs) and PIN photodetectors suitable for very short reach multimode fiber links that enable bit rates up to and beyond 40 Gb/s. Achievements in current modulated VCSELs, electrooptically modulated VCSELs, top illuminated PIN photodiodes and the related ICs and packaging solutions will be addressed.

7597-54, Session 12

Simulation of facet heating in high-power red lasers

J. G. Tijero, I. Esquivias, H. Odriozola, A. Martin-Minguez, L. Borruel, Univ. Politécnica de Madrid (Spain); A. Gomez-Iglesias, M. Reufer, M. Bou-Sanayeh, P. Brick, N. Linder, OSRAM Opto Semiconductors GmbH (Germany); M. Ziegler, J. Tomm, Max-Born-Institut für Nichtlineare Optik und Kurzzeitspektroskopie (Germany)

Catastrophic Optical Degradation (COD) continues to be one of the main limits to increase the output power in red emitting lasers. Modelling tools able to analyze and predict the physical origin of facet heating are needed for further understanding the mechanisms leading to COD as well as to analyze new improved designs.

In this work we present simulations of the facet heating in high power broad area GaInP/AlGaInP red emitting lasers. The simulations were performed by means of a laser simulator which solves the steady-state thermal and optoelectronic equations in two dimensions: the cavity and the current injection axes. The complete bipolar semiconductor equations are considered and the population of different conduction band valleys is also taken into account. Optical absorption and non-radiative recombination at the facets were considered as the main facet heating mechanisms. Non-Absorbing-Mirror (NAM) structures were included in the simulations.

The simulation parameters were calibrated by comparison with measurements of the standard characteristics of broad-area lasers. The temperature dependence of the threshold current and slope efficiency was properly reproduced when considering high non radiative recombination in the p-cladding.

Measurements of the facet temperature were carried out by micro-Raman spectrometry. Devices with standard facets were compared with devices with NAM facets, in which a lower facet temperature was observed. A good agreement between experiments and simulations was found when considering simultaneously both facet heating mechanisms.

7597-55, Session 12

3D modeling of superluminescent light-emitting diodes

Z. Li, S. Li, Crosslight Software Inc. (Canada)

We present a self-consistent electric and optic model for superluminescent light-emitting diodes (SLED) using 3D finite-element method. The carrier transport is calculated by the drift-diffusion method, which is coupled with the radiative recombination obtained from the solution of Shrodinger-Poison equations self-consistently. The spontaneous emission noise is described by the fundamental theory using the Green's function method. Our model allows 3D treatment of the carrier dynamics and optical confinement on the transverse plane, along with the electronic and optical variation on the longitudinal axis. The theoretical model has been benchmarked with an InP-based edgeemitting SLED. The device has non-identical quantum wells with broad bandwidth from 1300 nm to 1600 nm. The results show the importance of 3D effects and demonstrate the validity of the model.

7597-56, Session 12

Investigation of the saturation characteristics of InGaAsP-InP bulk SOA

A. Kapoor, Univ. of Delhi (India) and Institute of Photonics and Quantum Electronics (Germany); E. K. Sharma, Univ. of Delhi (India); W. Freude, J. Leuthold, Univ. Karlsruhe (Germany)

Semiconductor optical amplifiers (SOAs) can be used as linear in-line amplifiers for extended-reach passive optical networks (high saturation power required), or as gain/phase-switchable devices (low saturation power required). For these applications, gain, bandwidth and saturation power are important. The saturation power can be increased by decreasing the confinement factor and by increasing the length such that the overall gain remains constant. In this paper we investigate the saturation characteristics of 1.55μm InGaAsP-InP bulk SOA by varying device parameters like ridge width, length and p-doping of the active layer. We do so by using the physically based simulation tool ATLAS.

Basically, ATLAS supports simulation of semiconductor lasers only, but making the mirror reflectivities small reduces laser structures to amplifiers. Next, for investigating the saturation characteristics of SOA, the amplifier gain should be influenced by injecting an optical light power. However, ATLAS cannot simulate the required source. Instead, we use simultaneously two competing independent models for spontaneous radiative recombination in the electron rate equation, namely the so-called general model (total recombination rate Bnp with bimolecular recombination coefficient B, electron and hole concentrations n and p) and the standard model for recombination due to amplified spontaneous emission into the mode under consideration (determined by the product of Fermi functions for electrons and holes). In the photon rate equation, the standard model is used. We then increase B, and thus decrease the carrier concentration that would result from an external optical signal. We show that p-doping the active layer helps increasing the saturation power.

7597-57, Session 12

Vertically-stacked InAs quantum dots for polarization-independent semiconductor optical amplifiers

T. Inoue, M. Asada, O. Kojima, T. Kita, O. Wada, Kobe Univ. (Japan)

This paper describes a technique to control the polarization property in quantum dot (QD)- semiconductor optical amplifiers (SOAs) using vertical stacking of self-assembled InAs QDs. QD-SOAs have been

expected to realize high saturation power, multi-channel processing, and high-speed response. However, in conventional QDs, the significant polarization dependence in the optical gain caused by the flattened QD shape has been a serious problem. One of the well-known approaches to realize the polarization-independent gain relies on columnar QDs, in which InAs QDs layers are closely stacked with very thin (several monolayers) intermediate layers. The isotropic shape of columnar QDs realizes a polarization-independent gain. On the other hand, in this paper, we propose a different approach, where QDs are vertically stacked with moderately thick intermediate layers. Therefore each QDs layer is well separated geometrically and high precision control of overall QD shape is expected. Vertically aligned InAs QDs are known to create the electronically coupled states, where we expect the optical transition probability along the vertical direction to be enhanced. We have achieved such vertical stacking of QDs up to nine layers by optimizing the amount of GaAs and InAs deposition. Nine-layer stacked QDs have shown transverse-magnetic(TM)-mode dominant emission in edge photoluminescence in the 1.3 m telecommunication wavelength region. The waveguide-based QD-SOA device structure containing electronically coupled QDs has also shown strongly TM-mode enhanced electroluminescence. Our results have suggested that the electronically coupled QDs can be a powerful tool to realize the polarization-independent gain in QD-SOAs.

7597-58, Session 12

Electron-phonon and electron-photon intersubband scattering rates in asymmetric AlN/GaN coupled quantum wells

G. Liu, H. Zhao, N. Tansu, Lehigh Univ. (United States)

InP-based and GaAs-based intersubband quantum wells (QW) lasers have been demonstrated with superior performance from mid-IR up to far-IR regime. Significant recent advances on the pursuit of intersubband QW optoelectronics in the near IR regime have occurred by employing AlN / GaN material systems, however these advances are still lagging due to: 1) challenge in growing high-quality AlN / GaN superlattices, and 2) limited design consideration from AlN / GaN QW structures. Most of the recent works on nitride-based 1.55micron intersubband devices have focused on the use of multiple stages of GaN QW surrounded by AlN barriers grown on GaN template on sapphire substrates.

Here, we analyze and optimize the asymmetric AlN / GaN coupled quantum well design for achieving intersubband transition wavelength at 1.55micron. The computation of the electron-phonon and electron-photon scattering rates are carried out for optimizing the design of the asymmetric AlN /GaN coupled QW as gain media for intersubband QW lasers. The coupled QW structure employs two asymmetric GaN QWs separated by a thin AlN barrier (0.5nm), and the outer barriers of 4nm AlN layers are employed to surround the QWs. The asymmetric coupled QW structure is designed to support three quantized states in the conduction band, with the transition from level 3 to level 2 at near 1.55micron. The use of optimized asymmetric AlN / GaN coupled QW structure leads to improved design with significant enhancement in peak gain for the intersubband transition, in comparison to that of single stage GaN / AlN QW.

7597-59, Session 13

Experimental stability maps of a 1550nm-VCSEL subject to polarized optical injection

A. Hurtado, K. Schires, N. Khan, I. D. Henning, M. J. Adams, Univ. of Essex (United Kingdom)

We report an experimental study of the nonlinear dynamics of a 1550nm-Vertical Cavity Surface Emitting Laser (VCSEL) subject to external optical injection which is either parallel or orthogonal to each of the two orthogonal polarizations of the fundamental transverse mode of the device. Stability maps have been produced by measuring the regions of nonlinear dynamics in the plane of frequency detuning between the Master Laser (ML) and the Slave Laser (SL) as a function of the optical injected power. Results are presented for both cases of polarized optical injection, parallel and orthogonal, and for various levels of bias current applied to the 1550nm-VCSEL.

We show that the shapes of the measured stability maps were significantly different when the device was subject to parallel and to orthogonal optical injection. A rich variety of nonlinear dynamics have been observed outside the stable locking range, for both parallel and orthogonal optical injection, including periodic dynamics (such as limit cycle and period doubling), chaos and bistability. Additionally, polarization switching was also seen for the case of orthogonally polarized optical injection.

Finally, and for the first time to our knowledge we have also examined the effect of varying the bias current of the 1550nm-VCSEL on the measured nonlinear dynamics. We report a first experimental observation of the appearance of new regions of periodic dynamics and the changes in the shape of the measured stability map as the applied bias current is increased well above threshold when the 1550nm-VCSEL was subject to orthogonally polarized optical injection.

7597-60, Session 13

Experimental observation of the locking regimes and chaotic dynamics in laterally coupled diode lasers

H. R. Lamela, R. Santos, Univ. Carlos III de Madrid (Spain)

The dynamics and static behavior of lateral coupled diode laser arrays has been a subject of interest in past years. For the last three decades a large amount of work has been done on the study of these laser structures [1]. These studies have focused mainly on devices as suitable sources for high power low divergence lasers (multi-array) [2][3] and as a way to increase the modulation bandwidth beyond the intrinsic relaxation oscillation frequency of a single laser diode proposed theoretically by using two laterally coupled diode lasers (LCDL) [4] and experimentally demonstrated by means of locking the two lateral modes of these LCDL [5]. In multi array devices, theoretical developments for the description of the emission of these diode lasers were made using the coupled-mode theory to describe the array optical field in terms of the array eigenmodes (supermodes) [6] [7]. Experimentally, successful high power low divergence phase locking operation of these devices was reported by several authors [8][9].

In twin stripe laser diodes several studies were done concerning the emission and the dynamics of these devices. Theoretical aspects of the emission pattern were developed by using, mainly, the coupled mode theory, and it was predicted that these devices emit both in-phase and out-of-phase lateral modes [6]. This feature was experimentally reported in references [5] and [10]. More recently an experimental study showed that the relaxation oscillation of each laser waveguide is strongly influenced by the coupling between the two lasers [11]. Besides this, for these devices it was also predicted that temporal instabilities in sub-nanosecond scale occur due to the nature of the coupling between the laser waveguides [12][13]. These instabilities were assigned to the competition between the array supermodes and strength of the coupling. As pointed out by the review made in reference [14] on phase locking of coupled lasers, little experimental works have been done on the dynamics and on the complete characterization of the emission spectrum of the laterally coupled diode lasers (LCDL) [14].

In this work it is the objective of the authors to fill in the lack of information on the experimental studies of the emission and dynamic characteristics of the LCDL devices. The device under study permits independent bias of each one of the laser waveguides. By asymmetrically biasing the device, we, in turn, force asymmetry between the emission characteristics of each laser waveguide. This will lead to a different emission wavelength of each twin stripe and the condition of locking is broken down and unlocking takes place and, this leads to an experimental characterization of the emission spectrum at the different operation regimes. In order to study this phenomena an analysis of the Spectrally Resolved Far Field (SRFF) for different bias currents applied to the device is made. In parallel to the spectral analysis, an analysis of the RIN spectrum is made for analyzing the nonlinear regimes and chaos that are found in these devices [15]. From this analysis it was found that the amplitude of the RIN at the second resonance frequency is clearly affected by the locking conditions. It was also found that, when the device is in lateral mode locking, several nonlinear and chaotic regimes take place [15]. Finally, in this work a simultaneous analysis of both the SRFF and the RIN spectrum will allow us to obtain the identification of the phase relation between the fields emitted by each one of the waveguides and thus to identify the locking regime of the laser operation as well as to analyze the emission characteristics when nonlinearities are observed.

References:

[1] Dan Botez, "Diode laser arrays" Cambridge University Press, 1994.

[2] D. Scifres, R. Bumham, and W. Streifer, "Phase-locked semiconductor laser array," Appl. Phys. Lett., vol. 33, no. 12, pp. 1015-1017, 1978.

[3] D.S. Scifres, R.D. Burnham, and W. Sreifer, "Continuous wave high-power, high temperature semiconductor laser phase-locked arrays", Appl. Phys. Lett., vol. 41, (ll), pp. 1030-1032, 1982

[4] G. A.Wilson, R. K. Defreez, and H. G. Winful, "Modulation of phased-array semiconductor lasers at K-band frequencies," IEEE J. Quantum Electron., vol. 27, pp. 1696-1704, 1991.

[5] H. Lamela, B. Roycroft, P. Acedo, R. Santos, and G. Carpintero, "Experimental modulation bandwidth beyond the relaxation oscillation frequency in a monolithic twin-ridge laterally coupled diode laser based on lateral mode locking", Optics Letters, vol. 27, no 5, pp. 303 - 305, March 2002.

[6] E. Kapon, J. Katz, and A. Yariv,"Supermode analysis of phase-locked arrays of semiconductor lasers", Opt. Lett., vol. 10, pp. 125-127, 1984.

[7] J.K. Butler., D.E. Ackley, and D. Botez. "Coupled-mode analysis of phase-locked injection laser arrays", Appl. Phys. Lett., 1984, vol. 44, (3). pp. 293-295.

[8] D. F. Welch, B. Chan, W. Streifer, and D. Scifres, "High-power, 8W CW, single quantum well laser diode array," Electron Lett., vol. 24, pp. 113-115, 1988.

[9] J.-M. Verdiell, H. Rajbenbach, and J.-P. Huignard, "Array modes of multiple-stripe diode laser: A broad-area mode coupling approach," J. Appl. Phys., vol. 66, pp. 1466-1468, 1989.

[10] Th. Wolf, F. Kappeler, B. Stegmuller, M. C.Amann, "GaInAsP twin-stripe lasers with asymmetrical waveguide channels", IEE Proceedings J, vol. 135, Issue 1, pp. 5-10, 1988.

[11] G. Carpintero, R. Santos, and H. Lamela, "Experimental evidence of coupling effects in a twin-ridge laser", Optics Letters Vol. 34, Iss. 8, pp. 1267-1269 (2009).

[12] H. G. Winful and S. S. Wang, "Stability of phase locking in coupled semiconductor laser arrays," Appl. Phys. Lett., 53, pp. 1894, 1988.

[13] O. Hess and E. Scholl, "Spatio-temporal dynamics in twin-stripe semiconductor lasers," Physica D, vol. 70, pp. 165-177, 1994.

[14] A. F. Glova., "Phase locking of optically coupled lasers",Quantum Electron., 33, pp 283, 2003.

[15] R. Santos, and H. Lamela, "Experimental observation of chaotic dynamics in two coupled diode lasers through lateral mode locking". Acepted for publication in IEEE J. Quantum Electronics, Special Issue in Nonlinear Dynamics in Photonic Systems, 2009.

7597-61, Session 13

Frequency stabilization of a laser diode using Rb saturated absorption lines

A. Sato, K. Nakano, H. Arai, T. Sato, M. Ohkawa, Niigata Univ. (Japan)

While the advantages of LDs over competing technologies are great, in both number and scale; overall compactness, light weight, proven durability and energy-efficiency; one issue continues to disturb all efforts at their application in the precise interferometric systems; oscillation-frequency stabilization.

We have succeeded, thus far, in stabilizing LDs' frequencies to Rb absorption lines, by means of negative electrical feedback. While the absorption lines were stable over the long term, the Doppler Effect's influence was evident, in broadened spectrum linewidth. To avoid the problem in subsequent tests, we used Rb-saturated absorption signals.

The estimation of the stability is relative and obtained from the beat frequency, which is the frequency difference between two LDs oscillation frequencies.

So, the maintenance of the reference laser diode's frequency stability is critical to the task of pinpointing the sources of noises, and, as tests have shown, the stability of our Rb-saturated absorption line-based system is more than adequate in this regard.

Also of some interest, is the fact that we achieved a certain amount of success, in stabilizing the oscillation frequency of a LD, without adding to frequency modulation, using the Faraday effect. However, certain "issues" evade resolution, and will require more concerted efforts on our part.

More immediate tasks involve the use of LD's beat notes, to generate microwaves, due to the LD's tenability. While optical comb generators would provide signals of the highest strength and stability, but is prohibitive. Thus we have prospect of substituting signal stabilized in Rb saturated absorption lines.

7597-62, Session 13

Locking of three coupled lasers

H. Erzgräber, S. Wieczorek, The Univ. of Exeter (United Kingdom); B. Krauskopf, Univ. of Bristol (United Kingdom)

Arrays of coupled semiconductor lasers have emerged as promising devices for high-power coherent light sources and already find many applications. However, a major difficulty in many applications is the sensibility of semiconductor lasers to external perturbations, such as coupling to another laser, which can lead to instabilities and chaotic dynamics. Therefore, a better understanding of the coupling conditions for which a laser array is stable, that is exhibits continuous wave emission, is very desirable.

Here we investigate an array of three laterally coupled semiconductor lasers. This forms the simplest system with an underlying structure that is also found in larger arrays. Hence, this study constitutes a first step towards understanding the stability properties of large arrays. Of specific interest in this context is the phase difference of the individual laser fields, as it affects the far-field distribution of the laser array. We use a composite cavity model, where the individual lasers are coupled by the transverse modes of the entire composite cavity system. Specifically, we analyze the stable locking region, where the laser array exhibits continuous wave emission for different detunings and coupling strengths of the individual lasers. We find that only for small values of the linewidth enhancement factor in-phase locking (where all lasers oscillate in phase) is stable. Whereas for large linewidth enhancement factor the middle laser is out-of-phase with the outer lasers.

7597-63, Session 14

Theory of electron and few photon dynamics in light emitting quantum dot devices

A. Knorr, A. Carmele, M. Dachner, J. Wolters, M. Richter, Technische Univ. Berlin (Germany)

Quantum dot based light emitters can be used as a source of nonclassical light. In particular, we focus on the theory of InAs/GaAs quantum dots (QDs) embedded in a two dimensional wetting layer (WL). For real devices, the interactions between electrons and holes confined in the QDs and the wetting layer are important. Therefore, we include Coulomb interaction in the emission process as well as electron-phonon coupling, considering multi-phonon processes based on an effective multiphonon Hamilton operator. Here, we focus on the dynamics at low carrier densities, e. g. single photon emitter limit.

We treat electrical injection as well as emission on the same footing:

Carriers are electrically injected into the wetting layer and fill the QDs via multi-phonon processes. Evaluating the coupled electron-phonon dynamics, we predict a substantial carrier heating in such devices at low electrical pump currents: The QDs act as a sink for cold carriers, where electrons and holes recombine. If a single-photon emitter is realized, the electron and photon dynamics are strongly correlated. Perturbational approaches, such as cluster expansion, break down.

We access these systems by the photon-probability-cluster-expansion: a reliable approach for few photon dynamics in many body electron systems. We discuss also vacuum Rabi flopping and show that their amplitude determines the number of electrons in the quantum dot and present a simulation of a electrically driven single-photon source.

7597-64, Session 14

Scaling of plasmonic nanoring and nanopillar lasers

M. W. Kim, P. Ku, Univ. of Michigan (United States)

Nanoscale injection lasers can enable better integration of photonic and electronic components.

Although high-Q microdisk lasers have been demonstrated, further decrease in size is problematic because of inefficient light confinement. Additionally, efficient output coupling from nanolasers is still a challenge. Using metal-semiconductor or metal-semiconductor-metal structures in nanopillar and nanoring cavities, respectively, subwavelength-dimension light confinement and amplification can be realized.

Previously, we analyzed the scaling behavior of surface plasmon-based nanopillar lasers. Above D/ 0 = 0.4, they exhibit a relatively flat Q factor with respect to pillar diameter due to the dominance of metal loss over diffraction loss. The nanoring laser consists of a semiconductor ring resonator, a simple p-i-n structure with a gain medium in the intrinsic layer, covered with metal on all surfaces. In this symmetric metal-semiconductor-metal structure, most of the electric field is confined in the semiconductor, hence overcoming the high metal loss issue in the metal-semiconductor structure. Moreover, nanoring lasers have two design parameters, ring diameter and ring width, and, therefore, allow simultaneous optimization of gain-cavity mode matching and cavity-Q factor.

Using a 3D-Finite-Difference Time-Domain method, plasmonic nanoring lasers of various diameters and ring widths have been studied in comparison to surface plasmon-based nanopillars. While nanopillar lasers enable smallest dimensions, nanoring lasers exhibit a higher Q factor for D/ 0 > 0.5. Furthermore, according to a FDTD simulation, output can easily be coupled by inserting a metal-clad waveguide into the nanoring resonator. Thermal dissipation in the structure has also been studied using a 3D-Finite Element Method.

7597-65, Session 14

Polarization conservation and dephasing in InAs quantum dot ensembles

A. Chernikov, S. Horst, S. W. Koch, S. Chatterjee, W. W. Rühle, Philipps-Univ. Marburg (Germany); J. Sweet, B. Richards, J. Hendrickson, G. Khitrova, H. M. Gibbs, College of Optical Sciences, The Univ. of Arizona (United States); D. Litvinov, D. Gerthsen, M. Wegener, Univ. Karlsruhe (Germany)

Quantum dots are a possible candidate for various devices ranging from applications in quantum information processing to standard active material in lasers. Here, we present time-resolved photoluminescence measurements performed on an ensemble of InAs quantum dots with density of 1011 dots/cm2 and ground state transition energies centered at 1.216 eV. The wavelength of the 100-fs excitation pulse was tuned through the ground (excited) state transitions, resulting in resonant (optical phonon assisted) photoluminescence (PL). The PL was detected with its polarization both parallel with and perpendicular to the excitation polarization (along one of the crystal's cleave axes). The decay of the PL was time-resolved with a streak camera in the interval 1.5 - 3 ns to avoid scattered laser light. A strong polarization dependence was observed. Considerable amount of the resonant fluorescence signal and even of the non-resonant PL signatures remained linearly polarized on a nanosecond time scale. A phenomenological rate equation analysis is made, separating the excitations into two classes, one polarized along the excitation polarization and the other unpolarized. Both classes decay radiatively with a lifetime of 1 ns and a transfer from the polarized to the unpolarized species takes place with a distribution time of 12 ns at low temperatures and low excitation. The temperature dependence of the redistribution process closely resembles standard dephasing mechanism know from literature.

7597-66, Session 14

Multiscale thermal modeling of AlGaN/GaN quantum dot LEDs

G. Romano, Univ. of Rome Tor Vergata (Italy); G. Penazzi, A. Di Carlo, Univ of Rome Tor Vergata (Italy)

The Fourier heat equation has been found to be inadequate for modeling heat conduction through modern microelectronics devices. The phonons Boltzmann transport equation (BTE) can take in account microscopic behaviors as size effects and ballistic transport. Related to this approach, over the past decade several approaches have been investigated. In this work we adopt the gray model, where all phonons have the same group velocity (sound velocity) and scattering time.

In order to keep low the computational time, the Fourier's law is used to model heat dissipation far away the active region.

The two models are linked to each other by means of appropriate boundary conditions and the BTE/Fourier interface is assumed to be at local thermodynamics equilibrium.

A drift-diffusion approach, with thermoelectric effect included, is used to model heating phenomena.

Electrons, holes and phonons transport is computed in a self-consistent way.

Quantum states are provided by the envelope function approximation model whereas the optical spectrum is obtained by the standard Fermi Golden Rule approach. Strain related effects are also included.

The whole model has been implemented in TiberCAD, a multiscale simulator for optoelectronics devices developed by our group.

Calculations are perfomed for a GaN/AlGaN quantum dot LEDs.

Voltage-current trend as well as temperature dependence of the optical spectrum are investigated.

Conference 7598: Optical Components and Materials VII

Tuesday-Thursday 26-28 January 2010 • Part of Proceedings of SPIE Vol. 7598

Optical Components and Materials VII

7598-01, Session 1

New chalco-halide glasses and glass-ceramics with broaden transmission from the visible to the far infrared for passive and active applications

L. Calvez, M. Rozé, L. Yannick, C. Lin, E. Guillevic, B. Bureau, X. Zhang, Univ. de Rennes 1 (France)

Since few years, various glass-ceramics were obtained from compositions belonging to different systems such as Ge-Sb-(S/Se)-MX (MX: alkali halide). In order to extend the transmission range of these glasses, antimony has been substituted by gallium. For the first time, sulfur based glasses totally transparent in the visible range up to 11µm and selenium based glasses slightly transparent in the visible range up to 16µm were synthesized. From many compositions belonging to the Ge-Ga-(S/Se)-MX systems, glass-ceramics with controllable crystal size and number have been obtained with appropriated heat treatment time and temperature. Gallium acts as a nucleating agent leading to glass-ceramics with high crystallized proportion of about 40%. The closer refractive index between the glassy matrix and the Ga based crystalline phases tends to lower the scatterings, leading to highly transparent glass-ceramics in the visible and infrared range depending on the compositions. This phenomenon was observed in selenide glasses and in sulfur glasses as well. Most of these glass-ceramics present enhanced mechanical properties such as toughness and could be an interesting alternative solution to single-crystalline germanium lenses commonly used in infrared optics. Gallium is also well known to allow the introduction of higher content of rare-earth. Consequently, erbium was added in a GeS_2-Ga_2S_3-CsCl glass. Glass-ceramics with controllable crystal size were obtained. It has been demonstrated that Er^{3+} ions enter the crystalline phase leading to an increase of the luminescence efficiency. Consequently, these new glasses and glass-ceramics can lead to various application fields, in passive or active optics.

7598-02, Session 1

The influence of photonic mode density on the luminescence of erbium doped optical materials

F. Song, Nankai Univ. (China); Q. Wang, Nankai Univ. (China) and City Univ. of Hong Kong (Hong Kong, China); C. Ming, J. Tian, J. Xu, Nankai Univ. (China); S. Lin, E. Y. Pun, City Univ. of Hong Kong (Hong Kong, China)

According to the Fermi golden rule, the spontaneous emission rate from excited level |i> to lower level |j> is ,where Mij is the matrix element related to the two energy levels, is the optical density and is also known as the photon mode density (PMD). Er/Yb codoped phosphate glasses have been applied in eye safe laser ranger, high gain fiber amplifiers and lasers. However, the mechanical and chemical characteristics are not that good. Recently, we have successfully fabricated Er/Yb codoped phosphate glass ceramics. Detailed comparisons, including emission rates, lifetimes, intensity parameters, energy transfers, and so on, have been carried out on the glass and glass ceramics having the same chemical composition, and the role of the PMD is analyzed.

Another example is to use surface plasmon polariton (SPP) to change the PMD. The SPP will change the PMD of the material and the emission rate will be modified. We have observed enhancement in the visible wavelength and intensity increase at 1.5µm wavelength by introducing SPP in two ways. One is to deposit silver and gold nanostructure films on the erbium doped optical materials, and the other is to dope metal nanoparticles in the RE doped optical material.

7598-03, Session 1

Two-photon pumped random lasing in a dye-doped silica gel powder

S. Garcia-Revilla, Univ. del País Vasco (Spain); I. J. Sola, Univ. de Salamanca (Spain); R. Balda, Univ. del País Vasco (Spain); L. Roso, Univ. de Salamanca (Spain); D. Levy, M. Zayat, Instituto de Ciencia de Materiales de Madrid (Spain); J. M. Fernández, Univ. del País Vasco (Spain)

Random laser action has been recently demonstrated in the ground powder of silica gels containing rhodamine 6G (Rh6G) doped nanoparticles following one-photon excitation [1]. Moreover, the laser-like emission dynamics found in this amplifying disordered medium after picosecond optical pumping was accurately described by using a light diffusive propagation model with the feedback provided by the powder [1]. The advantages of this kind of dye random laser system are its solid-state nature, quenched disorder, high laser-like emission efficiency, and the possibility to be functionalized for various applications such as biomedical sensors. Concerning this challenging field of new applications, two-photon induced lasing could exhibit some advantages over the conventional single-photon pumping used until now. Note that the use of near infrared excitation usually provides better penetration depth into highly scattering media than visible light and, therefore, it makes possible to extract gain from the bulk rather than a thin layer of the medium. Nevertheless, due to the relatively small two-photon absorption cross section of the commonly used laser dyes, just few random laser experiments were performed following multiple photon excitation. Here we report the first observation of two-photon pumped random laser action in the ground powder of a silica gel containing 2 wt% Rh6G-SiO_2 nanoparticles. Random laser-like effects such as spectral narrowing and temporal shortening are explored exciting with femtosecond laser pulses at 800 nm. A comparison among the emission features, random laser behavior and onset of laser-like emission under one- and two-photon excitations of this solid-state dye system, is also performed.

[1] García-Revilla, S., Fernández, J., Illarramendi, M. A., García-Ramiro, B., Balda, R., Cui, H., Zayat, M. and Levy, D. “Ultrafast random laser emission in a dye-doped silica gel powder,” Opt. Express 16(16), 12251-12263 (2008).

7598-04, Session 1

Spectral-luminescence properties of Bi-doped bulk glasses and factors acting on them

B. I. Denker, B. I. Galagan, I. L. Shulman, S. E. Sverchkov, E. M. Dianov, A. M. Prokhorov General Physics Institute (Russian Federation)

The properties of optical centers emitting in 1.0 - 1.6 µm range under optical excitation were investigated in Bi-doped Al-B-phosphate and Mg-Al-silicate glasses having moderate melting temperatures to be fabricated by routine melting in Pt and alumina crucibles. It was shown that such factors as glass composition and Bi concentration, melting temperature, synthesis atmosphere, irradiation influence noticeably on the spectral-luminescence properties of NIR-emitting centers in these glasses. The analysis of the obtained experimental data allows to draw a conclusion that the NIR emitting centers are formed in a reversible endothermic chemical reaction in the glass melt. The quadratic concentration dependence of absorption in the visible range indicates that the considered optical centers contain a pair of bismuth ions.

7598-48, Session 1

Generation of wide color gamut visible light in NIR-excited thulium-holmium-ytterbium codoped tantalum oxide nanopowders

A. S. Gouveia-Neto, L. A. Bueno, E. B. Costa, Univ. Federal Rural de Pernambuco (Brazil); J. L. Ferrari, K. O. Lima, R. R. Gonçalves, Univ. de São Paulo (Brazil)

Multicolor visible light emitting NIR-excited Tm-Ho-Yb-codoped tantalum oxide nanopowders were produced using the sol-gel method. The generation of a wide color gamut fluorescence in glass-ceramic with orthorhombic Ta2O5 nanocrystals dispersed into amorphous silica-based matrix was observed. The Ta2O5 spherical shaped nanoparticles appear well dispersed in the SiO2 amorphous, and the average size increased with temperature up to 12 nm for the highest temperature of annealing(1100 oC). The crystallization process was monitored by vibrational and photoluminescence spectroscopy, X-ray diffraction, and High Resolution Transmission Electron Microscopy (HRTEM). The light emission spectroscopic properties of the rare-earth doped SiO2:Ta2O5 nanocomposites as a function of the tantalum content and temperature of annealing was examined. Multicolor simultaneously emitted fluorescence consisting of blue(480 nm), green(540 nm) and red(650 nm) upconversion signals in the SiO2:Ta2O5 system doped with holmium and thulium and sensitized with ytterbium, was observed. The proper choice of the RE3+ content and the NIR excitation power yielded the generation and control of the three primary colors and allowed the emission of a balanced white overall luminescence from the glass-ceramic nanopowder samples

7598-05, Session 2

Application of ceramic phosphors for bio- and medical-imaging technologies

K. Soga, Tokyo Univ. of Science (Japan)

Ceramic phosphors doped with trivalent rare-earth ions have been utilized under near infrared (NIR) excitation to emit NIR light for optical devices such as Nd:YAG laser and Er-doped fiber amplifiers. On the other hand, fluorescence bioimaging is one of the important technologies for biological researches and medical technologies. Currently, most of the fluorescence bioimaging are carried out under ultraviolet or visible light excitation to emit visible fluorescence. The short wavelength of the excitation and emission lights causes short penetration depth of the lights, which in turn results in shallow observation depth of biological objects. Beside the scattering, problems as color fading of the phosphor, phototoxicity and autofluorescence are also caused by the use of short wavelength light. All of them can be solved by using NIR excitation and emission for the imaging. The author's group has applied the rare-earth doped ceramic nanophosphors (RED-CNP) for the NIR fluorescence bioimaging. The RED-CNP are designed to give sufficient NIR emission under NIR excitation based on the host and dopant concentration design. The size of the RED-CNP was controlled to be in 20-200 nm with homogeneous size by using several precipitation routs by utilizing ceramic processing technologies. The surface of the RED-CNP was modified with PEG based block polymers to give dispersion and specific interaction to the RED-CNP in physiological conditions. NIR biological microscope and in vivo imaging system, which can detect the NIR fluorescence in 800-1700 nm wavelength region, are developed. Some of the cellular and in vivo bioimaging results will be demonstrated.

7598-06, Session 2

White LED phosphors: the next step

H. Yamamoto, Tokyo Univ. of Technology (Japan)

Application of white LEDs is expanding toward production of higher output and better color rendering. The former is typically aimed at room illumination or car headlights, which requires stability of phosphors under high-temperature and high-density photon flux. The latter is backlighting of LCD TV sets, which requires luminescence spectra of phosphors well matched with transmission characteristics of color filters. To meet such demands, new materials have been investigated with emphasis on their luminescence spectra, temperature characteristics and reliability. Recently developed nitrido- or oxonitrido-silicates activated with Eu^{2+} are promising materials, because their rugged frames consisting of [SiN_4] tetrahedra connected with each other can provide thermal and chemical stability as well as small thermal quenching of luminescence. Some materials of this group, e.g.beta-SiAlON:Eu^{2+} or $Ba_3Si_6O_{12}N_2$:Eu^{2+}, can also provide a relatively narrow emission band, which is favorable to matching with LCD color filters.

As far as a luminescence spectrum is concerned, Eu^{3+} and Mn^{4+} are ideal activator ions of backlighting red phosphors, because they show luminescence with a line-spectrum confined in a narrow wavelength region. However, they have weak absorption of excitation light resulted from forbidden transitions. It is required that this disadvantage is overcome by finding of an efficient energy donor. This will be a challenging target to improve LCD backlighting further.

7598-07, Session 2

Construction of photoconductivity measurement system as functions of excited wavelength and temperature: application to Eu2+-activated phosphors

T. Nakanishi, S. Tanabe, Kyoto Univ. (Japan)

In order to understand the thermal quenching of rare-earth doped phosphors, clarification of electronic energy structure of the excited states of the activator and of the host conduction band is an important step. As an experimental approach, the photoconductivity measurement of the phosphor is one of the effective methods to clarify the direct interaction of the excited electron (hole) and conduction- (valence-) band.

In this study, we constructed an automatic temperature- and wavelength-dependent measurement system of photocurrent in inorganic phosphors (single- or poly- crystals). From a 300W-Xe lamp, the monochromatic light of various wavelengths with constant power, which was controlled by an ND-filter and band-pass filters, was irradiated on the sample, the temperature of which was controlled in a cryostat at 15K~300K. In this study, we report the wavelength- and temperature-dependence of the photocurrent in a Eu^{2+}: $SrAl_2O_4$ phosphor measured by using this system.

Excitation wavelength-dependence of the photocurrent showed a similar profile to the PL-excitation spectrum of Eu2+. The results clearly indicate the interaction of 5d level of Eu^{2+} with the conduction band. The activation energy of the photocurrent was evaluated from its temperature dependence for each wavelength. It decreased with decreasing wavelength from 490nm to 400nm, and became constant (~20 meV) below 400 nm. The ground state of Eu^{2+} ($^8S_{7/2}$) was estimated to be 3.1 eV below the bottom of the conduction band. It is expected that the detailed characterization of photoconductive properties obtained with this measurement system will initiate further studies of energy level structure.

7598-08, Session 2

The efficiencies of energy transfer from Cr to Nd ions in silicate glasses

S. Mizuno, Toyota Central Research and Development Labs., Inc. (Japan); H. Nasu, M. Hughes, T. Suzuki, Toyota Technological Institute (Japan); H. Ito, K. Hasegawa, Toyota Central Research and Development Labs., Inc. (Japan); Y. Ohishi, Toyota Technological Institute (Japan)

The efficiencies of energy transfer (QEet) from Cr to Nd in alkali silicate glasses have been examined to develop a gain medium of high-efficiency solar pumped fiber lasers (SPFLs). Nd is one of the most commonly used active ions in solid-state laser materials, and Cr co-doping is a convenient way to collect sunlight which is unabsorbed by Nd. Thus, QEet from Cr to Nd are important for SPFLs. We used a glass composition of 5.03K2O-20.15Na2O-74.82SiO2. This silicate glass has been developed as a laser gain medium for nuclear fusion experiments. In this paper, Nd,Cr co-doping in this silicate glass was carried out to explore QEet from Cr to Nd. QEet is defined as the ratio of the quantum efficiencies (QEs) of Nd-doped glasses to the QEs of Cr,Nd co-doped glasses in this study. Nd2O3 and Cr2O3 were singly or co- doped into the host glass at several concentrations. The QEs of Nd and Cr in singly doped, and Cr,Nd co-doped glasses at several concentrations were measured to calculate QEet. For this measurement we used an integrating sphere, and a laser diode at a wavelength of 808 nm for Nd, and 650 nm for Cr or Cr,Nd co-doped glasses, respectively. The QEet obtained here tends to decrease with increasing Cr concentration when Nd concentration is fixed. This tendency is quite similar to the QEs of the Cr singly doped glasses. Thus an increase of QEs of Cr is essential to increase the QEet.

7598-09, Session 2

The influence of Yb2+ ions on optical properties and power stability of ytterbium-doped laser fibers

J. Kirchhof, S. Unger, A. Schwuchow, S. Jetschke, V. Reichel, M. Leich, A. Scheffel, IPHT Jena (Germany)

Up to now, the role of bivalent ytterbium ion has been controversially discussed in the literature concerning its influence on the photodarkening of ytterbium doped high power laser fibers. In general, however, the experimental findings are relatively sparse and some discussions are based more on speculations than on examined facts.

Here we report on systematical investigations concerning the formation of Yb2+ during the fabrication process of preforms and fibers. By Modified Chemical Vapor Deposition, fibers with different co-dopants (additional to the active ytterbium doping) have been prepared in a well-defined manner, regarding process parameters and glass composition. Additionally, ytterbium-doped samples were prepared by powder-sintering technology and compared with the MCVD fibers. The comprehensive characterization of the samples involves the ytterbium absorption and emission in the NIR, the cooperative visible fluorescence and the UV absorption and UV excited emission. The typical spectral features in the UV and visible range have been analysed and correlated with the presence of Yb2+. The amount of formed bivalent ytterbium ions shows a strong dependence on the process route and varies remarkably with the kind and concentration of the co-dopants. Photodarkening tests have been accomplished in order to correlate the power stability with the Yb2+ content. Moreover, the formation of Yb2+ during the process of radiation darkening could be detected. The results are discussed within the framework of different theories of the mechanism of photodarkening.

7598-10, Session 3

Silicon photonic parametric optical processing for ultra-high bandwidth on-chip signal grooming

K. Bergman, Columbia Univ. (United States)

Silicon photonics is a rapidly emerging platform for novel optical devices with exceptional performance for diverse applications ranging from short-haul optical communication links to on-chip interconnection networks. Its complementary metal-oxide-semiconductor (CMOS)-process compatibility enables low-cost, high-yield fabrication of monolithically integrated circuits that can combine the best of optical and electrical functionalities. Large index contrast enables waveguides with low bending losses and engineered dispersions, empowering a broad and flexible design space complemented with immense dispersion tunability. Leveraging this tuning capability, silicon waveguides have recently become a promising platform for ultrafast all-optical parametric processing based on four-wave mixing(FWM), supporting future transparent optical networks with data rates approaching 1 Tb/s per wavelength channel. Utilizing all-optical parametric processing in a silicon photonic chip, we demonstrate multiple signal grooming functionalities on-chip. These include wavelength conversion for 10and 40-Gb/s NRZ as well as 160-Gb/s pulsed-RZ data signals, and wavelength multicasting at 40-Gb/s NRZ data rates.

7598-11, Session 3

Optical properties of atomic layer deposited materials and their application in silicon waveguides

T. Alasaarela, Helsinki Univ. of Technology (Finland); J. Hiltunen, VTT Elektroniikka (Finland); A. Khanna, A. Saynatjoki, A. Tervonen, S. Honkanen, Helsinki Univ. of Technology (Finland)

Atomic layer deposition (ALD) is a promising method to grow optical materials on waveguide structures[1]. The wide variety of available materials, conformal growth properties and low scattering losses of ALD films enable their usage in various waveguide applications. ALD is increasingly being used in the latest generation products of the semiconductor industry.

Thin films of TiO2, Al2O3, and ZnO are ALD deposited on glass substrates to make slab waveguides. The prism coupling technique is used to determine the effective indices of the propagating modes of the slabs, and the thickness and refractive index of the films are solved. Also the propagation losses are roughly estimated.

The applications of ALD films in silicon-on-insulator (SOI) waveguides are discussed. As silicon has a very high refractive index, usually only the evanescent field of the waveguide structures can be reached with grown materials. Slot waveguides are high-index contrast structures where light is confined in the low index material, which allows one to use low index materials as effective media. Conformality of ALD films is very useful, when coating slot waveguide structures. Experimental results on coated SOI waveguide structures are discussed.

[1] T. Alasaarela, A. Säynätjoki, P. Stenberg, M. Kuittinen, S.Honkanen, “Filling of Slot Waveguides with Atomic Layer Deposition (talk)”, CLEO Europe -EQEC 2009, June 14-19 2009, Munich, Germany, Paper CK10.6

7598-12, Session 3

Mode properties in silicon based 2-dimensional slot waveguides for polarization-independent operation

A. Khanna, T. Alasaarela, A. Säynätjoki, A. Tervonen, S. Honkanen, Helsinki Univ. of Technology (Finland)

Recently, new schemes using slot geometry have been proposed for various applications in integrated optics [1]. In particular, they can be useful for integrating non-Si materials into silicon based waveguides for overcoming limitations of silicon (indirect bandgap, small electro-optic effect, two-photon absorption etc.) [2]. However, slot waveguides are severely polarization sensitive, and usually only suitable for single-polarization operation.

We have shown unique 2D slot waveguiding schemes operating in the single mode regime allowing both quasi-TE and the quasi-TM modes to propagate. One such 2D scheme, cross-slot geometry, can be used to achieve non-birefringent structures [3]. Dependence of quasi-TE and quasi-TM mode properties - such as eigen-modes, confinement factors, individual mode areas and mode overlaps - on geometrical and material parameters of cross-slot geometry is studied. Also, fabrication tolerances

are discussed. Moreover, external tuning of birefringence by thermo-optic effect is investigated.

Other alternative 2D slot waveguide structures are analyzed. Optimal structure depends on the functionality. The examples studied in this work aim for polarization-independent waveguides utilizing nonlinear or magneto-optic materials. Integration of different polymers and compounds in the 2D slot waveguides and manufacturability of waveguide structures for diverse functionalities is also discussed.

References

[1] Carlos Angulo Barrios and Michal Lipson, Optics Express, Vol. 13, No. 2512, 2005

[2] C. Koos et al. Nature Photonics, 216, Vol. 3, 2009

[3] A Khanna et al. CLEO Europe-EQEC 2009, June 14-19 2009, Munich, Germany, Paper CK.P.10

7598-13, Session 3

Optical microresonator based on silicon technology for applications to an optoelectronic oscillator

Y. Wu, L. Vivien, E. Cassan, Univ. Paris-Sud/IEF (France); V. H. N. Luong, L. D. Nguyen, B. A. Journet, École Normale Supérieure de Cachan (France)

One of the most important properties of optoelectronic oscillators (OEO) is their high spectral purity leading to applications such as photonics signal processing, communication or radio over fiber systems. In the OEO classical structure a long fiber optic feedback loop is acting as a delay line and determining the oscillation frequency, the different modes and the phase noise. Because of the length of the fiber loop the system has a rather important size and is very sensitive to the temperature changes. An integrated system would be a good solution in order to perform an efficient temperature control for all the different elements in a small volume. A first step toward integration is to introduce an optical micro-resonator replacing the fiber loop. Such resonators should present very high quality factor for maintaining the spectral characteristics of the OEO. In this paper a solution using resonators based on silicon materials is introduced. The OEO developed at the laboratory works at 8 GHz, then the optical micro-resonator should presents a free spectral rang equal to this oscillation frequency and of course a good quality factor. Because of the easy integration possibility it has been chosen to work on silicon technology. The design is a micro-ring with the shape of a stadium. With a ridge of 30 nm height, 1 µm width, a millimetric radius, and a gap of some microns the quality factor is about 500000, equivalent to a fiber length of 2 km. The micro-resonator is coupled to the OEO by using micro-lens on fiber tips.

7598-14, Session 4

Recent developments in bend-insensitive and ultra-bend-insensitive fibers

D. E. Boivin, L. de Montmorillon, L. Provost, N. Montaigne, Draka Comteq France (France); F. Gooijer, Draka Comteq Fibre B.V. (Netherlands); E. Aldea, Draka Holding N.V. (Netherlands); J. Jensma, Draka Comteq Fibre B.V. (Netherlands); P. Sillard, Draka Comteq France (France)

Fastest-growing broadband technology, Fiber To The Home (FTTH) has spurred the emergence of a new fiber generation exhibiting exceptional low bend losses that are two and three orders of magnitude lower than those of standard single-mode fibers without degrading any backward compatibilities [1]. Designed to overcome the limitations in case of extreme bending conditions, these Bend- and Ultra-Bend-Insensitive Fibers (BIFs and UBIFs) appear as ideal solutions for use in FTTH networks and in components, pigtails or patch-cords for ever demanding applications such as military or sensing.

Recently, however, questions have been raised concerning the Multi-Path-Interference (MPI) levels in these fibers. Indeed, they are potentially subject to interferences between the fundamental mode and the higher-order mode that is also bend resistant. This MPI is generated because of discrete discontinuities such as staples, bends [2] and splices/connections that occur on distance scales that become comparable to the laser coherent length.

In this paper, we will demonstrate the high MPI tolerance of all-solid single-trench-assisted BIFs and UBIFs. We will present the first comprehensive study combining theoretical and experimental points of view to quantify the impact of fusion splices on coherent MPI. To be complete, results for mechanical splices will also be reported. Finally, we will show how the single-trench-assisted concept combined with the versatile PCVD process allows to tightly control the distributions of fibers characteristics. Such controls are needed to massively produce BIFs and to meet the more stringent specifications of the UBIFs.

[1] Boivin & Al., in Proc. of SPIE Vol. 7212 (2009).

[2] Chen & Al., in Proc. of OFC/NFOEC, paper NTuC5 (2009).

7598-15, Session 4

Innovative fiber coating systems based on organic modified ceramics

K. Schuster, J. Kobelke, IPHT Jena (Germany); K. Rose, Fraunhofer-Institut für Silicatforschung (Germany); M. Helbig, SurA Chemicals GmbH (Germany); M. Zoheidi, A. Heinze, FiberTech GmbH (Germany)

The demand of high temperature and power stable coatings for BRAGG-grating sensors and high power fiber lasers requires new coating concepts. Based on their chemical structure inorganic organic hybrid materials (ORMOCERs®) afford the possibility for an easy coating applicability for optical fibers in combination with a high short as well as long time temperature stability (up to 350 °C for minutes and 200 °C for 48 h, respectively). Regarding the fiber protection the coatings have been investigated using tensile strength measurements before and after temperature load. Best coatings remaining the high tensile strength of 66 N (125 µm fiber) with a Weibull parameter >140 after a temperature cycling of 200 °C for 48 h.

For the first time a low refractive index ORMOCER® will be presented showing a numerical fiber aperture of 0.47 at a wavelength of 1000 nm. This corresponds to a refractive index of 1.37. The fiber possesses a fiber loss of 18 dBkm-1 at a wavelength of 1000 nm. The low index coated fibers will be examined by a power stability test up to 500 W.

The fibers have been coated using a pressure technology with extremely minimized die equipment. This coating pressure equipment is well applicable for small coating amounts. The so called dead volume within the coating die is about 1 ml. The overall dead volume is only influenced by the supply pipe and can be reduced down to 5 ml.

7598-16, Session 4

Novel shape memory alloy optical fibre connection method

G. Trouillard, Phasoptx Inc. (Canada); P. Zivojinovic, Phasoptx Inc (Canada); R. Cerutti, E. Weynant, Phasoptx Inc. (Canada)

Optical fibres demand is increasing every day in fields as varied as FTTH, fiber lasers, automotive and aerospace. This leads to a permanent search for improvement of optical communications systems. Working through partnerships, Phasoptx has developed the Optimend® splice that meets the optical fibre connections requirements in all these domains of application. In this article, Phasoptx is demonstrating the capacity and quality of its shape memory alloy splice for installation and connection of optical fibres.

The Optimend® is an optical fibre connection method which use the

super-elastic property of CuAl based shape memory alloy to connect optical fibres together (single fibres as well as multiple fibres). Optimend® is available for all fibres dimensions varying from 125 µm up to 1 mm. In this article the principle of operation of Optimend® technology that mechanically connects the fibres is explained. Phasoptx mechanical splice has the particularity to align and hold the cladding of fibres itself without using glue. A very simple tool has also been designed. This technology, which does not require expensive tool or complex fibre preparation, has already shown very good optical and mechanical performances (insertion loss lower than 0,3 dB without index matching gel).

Optimend®'s main characteristics are its small dimensions (few millimetres), reusability (at least 25000 cycles), glueless, ruggedness, low temperature variation, heat dissipation (very useful in high power laser applications) and ease of use. These properties are very suitable for many optical fibre applications where quick and reliable connection is desirable.

7598-17, Session 4

Tunable birefringent phase shift induced in fiber Bragg gratings by a shape memory alloy phase modulator

A. Fraser, PhasOptx (Canada) and Université Laval (Canada); M. Bernier, Univ. Laval (Canada); E. Weynant, PhasOptx Inc. (Canada); R. Vallée, Univ. Laval (Canada)

Phase shifted fiber Bragg gratings (PSFBG) are very compact transmission filters that have a great potential for spectral filtering, especially for dense WDM applications. They also found a wide range of applications in the domain of distributed feed-back fiber lasers (DFBFL) and sensors. In the present paper, we propose a new method to induce low loss tunable birefringent phase shifts in fiber Bragg gratings (FBG) by applying mechanical stresses at precise locations along the FBG. A specially designed shape memory alloy (SMA) ferrule is used to transfer mechanical stress to the optical fiber. A piezoelectric actuator control the amount of stress delivered to the fiber by the SMA ferrule, thus allowing a precise and dynamic tuning of the amplitude of the phase shift induced in the FBG. The small footprint of the SMA ferrule allows placing several independent phase modulators along the FBG. The losses induced by the device are below 0.02 dB for the whole range of phase shift, which can be as high as 5π radians. We believe that this device can be very attractive in the design of tunable DFBFL because it will allow rapid tuning of the emission wavelength as well as the polarization state of the laser. It can also be useful in the design of tunable narrow pass-band filter, all-fiber polarization switch or PSFBG based fiber sensors.

7598-18, Session 4

Novel fiber bottle microresonator add-drop filters

G. Senthil Murugan, J. S. Wilkinson, M. N. Zervas, Univ. of Southampton (United Kingdom)

Novel bottle microresonators fabricated from standard telecommunications optical fiber were recently shown to support helical whispering gallery modes (WGMs) extending along the bottle length between the bottle necks. Intensity maxima were observed around the turning points on both sides close to the bottle necks where the WGMs are effectively reflected [Optics Express Vol.17 pp.11916-11925, 2009]. Selective excitation on one side of the bottle microresonator leads to strong power localization at a symmetrically located turning point for the WGMs and can potentially be exploited to form effective add-drop filters. Channel dropping characteristics have been studied experimentally for the first time in this novel type of microresonator. A tapered optical fiber (drawn down to 2-3 microns in diameter with effective index of approximately 1.2) was placed on one side of the bottle to excite the bottle WGMs. A similar tapered fiber placed symmetrically on the other side of the bottle acted as a probe to extract the excited modes. We have successfully extracted power from all the resonance wavelengths using the probe placed at appropriate positions along the bottle. By properly matching the effective indices of the excitation and probe fibers with the bottle microresonator modes and satisfying critical coupling conditions, an efficient add-drop filter can potentially be realised.

7598-19, Session 5

Ultra-wideband integrated 2x2 optical router using novel MMI design

M. A. Swillam, M. H. Bakr, X. Li, McMaster Univ. (Canada)

We propose a novel design of optical routers and switches based on the multimode interference phenomenon in waveguide with parabolic index profile. A stair case index approximation of this index profile is utilized to facilitate the fabrication process. The fabrication of this profile is feasible through the current technology using multiple etching.

A new design methodology is also proposed to ensure that the response of the stair case MMI (SCMMI) imitates the response of the parabolic MMI [1]. In this methodology, a two-stage optimization procedure is exploited to obtain the optimal design. Gradient-based optimizers are utilized in these two stages exploiting the wide angle BPM. The required response gradient is efficiently obtained using the adjoint variable method.

The proposed design operates over a wide bandwidth. This bandwidth covers from 1.3 m to 1.6 m. The cross coupling is less than -21 dB and the insertion loss is 0.45 dB. The width of the device is 20 m.

[1] M. A. Swillam, M. H. Bakr, and X. Li, "Design optimization of compact wideband optical switch exploiting stair case index MMI," IEEE J. Lightwave Technology, vol. 27. pp 80 - 87, Jan. 15th 2009.

7598-20, Session 5

Polarization-dependent mode coupling in mechanically induced long-period fiber gratings based on polarization-maintaining fibers

H. Kim, O. Kwon, S. Chu, M. Yoon, Hanyang Univ. (Korea, Republic of); S. B. Lee, Korea Institute of Science and Technology (Korea, Republic of); Y. Han, Hanyang Univ. (Korea, Republic of)

Long-period fiber gratings (LPFGs) have been widely investigated in many applications to fiber-optic communication systems, fiber-optic sensors, and integrated optical processing. However, the transmission characteristics of mechanically induced LPFGs based on polarization-maintaining fibers (PMFs) with the variation of axial rotation of the principle axis and the input polarization state were not fully reported. In this study, the effect of polarization state and the axial rotation of external pressure on the transmission characteristics of the mechanically included LPFGs based on PMFs are investigated. The transmission characteristics of the PMF-based LPFG are changed by the variation of the magnitude of external pressure and the axial rotation of the PMF. The coupling strength is optimized by changing the angle between the periodic groove plate and the fast axis of the PMF at 0 o, 45 o, and 90o. When the angle between the periodic groove plate and the fast axis of the PMF is 0o, the coupling strength of the LPFG is easily improved with a small value of external pressure compared with the case of the angle at 90o. Two resonant peaks caused by the birefringence of PMF are effectively switched by controlling the input polarization state. The experimental results are very useful for versatile applications to in-line polarizers, tunable filters, and polarization-dependent loss compensators.

7598-21, Session 5

Active attenuation control of long-period fiber grating written in erbium-doped fiber

R. Singh, E. K. Sharma, Univ. of Delhi (India)

Long period gratings (LPG) have emerged as attractive gain flattening filters. The idea of integration of the filtering function of LPG with the active amplifying medium like a 980 nm pumped Erbium Doped Fiber (EDF) was proposed by us as an efficient intrinsic gain flattening filter. It was shown that in addition to gain flattening, enhancement of gain occurs for the wavelengths in the 1540-1560nm range. We now extend this analysis to the use of an LPG inside a short length of EDF as a wavelength attenuation element with active attenuation control. The attenuation at the resonance dips can be controlled by the varying pump power. Further, the coupling length for the LPG also varies with pump powers. Hence, the transmission characteristics of the grating at different pump powers and different lengths of the grating show an interesting behavior. The choice of the grating length plays a vital role in the pump controlled behavior of the transmission spectrum. In a recent paper, the authors have reported some experimental results on an LPG written by CO2 laser technique in an EDF. In this paper we study the control of the variation of the pump power and the dependence of the transmission spectrum on grating length and the chosen cladding mode. This is used to explain the experimental results reported. The small shift in the resonance wavelength in the reported results is shown to be due to the small change in the refractive index near the resonance absorption wavelengths.

7598-22, Session 5

Fabrication of low-loss chalcogenide photonic-crystal fibers by a moulding process

Q. Coulombier, L. Brilland, P. Houizot, Univ. de Rennes 1 (France); T. N. Nguyen, T. Chartier, Ecole Nationale Supérieure des Sciences Appliquées et de Technologie (France); G. Renversez, Univ. Paul Cézanne (France); J. Fatome, F. Smektala, Univ. de Bourgogne (France); J. Sangleboeuf, T. Pain, J. Troles, Univ. de Rennes 1 (France)

Chalcogenide glasses are known for their large transparency in the mid infrared region and their high refractive index (>2). They present also a high non linear refractive index (n2), 100 to 1000 times larger than for silica, depending on the composition. An original way to obtain single-mode fibers is to design microstructured optical fibers (MOFs). In addition, photonic crystal fibers (PCFs) present unique optical properties thanks to the high degree of freedom of the design of their geometrical structure. Up to now; the chalcogenide PCFS are realized using the stack and draw process. However this technique can be problematic in the case of theses glasses. A lot of defects, like bubbles, have been observed at the capillaries interfaces causing significant scaterring losses. Up to now, the best transmission obtained was 3dB/m at 1,55µm but in the most of case, it is greater than 5 dB/m. So, the poor PCF transmission reduces significantly their application potential.

So, we present for the first time a new efficient method to realize low loss chalcogenide PCFs. This new original method based on a moulding process permits to reduce the optical losses down to 1 dB/m at 1,55µm and less than 0,5 dB/m between 3 and 5 µm for an AsSe PCF. Single mode AsSe fibers were realized. Moreover, very small core fibers have been realized with this method, obtaining a non linear coefficient of 15 000 W-1 km-1 with an AsSe PCF. We also observed self phase modulation (SPM) à 1,55 µm on a fiber with a 2.3 µm² effective mode area.

7598-23, Session 6

Fabrication and characterization of colloidal crystals infiltrated with metallic nanoparticles

A. Chiappini, Univ. degli Studi di Trento (Italy); S. Guddala, Univ. degli Studi di Trento (Italy) and Univ. of Hyderabad (India); C. Armellini, Univ. degli Studi di Trento (Italy); S. Berneschi, I. Cacciari, Istituto di Fisica Applicata Nello Carrara (Italy); C. Duverger-Arfuso, Univ. du Maine (France); M. Ferrari, Univ. degli Studi di Trento (Italy); G. C. Righini, Istituto di Fisica Applicata Nello Carrara (Italy)

3D Photonic Crystals (PhCs) have been actively explored as a unique system for generating photonic band gaps that could be used to control the propagation of electromagnetic waves in all the three dimensions of space. A simple and inexpensive method to realize 3D-PhCs exploits the properties of self-assembly of colloidal nanospheres [1].

Furthermore, the possibility to infiltrate these structures with suitable materials permits to modify their optical properties, to use these new systems in several applications such as optical devices, catalysis, and also as chemical and physical sensors [2].

In particular, the infiltration of the opal structures with metallic nanoparticles is extremely interesting because it permits to develop systems that can be use as SERS substrates or chemical sensors.

Here we will report the results obtained on colloidal crystal systems infiltrated with metallic nanoparticles. In particular we will present in detail the procedure used to realize the photonic systems and we will also discuss their optical properties.

Finally, we will report the results of the structures realized and used as SERS substrates and as chemical sensors.

[1] A. Chiappini, C. Armellini, S. N. B. Bhaktha, A. Chiasera, M. Ferrari, Y. Jestin, M. Mattarelli, M. Montagna, E. Moser, G. Nunzi Conti, S. Pelli, G. C. Righini, V. M. Sglavo "Fabrication and optical assessment of sol-gel-derived photonic bandgap dielectric structures" SPIE 6182 (2006) pp. 454-463.

[2] D. Zonta, A. Chiappini, A. Chiasera, M. Ferrari, M. Pozzi, L. Battistia, M. Benedetti, "Photonic crystals for monitoring fatigue phenomena in steel structures" 7292 SPIE (2009) pp.215-1-215-10.

7598-24, Session 6

Planar long-period gratings for photonic applications

J. Jiang, C. L. Callender, J. P. Noad, C. Ledderhof, Communications Research Ctr. Canada (Canada); J. Ding, National Research Council Canada (Canada)

This work presents long period grating (LPG) devices based on a silica-on-silicon planar waveguide platform. All-silica and hybrid polymer / silica device architectures are demonstrated for potential applications in wavelength filtering, power distribution, and various types of sensors. The grating structure was realized through a periodic corrugation on a thermally oxidized silicon layer that also serves as the waveguide lower cladding. For the hybrid architecture, waveguide ridges were photo-patterned in a layer of low-loss fluorinated poly(arylether ketone) , and covered with a similar polymer cladding having lower refractive index. For all-silica LPGs, Ge-doped silica waveguides were fabricated over the grating by PECVD and reactive ion etching, and embedded in a layer of borophosphosilicate glass (BPSG) with a refractive-index matched to that of the lower cladding material. In these structures, the corrugated silica layer allows a stable grating structure, while the fluorinated polymer or silica waveguides offer low propagation loss and versatile processability. Strong rejection bands have been observed in the C+L wavelength region, in good agreement with theoretical calculations. Based on these designs, an array of waveguides incorporating long period gratings, has also been fabricated. Distribution of light at the resonance wavelength

across all channels, from a single input, has been demonstrated. These results are promising for power distribution in photonic network applications or on-chip sensors. The sensitivities of the fabricated LPGs to temperature and to the refractive index of the surrounding medium have been investigated and are discussed.

7598-25, Session 6

Time evolution of an electro-optic modulator by detection of its nonlinear behavior

D. T. Bui, L. D. Nguyen, B. A. Journet, I. N. Ledoux-Rak, École Normale Supérieure de Cachan (France)

Optoelectronic oscillators use electro-optic modulators for converting the microwave signal into optical modulated signal. These oscillators must present a very low phase noise and a very time stable oscillation frequency. Stabilization of the different elements is absolutely required and especially for the modulator. By using a digital system for controlling both temperature and optical bias point it is possible to improve the time evolution of the oscillator and to reduce the phase noise. This system can also be used as a complete instrumentation tool for analyzing the behavior of the modulator. By using the system as an open loop the evolution of the modulator can be monitored. The technique is based on non-linearity measurement. A low frequency is applied to the modulator and the phase of second harmonic component is determined in order to know the evolution of the real optical bias point on the transfer function of the modulator. The drift of the modulator is observed according to different experimental conditions. Different temperature changes have been applied by small steps and the corresponding non linearity has been recorded. Temperature and optical bias point drift are clearly correlated. By controlling the temperature it can be shown that the drift of the optical bias point is significantly reduced. But hysteresis effects are underlined, proving that other physical effects lead to the drift of the modulator bias point. This technique has been applied to modulators made of lithium-niobate material but are also currently used for analyzing electro-optic polymer based modulators.

7598-26, Session 6

Ultra-narrowband notch filter for Raman applications

C. Moser, F. Havermeyer, Ondax, Inc. (United States)

We report on an angularly tunable notch filter from 760 nm to 785 nm with an OD of 5.5, more than 80% transmission and narrow 3dB bandwidth of 9 cm-1 (0.55 nm). The notch filter is a single element composed of six bonded slanted reflective volume holographic gratings in glass.

Notch filters are an essential component in Raman instruments. They greatly attenuate the backscattered light from the laser illuminating the sample, while letting the faint spectrally shifted Raman signature pass through. Two non-dispersive filter technologies are currently used for wavelength blockers: holographic (with dichromate gelatin) and thin film. Both are limited to 3dB rejection bandwidth of approximately 400 cm-1 or greater.

The Raman signal in the low frequency shift region, i.e near the frequency of the excitation laser, contains critical information about the molecular structure. For example, carbon nanotubes exhibit vibration modes in the range of 150 cm-1 to 200 cm-1 depending on their size. Relaxation in liquids, solutions and biological samples exhibit Raman shift, in the range between 0 and 400 cm-1.

We have demonstrated a non-dispersive holographic notch filter technology capable of observing the Raman signal near the excitation wavelength (10 cm-1). The novelty of the approach is the compactness of the notch filter (~ 10 mm thickness) realized by bonding individual notch filters without creating spurious multiple diffractions. Such ultra-narrow-band wavelength blockers can thus be used in standard compact Raman instruments and help bring high-end research to a greater number of users.

7598-27, Session 6

A new class of polarization filters for laser applications

T. Erdogan, L. Wang, C. Hodgson, Semrock, Inc. (United States)

We describe a unique new, high-contrast, laser-grade polarizer which also acts a high-performance bandpass filter for the desired, transmitted polarization. This thin-film based polarizer combines a polarization contrast ratio greater than 1,000,000-to-1 (extinction ratio < 10-6) with the a bandpass filter with transmission > 93%, very steep edges, and high out-of-band blocking, all in a single, high-layer-count optical coating. Compared to other polarizer technologies, it offers superior optical quality, high angle-of-incidence tolerance, and large clear apertures making it suitable for high-performance imaging applications. And this filter exhibits excellent environmental reliability and high laser damage threshold (> 1 J/cm2).

These new polarizing bandpass filters are excellent laser source clean-up filters to eliminate the undesired polarization at the laser line and light noise away from the laser wavelength, as well as detection filters to pass a laser wavelength range and block background noise. They are ideal for a wide variety of laboratory laser applications, especially those involving holographic and interferometric systems, as well as laser materials processing, polarization diversity detection in communications and rangefinding, and fluorescence polarization and second-harmonic-generation imaging.

7598-28, Session 7

High-aperture narrowband filter based on Moiré Principle

S. Mokhov, J. Lumeau, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States); V. Smirnov, OptiGrate Corp (United States); B. Zeldovich, L. Glebov, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States)

Uniform reflective volume Bragg grating (VBG) is common distributed feedback system with high spectral selectivity typically hundreds of picometers at optical frequencies. We propose implementation of narrow-band filter in VBG with bandwidth less than ten picometers. Two recorded Bragg gratings with the same modulation amplitudes and slightly different resonant wavelengths form moiré pattern with average carrier spatial frequency and slowly varying envelope of modulation amplitude. Each semi-period of modulation is just apodized reflective VBG; however two of them together form Fabry-Perot cavity due to phase π-shift as result of sign change of slowly varying envelope. This cavity demonstrates very narrow transmission peak at resonant frequency. Spectral properties of such filter were investigated, using our recently formulated approach based on theoretical concept of Strength of Reflection. We fabricated first moiré VBG filter in photo-thermo-refractive glass by two consecutive recording of gratings with close resonance wavelengths near 1550 nm in the same wafer. After cutting of two semi-periods, polishing and coating we got filter with aperture size 5 mm, bandwidth 50 pm and 95% maximum transmittance. Transverse degrees of freedom in VBG give tuning possibilities. Resonance wavelength is shifting quadratically with small angle of grating tilt. We discuss also cases when carrier Bragg grating wave vector does not coincide with moiré pattern wave vector. It allows creating filters with tunable bandwidths and peak profiles. Robust solid-state moiré VBG filters tolerant to high-power laser radiation with tunable filtering characteristics are suggested as optical elements for laser design and spectroscopy applications.

7598-29, Session 7

Manufacturing and quality analysis of high precision thermoplastic optical lenses

S. Hessner, W. Michaeli, F. Klaiber, RWTH Aachen (Germany)

The manufacturing of optical components by injection moulding and injection-compression moulding is a serious challenge for tool and machine technology as well as for process control. To evaluate the quality of optical parts the accuracy of the moulded geometry as well as the resulting optical performance has been analysed. At present a geometrical moulding accuracy in the lower micron range has been achieved for the production of thick-walled lenses. Overall injection-compression moulded lenses showed a better optical performance than injection-moulded lenses.

Due to these preliminary investigations different injection-compression moulding technologies are to be examined. Thus, a mould has been developed which enables the comparison of different injection-compression technologies. On the one hand the compression step is realised by the mould motion of the injection moulding machine, on the other hand by integrated hydraulic pistons. With this mould design the compression-technique using integrated hydraulic pistons achieves better results regarding the optical and the geometrical properties of the lenses.

To analyse the moulded optics a Shack-Hartmann-Sensor was used in order to characterise the deformation of the wave front, for the geometrical accuracy of the moulded lenses a chromatic sensor was used.

7598-30, Session 7

High-speed simplified analog-to-digital converter using non-sequential counting methods for use in focal plane pixels

E. D. Larson, National Security Technologies, LLC (United States)

This advancement in analog-to-digital converter (ADC) architecture reduces the pixel and data size, plus it increases speed for use in a focal plane. This new approach to linear feedback shift register counting reduces the data path from the counter to the pixel register of the ADC from as many as 16-bits to a single bit. A comparator and shift register in the pixel complete the single-slope integrating pixel ADC architecture. Previous work has produced a parallel pixel counter of a sequential architecture for row readout. This serial ADC connection is similar to the latest parallel method with the exception that the pixel ADC register is a shift register and the data path is a single bit. The resulting pixel data is then decoded from the pseudo-random number format into a standard sequential format before further processing and display. Using this method, a 4 KHz frame rate was achieved (extrapolated) running at 10 MHz clock.

7598-31, Session 8

Metallic nanoparticles for molecular electronics and photovoltaics

D. S. Kilin, Univ. of Florida (United States)

DNA-templated nanowire composed of an infinite periodic chain of gold nanoparticles and porphyrin linkers is studied theoretically. The design of this optically-gated quantum wire investigated in the present work rests on molecular interactions between the DNA, the gold nanoparticle, the porphyrin, and the bridge promoting self-assembly of the wire on the sub-nanometer scale. The electrical conductivity of this nanowire was investigated as a function of frequency of the applied electric field. Both ground state conductivity and its enhancement by a range of optical excitations of the porphyrin were calculated. Porphyrin excitations were found extremely important for achieving good conductivity, because they generated charge carriers in the resonant states of the porphyrin molecules and the nanoparticles. The electron-phonon relaxation time determines the response time of the nanowire, in the cases when fast optical control of the nanowire conductivity is desired. The nanowire has low latency time and can be optically switched on a picosecond time-scale, as determined by the expected rapid recombination of electrons and holes inside the metal cluster. The reported study is supported by the available experimental data and provides further guidelines for the design of self-assembling molecular electronics units of nanometer and sub-nanometer sizes.

7598-32, Session 8

Simulation based design for backside illuminated ultrahigh-speed CCDs

T. Arai, T. Hayashida, K. Kitamura, J. Yonai, H. Maruyama, Japan Broadcasting Corp. (Japan); T. G. Etoh, Kinki Univ. (Japan); H. van Kuijk, DALSA Corp. (Netherlands)

A structure for backside illuminated ultrahigh-speed charge coupled devices (CCDs) designed to improve the light sensitivity of CCDs was investigated. The structure's shooting speed of 1,000,000 frames/second was made possible by directly connecting CCD memories, which record video images, to the photodiodes of individual pixels. The simultaneous parallel recording operation of all pixels results in the ultimate frame rate. Because backside illumination enables a fill factor of 100% and a quantum efficiency of 60%, a sensitivity ten or more times that of front side illumination can be achieved. Applying backside illumination to ultrahigh-speed CCDs can thus solve the problem of a lack of incident light. An n-epitaxial layer/p-epitaxial layer/p+substrate structure was created to collect electrons generated by photoelectric conversion to the collection gate. When a photon reaches the deep position near the CCD memory in the p-well, an electron generated by photoelectric conversion directly mixes to the CCD memory. This mixing creates noise, making it necessary to reduce the reach of the incident light. The noise generation was inhibited by setting the thickness of a double epitaxial layer to 30 um. A potential profile for the n-/p-/p+ structure was calculated using a three-dimensional semiconductor device simulator. The transit time from electron generation to the collection gate was also calculated. The concentrations of the n- and p- epitaxial layers were optimized to minimize transit time, which was ultimately 1.5 ns. This is a small enough value compared with the inverse of the 1,000,000 frames/second frame rate.

7598-33, Session 8

Modified uni-traveling-carrier photodiode-based V-band optoelectronic mixers with high up-converted power and high responsivity

H. Pan, Z. Li, J. Campbell, Univ. of Virginia (United States)

Optoelectronic mixers are key components in V-band radio-over-fiber communication systems. Compared to the bias modulation technique, signal mixing with optical local oscillator (LO) and intermediate-frequency (IF) signals has the advantage that the optical IF signal can be easily distributed from central stations to base stations through optical fibers. In this paper a modified uni-traveling-carrier photodiode-based V-band (60 GHz) optoelectronic mixer is demonstrated which can up-convert low frequency IF signals with optical LO and IF signals. The photodiode has a relatively large diameter of 20 µm compared with previous reports, which eases the fabrication process. High up-converted power was achieved by carefully designing the epi-layer structure of the photodiode to achieve high optical injection levels. Operation up to 30 mA was achieved without cooling. The responsivity was 0.75 A/W. Photonic mixing was achieved by simultaneously injecting both optical LO and IF signals into the photodiode. The high frequency optical LO signal at 59.5 GHz was produced by heterodyning two external cavity lasers and the optical IF signal at 500 MHz was produced with an optical modulator. At

a given photocurrent level, the power of the up-converted signal varies with ratio of the injected optical LO and IF and the reverse bias applied to the photodiode. By optimizing the relative LO and IF signal levels and the reverse bias, a record high up-converted signal power of -13.1 dBm and a very low conversion loss of 9 dB were obtained.

7598-34, Session 8

On dark counts in single photon avalanche Si detectors

R. Pagano, Univ. of Catania (Italy); S. A. Lombardo, S. Libertino, Istituto per la Microelettronica e Microsistemi (Italy); G. Valvo, G. Condorelli, A. Piana, M. C. Mazzillo, D. N. Sanfilippo, STMicroelectronics (Italy)

Silicon-based photodetectors are very appealing for many applications thanks to their reduced dimensions, weight and costs. In particular, Si avalanche photodetectors (SPAD) and Si photomultipliers (SiPM) are considered interesting devices for biomedical and sensor applications.

We electrically and optically tested both SPAD, with active area of 40μm×40μm, and SiPM arrays, from 5x5 to 64x64, fabricated by STMicroelectronics. The operation of single cell devices, having a 220 kΩ integrated quenching resistor, were studied as a function of the temperature from -25°C to 85°C, of the voltage over breakdown (from 5% up to 20% of BV) and illumination conditions, using lasers at 488 nm and 659 nm. We measured the dark count rate, the device gain, and the resulting average current signal, and accurately modeled them as a function of the operation conditions. Typical gain values above 1×105 and above are obtained for operation times of 10 ns, while higher gains are obtained for longer integration times. The complete electrical behaviour as a function of temperature and voltage is modelled in the full studied range, with an excellent agreement with the experimental data. The model assumes that the dark counts are originated by carriers arriving in the device active layer by diffusion from quasi-neutral regions or by thermal emission from defects. Applications to biomedical (Positron Emission tomography) and environmental fields (water quality control) will also be discussed.

7598-52, Poster Session

Novel design of AOTF using film-loaded SAW waveguides

X. Hehua, Hebei Univ. of Engineering (China)

In this paper, new non-collinear configurations of acousto-optic tunable filters (AOTF) which use ZnO strip film-loaded surface acoustical waveguide (SAWG) or MgO slot film-loaded SAWG on X-cut Y-propagating LiNbO3 (X-Y LiNbO3) are designed in which the interdigital transducer should be inclined an angular that are the walk-off angulars (the angular from the propagation direction to the power-flux vector) when the surface acoustical wave (SAW) propagate in SAWG. The thickness of the film makes the changes of the velocity of surface wave are about 3%. The two walk-off angulars are 3.21°and 4.18°.Cubic spline interpolation method is used to obtain the walk-off angular curve with the gained velocity curve of SAW directly. The new design can make better use of the energy of SAW.

7598-53, Poster Session

Direct surface relief formation in As-S(Se) layers

M. Trunov, The Univ. of Debrecen (Ukraine); P. M. Lytvyn, Institute of Semiconductor Physics (Ukraine); P. Nagy, Institute of Surface Chemistry (Hungary); C. Cserhati, S. Charnovich, S. J. Kokenyesi, The Univ. of Debrecen (Hungary)

The process of direct holographic recording and periodic surface relief formation on AsxSe1-x (0 x 0.5) and As2S3 layers was investigated by in situ AFM depth profiling and compared with data on diffraction efficiency of similar holographic gratings, measured in a reflection mode. It was discovered, that the time (exposure) dependence of the surface deformation Δd has at least two components, which correspond to the stable sinusoidal relief formation up to the giant, Δd/d 10% changes in the best As0.2Se0.8 or As2S3 compositions. Correlation was found between light and e-beam induced surface deformations during recording in a similar compositions. It is assumed that the surface relief formation is connected with induced volume expansion as well as with lateral mass transport. A small dynamical component of appears when the light is switched on. Most probably it depends on the charge carrier generation and corresponding changes of the refraction index. Applications for prototyping phase-modulated optoelectronic elements are considered.

7598-54, Poster Session

Thermally controllable multiguide coupler of liquid crystal

S. Huang, Chung Shan Medical Univ. (Taiwan)

This work investigates a thermally controllable multiguide coupler based on a liquid crystal cell with a grating-like indium-tin-oxide electrode.

Many studies have discussed the effects of applying external voltage and the polarization dependence of the coupler; however, temperature has rarely been discussed relative to the device performance, especially for the temperature range of the nematic to isotropic phase of a liquid crystal.

The coupling effect may be switchable via controlling the temperature of liquid crystal. Additionally, an obvious nonlinear light self-focusing phenomenon was induced by light at very low power of 15 uW.

This study reports a modified liquid crystal waveguide structure and confirming experimental results.The channel waveguide structure and the nonlinear (self-focusing) results are interesting.

7598-55, Poster Session

Potentials of the acousto-optical spectral data processing on a basis of a novel algorithm of the collinear wave heterodyning in a large-aperture KRS-5 crystalline cell

A. S. Shcherbakov, Instituto Nacional de Astrofísica, Óptica y Electronica (Mexico); J. Maximov, Molecular Technology GmbH (Germany); D. Sanchez, Instituto Nacional de Astrofísica, Óptica y Electrónica (Mexico)

Recently proposed modern technique of a precise spectrum analysis within an algorithm of the collinear wave heterodyning implies a two-stage integrated processing, namely, the wave heterodyning of a signal in a dispersion-free medium and then the optical processing in the same cell. Technical advantage of this approach is in providing a direct processing of ultra-high-frequency radio-wave signals with an improved resolution. This algorithm can be realized on a basis of various physical principles, and we consider an opportunity of involving the potentials of modern acousto-optics for these purposes. From this viewpoint, one needs a large-aperture effective acousto-optical cell, which operates in the Bragg regime and performs the ultra-high-frequency collinear acoustic heterodyning. The technique under consideration imposes specific requirements on the cell's material, namely, high optical quality large crystalline boules, high-efficient acousto-optical interaction, low attenuation and low group velocity of acoustic waves. We focus our attention on the solid solutions of thallium chalcogenides and take the TlBr-TlI (thallium bromine - thallium iodine) solution, which forms KRS-5 cubic-symmetry crystals with the mass-ratio 58% of TlBr to 42% of TlI. Analysis shows that the cell made of KRS-5 crystal oriented along the

[111]-axis and the longitudinal elastic mode for producing the dynamic diffractive grating should be exploited. With the acoustic velocity 1.92 mm/ s and attenuation 1.0 dB/(mm GHz2), this cell provides an aperture of 50 mm and one of the highest figures of acousto-optical merit in solid states in the visible range. Our analysis made possible creating the corresponding acousto-optical cell and its successful testing.

7598-56, Poster Session

Some peculiarities of designing the optical scheme of tellurium dioxide crystalline cell based acousto-optical spectrometer for the Mexican large millimeter telescope

A. S. Shcherbakov, Instituto Nacional de Astrofísica, Óptica y Electronica (Mexico); D. Sanchez, A. Luna, Instituto Nacional de Astrofísica, Óptica y Electrónica (Mexico)

The most important peculiarities of arranging the optical scheme of a 1000-channel acousto-optical spectrometer for needs of the star radio-astronomy are considered. To realize a wide-band and high-resolution spectrum analysis a large-aperture acousto-optical cell has to be exploited. For this cell a tellurium dioxide single-crystal oriented along the [001]- and [110]-axes has been chosen and the slowest shear elastic mode is used for producing the dynamic diffractive grating. Due to an extremely high anisotropy of this crystal, the efficiency of light scattering depends essentially on the ellipticity of the incident light polarization and increases by 1.5 - 2 times when the state of polarization varies from linear one to the eigen-state elliptic polarization, which is determined by the incidence angle, light wavelength, and accuracy of the cell's crystallographic orientation. This is why we analyze peculiarities of designing the beam-shaping scheme, which includes a tunable light polarizer and a four-prism beam expander. Rather compact scheme (about 10 cm in length) realizes expanding the initial laser beam of about 1 mm in diameter to a 60-microsecond cell aperture with an efficiency of 75% at various visible light wavelengths and provides shaping the eigen-state of elliptic polarization with the pre-assigned direction of rotation for light reaching the input cell's aperture. Together with that, we characterize lens system with variable focal distance and spot size, aligning the output cell's aperture with the CCD-pixels. Taking into account the main aberrations, we estimate the performance data of this multi-channel Fourier spectrometer and compare them with the experimental results obtained.

7598-57, Poster Session

Excitation wavelength dependence of quantum efficiencies of Nd-doped glasses for solar pumped fiber lasers

T. Suzuki, H. Nasu, M. A. Hughes, Toyota Technological Institute (Japan); S. Mizuno, K. Hasegawa, Toyota Central Research and Development Labs., Inc. (Japan); Y. Ohishi, Toyota Technological Institute (Japan); H. Ito, Toyota Central Research and Development Labs., Inc. (Japan)

Solar pumped lasers have been attracted much attention as a novel renewable energy source in recent years. In order to spread worldwide this technology, reliability, cost performance, and light-light conversion efficiency of the system etc. must be raised considerably. The conversion efficiencies of Nd-doped solar pumped transparent ceramic lasers by real sunlight excitation were reported as no more than 2 %, though the quantum efficiency (QE) of Nd:YAG pumped at 808 nm is about 80 %. We believe the efficiency can be improved by utilizing fiber lasers made of glass materials. In this paper, we have investigated excitation wavelength dependence of the QEs of near-infrared emission of Nd-doped glasses to clarify the feasibility of solar pumped fiber lasers used glass gain media.

The quantum efficiencies were measured by an integrating sphere method with a laser diode at a wavelength of 808 nm, and a Xe lamp as excitation sources. The relaxation efficiencies from the higher excitation levels to the emission initial 4F3/2 level of Nd are thought to be almost 100 % regardless of the excitation levels. The QEs strongly depend on the excitation wavelengths ranging from 505 to 690 nm. The QEs were higher at the excitation wavelengths where absorption by Nd is remarkable as compared to absorption by host glass. Thus a decrease of absorption by host is essential to increase the QEs at low Nd concentrations where concentration quenching is negligibly low.

7598-58, Poster Session

Ultraflat supercontinuum generation in an As2S3-based chalcogenide core microstructure fiber

X. Yan, C. B. Chaudhari, G. Qin, T. Suzuki, Y. Ohishi, Toyota Technological Institute (Japan)

We propose a chalcogenide (As2S3) core tellurite cladding microstructure fiber with flattened normal dispersion for ultraflat supercontinuum (SC) generation. The resultant structure maintains high nonlinearity because both core and cladding materials have high nonlinearity. The nonlinear effects including SC generation can be realized easily using highly nonlinear microstructure fibers. We propose the microstructure fiber structure with the hexagonal identical air hole introduced in tellurite cladding surrounding a chalcogenide core. A full vector finite element method (FEM) with the perfectly matched layer (PML) boundary condition is utilized to analyze the dispersion and nonlinear coefficient. To realize flattened normal dispersion, the structure parameters are optimized such as the chalcogenide core diameter, the air hole diameter and the distance between the centers of the two neighboring air holes. The ultraflat normal dispersion curve is obtained for the designed microstructure fiber with one ring of air holes, and the pulse propagation is investigated using a nonlinear SchrÖdinger equation. To investigate the generation of an ultraflat wideband SC, we show the spectrum evolutions of the pulsed light traveling through the designed microstructure fiber for the different propagation distances and input pulse peak powers. As a result, an ultraflat SC spectrum with deviations less than 4 dB over an octave (from 1400 nm to 3000 nm) is achieved by the illumination of a pulsed light with a pulse width of 200 fs, central wavelength of 2000 nm and peak power of 1000 W. Such an ultraflat SC is promising for the application of wavelength conversion and all optical signal processing.

7598-59, Poster Session

Optical parametric amplification in composite tellurite: fluorophosphate fiber

C. B. Chaudhari, T. Suzuki, Y. Ohishi, Toyota Technological Institute (Japan)

We present the design, dispersion calculations and tailoring, and parametric gain simulation for the composite tellurite-fluorophosphate glass fiber. The composite fiber structure has the tellurite core subsequently surrounded by fluorophosphate and tellurite claddings. With our analysis we have observed that the dimensional parameters: fluorophosphate as well as the tellurite cladding thickness along with the fiber core diameter, have control on the dispersion and therefore on the parametric gain. The wavelength band, over which the anomalous dispersion is achieved, increases with increase in the tellurite core diameter. For longer wavelengths, increasing the fluorophosphate cladding thickness causes increase in the bandwidth over which anomalous dispersion is achieved and further flattening of the dispersion curve. The slope of the dispersion curve near the zero dispersion wavelength (ZDWL) is greatly reduced for thicker outer tellurite ring claddings. We show that it is possible to design the zero flattened dispersion fiber or the fiber providing two ZDWLs in the communication band, which can generate broadband parametric amplification. The

gain obtained has strong bandwidth dependence on the dispersion slope. With multiple pumping with proper selection of the pump wavelengths, the parametric amplification process can generate ultra flat, broadband amplifiers as the dispersion provided by the composite fiber is anomalous over a wide bandwidth. The composite fiber introduced here has the advantage of easy handling over the fiber tapers or the air cladding tellurite nanofibers. The thermal properties of the tellurite and fluorophosphate glasses match, depicting the feasibility of the fabrication of the fiber under controlled environment.

7598-60, Poster Session

Design and fabrication of high-performance photodiodes

H. Yang, C. L. L. M. Daunt, F. H. Peters, Tyndall National Institute (Ireland)

Ultrafast and high responsivity photodetectors that operate at long wavelengths are key components of modern high bit rate optical and wireless communication systems as well as ultrafast measurement systems . The InP-InGaAs based uni-traveling carrier (UTC) photodiode is a promising solution because of its unique mode of operation compared with the conventional PIN photodiode. In this paper, an optimized structural design of TW-UTC PD is exploited to realize high speed, high efficiency and high output performance, and at the same time, a new device structure was developed to simplify the process and increase the yield.

At first, the epitaxy structure of our UTC PD was optimized, in which the thicknesses of the absorption and collection layers were optimized by Beam Propagation simulations and Bandwidth Model calculations to balance between high speed, high efficiency and low driving voltage. InAlGaAs material is chosen as the barrier material to facilitate the holes while blocking the electrons from entering the p-type barrier layer through the band discontinuity ratio of 70:30 between conduction and valence bands. Between the absorption and collection layer, an intermediate bandgap layer InGaAsP is inserted to lower the abrupt conduction band discontinuity for the electron diffusion. In addition, graded doping is adopted in the absorption and cladding layers to accelerate the transportation of carriers.

In fabrication, the waveguide mesa was formed by ICP dry etching . The G-S-G travelling wave electrodes with 50 ohm impedance were deposited on the top of the device and isolated by deep etching into the semi-insulating substrate, and BCB planarization was used to form metal bridge connecting the waveguide and G-S-G lines. Finally, a 65GHz high frequency measurement system is used to characterize the performance including bandwidth, saturation power and efficiency.

7598-61, Poster Session

Electronic polarizability and optical parameters of Er3+/Yb3+ co-doped phosphate glasses

F. Song, C. Ming, W. Wang, Nankai Univ. (China)

The samples of Er3+/Yb3+ co-doped phosphate glasses with different Er3+ doped concentrations were prepared by high-temperature melting method. By calculating the electronic polarizabilities and optical basicity of the samples, we find, with the increasing of Er3+ ions concentration, the polarizability and optical basicity of oxide ions become large, which indicates that the covalence of the glasses becomes small. Based on Judd-Ofelt (J-O) theory, the J-O intensity parameters Ω (=2,4,6), spontaneous radiative lifetime, and fluorescence branching ratio were calculated. With the increasing of Er3+ concentration, the Ω2 values are decrease gradually, which also proves that the covalence of the glasses becomes small. The ratios of Ω4/Ω6 are within the range of 7.51-9.84, which are larger, thereby, our glasses are suitable laser materials. We also studied the upconversion (UC) emission of samples, the strong 657 nm red emission, 546 nm and 523 nm green emissions were observed under 975 nm laser diode (LD) excitation, and the UC emission intensities depend on the ratio of Er3+/Yb3+, when the ratio is 0.125, the emissions are strongest. The emission cross sections of UC emissions were analyzed using McCumber theory and Füchtbauer Ladenburg (FL) method, the emission cross section of UC red emission is larger (about 0.5×10-20cm2),which proves our samples are better red light materials.

7598-62, Poster Session

The fluorescent properties of rare-earth ions-doped bismuth glasses

L. Hu, H. Fan, G. Gao, Shanghai Institute of Optics and Fine Mechanics (China)

Bismuth glass has low phonon enengy, high refractive index and long IR cutoff wavelength.But usually bismuth glass is difficult to fabricate. In order to develop a new series of fluorescent even laser bismuth glass, glass formation regions and basic properties were researched in bismuth glass system. Three kinds of bismuth glasses were developed for rare earth ions doping purpose. There are Bi2O3-B2O3-Ga2O3-SiO2, Bi2O3-GeO2-Na2O and Bi2O3-GeO2-Li2O glasses. These glasses have large Tx-Tg(>130oC),high refractive index(nd>2.0) and high transmission through 0.5-4.5um. The phonon energy of Bi2O3-GeO2-Na2O and Bi2O3-GeO2-Li2O is found to be as low as 440cm-1 from Raman spectrum measurement. The B2O3 content is very detrimental to 1.8um emission of Tm3+ doped bismuth glass because of its high phonon energy. The intense 1.8um emission was detected in Tm3+ doped Bi2O3-GeO2-Na2O and Bi2O3-GeO2-Li2O glasses. The peak stimulated emission cross section at 1810nm is about 7x10^-21 cm^2. The radiative lifetime is about 2.6ms for Tm3+:3F4 level. The fluorescent properties of Eu3+, Yb3+ and Er3+ doped Bi2O3-B2O3-Ga2O3-SiO2 glass were also investigaed. Spectroscopic properties were calculated according to Judd-Ofelt and McCumber theories.The unique fluorescent properties of bismuth glasses are explained based on their structure, phonon energy and OH contents.

7598-63, Poster Session

Polymer microlens array with tunable focal intensity by the polarization control of the incident light

S. Huang, National Cheng Kung Univ. (Taiwan)

This paper proposes an optically tunable-focus microlens array (MLA) by using a focusing unit with birefringent liquid crystalline polymer (LCP) and a tuning unit with photoalignment for controlling the polarization state of the incident light. Due to the different refractive indices of LCP, it acts as a positive or negative microlens with respect to the polarization state. The resultant tunable focal intensity MLA shows the fast optical switching time without voltage and the multi-stable characteristics.

7598-64, Poster Session

Fabrication of one-dimensional SWS on bismuth borate glass by glass-imprinting method

N. Yamashita, T. Suetsugu, T. Einishi, Isuzu Glass Co., Ltd. (Japan); K. Fukumi, N. Kitamura, National Institute of Advanced Industrial Science and Technology (Japan); J. Nishii, Hokkaido Univ. (Japan)

Periodic sub-wavelength structures (SWSs) attract much attention as key elements for realization of several optical functions such as antireflection, polarization-independent diffraction, polarization splitting, isolation, and phase control. Several research groups have fabricated SWSs on resin plates or films using ultraviolet-imprinting and thermal-imprinting processes. Since inorganic glasses have mechanical strength, chemical durability and thermal stability higher than resins, it is important to fabricate SWSs on glass surfaces for the wide application. In the present study, glasses for glass-imprinting have been developed and a one-dimensional periodic SWS has been fabricated on glass surfaces by a glass-imprinting method.

First of all, we have developed lithium bismuth gallium borate glasses which have refractive indexes higher than 1.80 at 587.6 nm, deformation temperatures lower than 470°C and internal transmittance higher than 80% (3 mmt) at 400 nm. Although lithium bismuth borate glasses are known to have low deformation temperature and high refractive index, the glasses are not transparent in the visible-ray region. The addition of gallium oxide into lithium bismuth borate glasses shifted the absorption edge toward shorter wavelength and improved the transparency of the glass.

A one-dimensional SWS with a period of several hundreds nanometer was fabricated on a high strength and heat resistant material by an electron-beam lithography followed by dry etching, which was used as a mold for glass-imprinting. The glass- imprinting was carried out at a temperature near the glass deformation temperature. The one-dimensional SWS was successfully transferred on the glass surfaces, which showed the phase retardation due to form birefringence.

7598-65, Poster Session

A small and fast SCPEM-based ellipsometer

F. Bammer, Technische Univ. Wien (Austria); R. Petkovsek, J. Mo?ina, Univ. of Ljubljana (Slovenia)

We propose a small and fast ellipsometer with a basic layout similar to that of conventional ellipsometers using photo-elastic modulators (PEM) oscillating with 50kHz. A conventional PEM is rather large, ~10x20x100mm, since it consists of one piece of glass and an actuator. Both parts are carefully adjusted to the desired frequency and then glued together. We replace such a standard modulator by a 130kHz Single Crystal Photo-Elastic Modulator (SCPEM), a LiTaO3-crystal with a size of ~5x7x20mm. With electrodes on the y-facets a proper alternating voltage excites a strong x-longitudinal oscillation. The polarization of light that travels through the crystal in z-direction is then strongly modulated due to the photo-elastic effect. The voltage amplitudes are usually in the range of ~3 Volts. The modulated light is reflected from the sample, passes a polarizer and hits a detector. Its signal is split into the dc-value and the amplitudes of the 1st and 2nd harmonic of the modulation frequency. These values lead via simple formulas to the ellipsometric parameters. Usually a Lock-In-Amplifier is used here, whereas we propose a simple automated digital processing based on a fast analog to digital converter controlled by an FPGA (Field Programable Gate Array). This allows higher level of flexibility and enables fast measurements at (potentially) lower costs. This and the extremely compact and efficient polarization modulation make this photonic device to a compact solution for fast ellipsometric measurements as needed in high volume manufacturing of optics.

7598-66, Poster Session

Enhanced switching characteristic of a Ti: LiNbO3 1x2 digital optical switch using optimized electrode regions

G. Singh, R. P. Yadav, V. Janyani, Malaviya National Institute of Technology (India)

Design Steps: The switch is created on x-cut lithium niobate substrate and is surrounded by air cladding. The device is oriented along the Y-optical axis of the substrate. The crystal lithium Niobate has a crystal cut along x- axis and propagation direction along y axis. The dielectric material selected is air with refractive index 1.0. The waveguides of DOS are created by diffusion of Titanium in Lithium Niobate substrate. Only one diffused profile is needed (TiLiNbO3). The whole switch device is about 30750 µm long and 40 µm wide. The waveguide has a width of 8.0 µm with Ti indiffused profile. The device has been created using the layout designer, OptiBPM. The RI profile of the XY slice has been examined. An electrode region has also been defined on the substrate. The electrodes can be built up on the top of a buffer layer. The buffer layer of silicon oxide having the thickness of 0.3 µm and a refractive index of 1.46 was used for the design.

Results: When the optical signal is transmitted through the wave guide at the input port with no switching voltage, i.e. the voltage on all the electrodes is set to zero; the waveguide behaves as power divider. This is due to geometric symmetry. On application of switching voltage at the electrodes, the Y shaped waveguide behaves as a switch, forcing the light to be propagated in either of branch of y shaped waveguide due to the electro-optic effect. The effect of electrode length and the gap between the electrodes were investigated. The results show that, at the specific electrode length i.e. 0.030 mm and a gap of 7 µm between the electrodes for our design resulted in better switching performance with overall switch losses in the range of 3.5% to 5% only.

7598-67, Poster Session

Performance improvement of HgCdTe photoconductors by means of band-gap grading

B. S. Sokolovsky, Ivan Franko National Univ. of L'viv (Ukraine)

The report theoretically considers possibilities of improving the sensitivity of HgCdTe photoconductors using such an efficient method of band-gap engineering as purposeful forming in a photoconductor the band-gap graded layers. It is studied in detail two ways of using the band-gap grading for the cases of large and small distances between Ohmic contacts. In the first case the band-gap graded layer is proposed to be created in the near-surface region of a photoconductor with the band-gap being linearly increased towards the illuminated surface. This layer due to the presence of strong quasi-electric field promotes removing photocarriers from the illuminated surface, and, as a result, weakening the influence of carrier surface recombination on the photoconductor's sensitivity,especially in the short-wavelength range. In the case of small distance between contacts it is proposed to use the band-gap graded layers adjoining to the contacts which is proved to allow to reduce the influence of sweep-out effect on the sensitivity of HgCdTe photoconductor. Calculation of the sensitivity of a small-size photoconductor shows that it exhibits a non-monotonous dependence of the photoelectric coefficient on the applied bias and maximum value of the photoelectric coefficient can substantially (by one order or larger) exceeds the magnitude achieved in homo-band-gap HgCdTe photoconductive IR detectors.

7598-68, Poster Session

Birefringence control of pigtails in fiber optic devices

D. Tentori-Santa Cruz, Ctr. de Investigación Científica y de Educación Superior de Ensenada (Mexico); C. Ayala-Diaz, Univ. Autónoma de Baja California (Mexico); F. Treviño-Martinez, Univ. Autonoma de Nuevo Leon (Mexico)

Polarization devices developed for fiber optic systems are pigtailed. These pigtails, built with standard single-mode optical fiber (~1 m long) modify the input and output characteristics of the signal's polarization state. Even though this contribution is negligible when the fibers are kept straight, it increases when they are wound up to form compact systems. In this work, we used Mueller calculus and experimental results to analyze the polarization performance of a helically wound single-mode fibers. These results have been used to propose the cascaded helical structures we have built. Within this study we have also considered the effect of the jacket on the polarization performance of the helically

wound fibers. We worked with naked fibers and fibers with 0.9 and 3 mm jackets. They presented very strong birefringence dispersion variations for some helix curvatures. Since this behavior was observed for the three types of jackets, for the results we present for the cascaded structures we used only naked fibers. For different helix diameters the fiber elongation was varied in order to minimize the birefringence dependence on wavelength. Using linear and circular input polarization states and the Poincaré sphere it is shown that to control the total birefringence the relative orientation of the symmetry axes of these helices must be varied. This result is in agreement with the theoretical model. The experimental results obtained for the birefringence of these structures demonstrates that it is possible to minimize their birefringence contribution within a limited spectral bandwidth.

7598-69, Poster Session

AlN antiresonant layer ARROW waveguides

M. V. Pelegrini, D. O. Carvalho, M. I. Alayo Chavez, I. Pereyra, Univ. de São Paulo (Brazil)

Aluminum Nitride films have received increasing attention of the scientific community because they have interesting properties such as a wide bandgap, high electrical resistivity, high resistance to breakdown voltage, high thermal conductivity, chemical stability and others, which make this material very interesting for applications in surface acoustic wave (SAW) devices, insulating layer and optical sensors in the ultra-violet spectral range [1,2].

In this work we present a study of the influence of using AlN films, obtained by reactive magnetron sputtering, with different Nitrogen/Argon concentrations, on the losses of ARROW waveguides, with the purpose of finding the composition which diminishes the radiation losses. The optical and chemical properties of the AlN films were also studied by Ellipsometry, FTIR, RBS and the results are presented. It is important to mention that AlN films have a relatively high refractive index (n=2.1) [3], which is a very important characteristic for the first ARROW layer, since this layer behaves like a Fabry-Perot resonator in anti-resonance. To measure waveguides propagation losses the top view technique [4] was used.

Routines based on the Transfer Matrix Method (TMM) [5] and the Non-Uniform Finite Difference Method (NU-FDM) [6] were used for the determination of the optimum thickness values of the Fabry-Perot layers and of the maximum width that allows single-mode operation, respectively. NU-FDM is better suited than conventional FDM for the analysis of ARROWs, since the thickness of the anti-resonant layer is much smaller than the thickness of the other layers and in NU-FDM the size of the grid cells may vary.

[1] J. Hwang, W. Schaff, B. Green, H. Cha, L. Eastman, Solid-State Electron. 48 (2004) 363.

[2] C. Men, Z. Xu, Z. An, X. Xie, M. Zhang, C. Lin, Phys., B Condens. Matter. 324 (2002) 229.

[3] Venkataraj S., et al., Thin Solid Films 502 (2006) 235 - 239.

[4]Daldosso N., et.al., Journal of Lightwave Technology 22 (2004) 1734-40.

[5]Tee C. W., Tan C. C. and Yu S. F., IEEE Photonics Technology Letters 15 (2003) 1231-1233.

[6] Kim C. M. and Ramaswamy R. V., Journal of Lightwave Technology 7 (1989) 1581-89.

7598-70, Poster Session

Steep and flat optical bandpass filter using linearly chirped and apodised fiber Bragg gratings

X. Wu, Supélec (France); G. Duan, Alcatel-Thales III-V Lab. (France); J. Jacquet, Supélec (France)

The development of new optical systems requires the design of novel components that fulfill the market constraints. In particular, low loss, high optical rejection and low cost narrowband filters can play an important role for the introduction of the Wavelength Division Multilplexing (WDM) technology in the local network. In this paper, we proposed a novel type of fiber filter with a special combined apodized Linearly Chirped Fiber Bragg Gratings (LCFBG) which presents the preferable flat-top and steep-edge characteristics. In the design, we use a continuum cavity condition which is obtained when the effective round-trip phase of oscillated wavelength band is kept identical over the whole wavelength range. We calculated the transmission spectra by the reconstruction of the matrixes with the continuum oscillation conditions. Our work show that the ideal square shaped filter is obtained with a low chirp value together with symmetric reflectivities on both mirrors. The coupling coefficient of the FBG is adjusted to get the same reflectivity values and then to get a transmission filter close to unity. We have then introduced an apodization function of the filter to get a flatter transfer function. Various apodisations schemes have been tested ; results will be discussed and some characteristics presented.

7598-71, Poster Session

Characteristics of modulation for the near-infrared diode laser basing on the quantum well structure

L. Li, Y. Wang, Jilin Univ. (China)

The quantum well diode laser working in the near-infrared region is a valuable laser source for spectroscopy since plenty of overtones or combined bands of many gas species existing at this wavelength. Tunable diode laser spectroscopy with modulation technique, including amplitude modulation, wavelength modulation and frequency modulation, has been frequently used in the analysis of spectrum. This paper characterizes the 1.9μm near-infrared DFB quantum well diode laser in the case of wavelength swept, amplitude and wavelength modulation. At the same time, this paper presents the technique of wavelength reference for wavelength swept, measurement method of modulation depth and index for amplitude and wavelength modulation respectively. Furthermore, the phase shift between amplitude modulation and frequency modulation since the thermal effect of grating is measured for different modulation frequency. This paper is the fundamental of gas detection basing on the quantum well diode laser at next stage.

7598-72, Poster Session

Spectroscopy of Yb:Tm doped tellurite glasses for efficient infrared fiber laser

S. Taccheo, M. Taher, Swansea Univ. (United Kingdom); J. Lousteau, H. Gebavi, D. Milanese, Politecnico di Torino (Italy); A. Schulzgen, College of Optical Sciences, The Univ. of Arizona (United States)

Increase pumping efficiency is a key issue for 2 micron fiber laser. In order to asses pumping efficieny at 980 nm using Yb codoping we invesigated the optical properties of tellurite glasses doped with Tm:Yb and we calculate energy-transfer and cross-relaxation parameters. Sample doped with only Tm or Yb were used to calculate lifetime, quenching concentration and cross-relaxation of Tm and Yb ions alone.

We fund tellurite glasses are promising candidate for 980-nm pumping of 2 micron Tm-doped fiber laser.

7598-73, Poster Session

NIR to visible upconversion in rare-earth Ion-doped NaYF4 crystals

D. N. Patel, Oakwood Univ. (United States); S. Sarkisov, SSS Optical Technologies (United States); C. Vance III, M. Jessup, Jr., L. Green, N. King, Oakwood Univ. (United States)

In this paper we investigate the infrared-to-visible upconversion luminescence in bulk crystals and nanocolloid filled photonic crystal fiber with ytterbium and erbium co-doped NaYF4 upconversion phosphor. The phosphor was prepared by using simple co-precipitation synthetic method. The initially prepared phosphor has very weak upconversion fluorescence. The fluorescence significantly increased after the phosphor was annealed at a temperature of 400 0C. Nanocolloids of this phosphor were obtained using water and methanol as solvents and they were utilized as laser filling medium in photonic crystal fibers. Under 980 nm laser excitation very strong upconversion signals were obtained at 408 nm, 539 nm and 655 nm. Efficiency and decay life time study of the upconverted emissions was conducted to understand the upconversion mechanisms. The reported nanocolloids are good candidates for fluorescent biosensing applications and also as a new laser filling medium in fiber lasers.

7598-76, Poster Session

Detector development for X-ray imaging

M. A. Mentzer, D. Herr, U.S. Army Aberdeen Test Ctr. (United States)

X-ray imaging requires unique optical detector system configuration for optimization of image quality, resolution, and contrast ratio. A system is described whereby x-ray photons from multiple anode sources create a series of repetitive images on fast-decay scintillator screens, from which an image intensified image is transferred to a fast phosphor on a GEN II image intensifier, and collected as a cineradiographic video with high speed digital imagery. The work addresses scintillator material formulation, flash x-ray implementation, image intensification, and high speed video processing and display. Novel determination of optimal scintillator absorption, x-ray energy and dose relationships, contrast ratio determination, and test results are presented.

7598-35, Session 9

First test results of a cross-delay-line imaging photon counter

P. L. Hink, PHOTONIS (United States); P. Betten, A. Boer, P. Delger, R. Glazenborg, PHOTONIS Netherlands B.V. (Netherlands); E. Schyns, Photonis France S.A.S. (France)

We present the first test results of a new Imaging Photon Counter incorporating a Super S-25 photocathode for high sensitivity, a Z-stack micro-channel plate assembly for high gain, and a cross-delay-line anode, giving a unique combination of high spatial resolution and fast timing. The detector's performance is compared to its design of 50 µm single photon spatial resolution, 50ps timing resolution, near 10% QE at 800nm and count rates of up to 5MHz. The associated readout electronics will be described and their performance assessed. Potential applications and future developments of the Imaging Photon Counter will be presented.

7598-36, Session 9

DC and AC performance of leaky mode MSM polysilicon photodetectors

R. Pownall, C. Thangaraj, T. W. Chen, K. L. Lear, Colorado State Univ. (United States)

A leaky-mode metal-semiconductor-metal (MSM) polysilicon photodetector with Schottky contacts which is fully compatible with all standard complementary metal-oxide-semiconductor (CMOS) processes is investigated theoretically and experimentally. Devices were fabricated in a commercial 0.35 um CMOS process. Measured values include a dark current below 5 nA at 10 Volts, DC responsivity in excess of 1.2 Amps/Watt, contrast ratios over 500 and 3dB bandwidths in excess of 300 MHz. AC performance is limited by carrier lifetime, not by transit time or RC time constant effects. Measured AC performance is limited by experimental capabilities. Optical energy which is propagating in a silicon nitride waveguide core (n = 1.8) surrounded by a silicon dioxide cladding (n = 1.45) transfers, by leaky-mode coupling, to the n = 3.85 undoped polysilicon which is the photodetective layer. Photodetection is by a photoconductive effect in the polysilicon. The grain structure of the polysilicon causes the very low measured dark currents. An analytical expression for the AC response has been derived. The analytical expression incorporates photoconductive gain effects, suggesting how trade-offs can be made between gain and speed. Detector size is approximately 55 um2, exclusive of the waveguide leading to the detector, allowing for easy integration into an integrated circuit layout. Demonstrated detector applications range from on-chip optical interconnects to biosensors.

7598-37, Session 9

Integrated amplification and passivation nanolayers for ultra-high-sensitivity photodetector arrays

J. Yao, S. Wang, J. Zhou, K. Li, I. Mokina, M. Lange, B&W Tek, Inc. (United States); J. H. Hunt, L. Peltz, R. Frampton, The Boeing Co. (United States); P. Gardner, W. Yang, Western Carolina Univ. (United States); J. Becker, Cambridge Nanotech Inc. (United States)

A novel, high-gain hetero-junction phototransistor (HPT) detector is being developed, which employs two nano-structures simultaneously to achieve 100 times higher sensitivity than InGaAs avalanche photodiodes, the most sensitive commercially available photo-detector in the near infrared (NIR) wavelength range, under their normal operation conditions. Integrated into a detector array, this technology has application for Laser-Induced Breakdown Spectroscopy (LIBS), pollution monitoring, pharmaceutical manufacturing by reaction monitoring, chemical & biological transportation safety, and bio-chemical analysis in planetary exploration.

7598-38, Session 9

Two micron pore size MCP-based image intensifiers

J. W. Glesener, J. P. Estrera, L-3 Electro-Optical Systems (United States)

Image intensifiers (I2) have many advantages as detectors. They offer single photon sensitivity in an imaging format, they're light in weight and analog I2 systems can operate for hours on a single AA battery. Their light output is such as to exploit the peak in color sensitivity of the human eye. Until recent developments in CMOS sensors, they also were one of the highest resolution sensors available. The closest all solid state solution, the Texas Instruments Impactron chip, comes in a 1 megapixel

format. Depending on the level of integration, an Impactron based system can consume 20 to 40 watts in a system configuration.

In further investing in I2 technology, L-3 EOS determined that increasing I2 resolution merited a high priority. Increased I2 resolution offers the system user two desirable options: 1) increased detection and identification ranges while maintaining field-of-view (FOV) or 2) increasing FOV while maintaining the original system resolution.

One of the areas where an investment in resolution is being made is in the microchannel plate (MCP). Incorporation of a 2 micron MCP into an image tube has the potential of increasing the system resolution of currently fielded systems. Both inverting and non-inverting configurations are being evaluated. Inverting tubes are being characterized in night vision goggle (NVG) and sights. The non-inverting 2 micron tube is being characterized for high resolution I2CMOS camera applications. Preliminary measurements show an increase in the MTF over a standard 5 micron pore size, 6 micron pitch plate. Current results will be presented.

7598-75, Session 9

Backthinned CMOS sensor optimization

P. Jerram, N. Guyatt, e2v technologies plc (United Kingdom); V. Hibon, J. Vaillant, e2v semiconductors SAS (France)

Backthinning of CCDs is a very well established process and the majority of high specification space and science systems have used back-thinned CCDs for many years. CMOS sensors offer advantages over CCDs for a number of these applications and in principle it should be possible to back-thin CMOS imagers and obtain the same performance as CCDs.

We will report results from two recent Backthinning projects. Despite being performed on devices that were not originally designed for thinning excellent results have been obtained on both cases. A 5T global shutter CMOS sensor manufactured on thick epitaxial silicon has enabled the process to be optimized for near Infra-red response, data will be reported including the quantum efficiency, and shuttering efficiency of the back-thinned and front illuminated version of this sensor. Results on a second sensor made on thinner epitaxial silicon back-thinned with a process for improved UV sensitivity will also be reported.

These results show that CMOS sensors can as expected be backthined with existing CCD thinning processes. And that provided that the pixel design is such that the charge produced by incoming photons is collected onto the photodiode and not lost into other parts of the structure then a fill factor of 100% can be obtained from a backthinned CMOS sensor.

7598-40, Session 10

Progress in crystalline semiconductor core optical fibers

J. M. Ballato, T. W. Hawkins, P. R. Foy, C. D. McMillen, R. Stolen, Clemson Univ. (United States); R. R. Rice, Northrop Grumman Aerospace Systems (United States)

Recently developed glass-clad crystalline semiconductor core optical fibers potentially offer a series of advantages over present optical fiber materials including greatly enhanced Raman cross-sections and extended infrared transparency. Indeed, the low-cost high-through-put fiberization of crystalline materials could permit a step-jump in performance critical for use in high energy laser, infrared counter-measure, communication, and sensor systems. Further, the high degree of crystallinity is of considerable scientific value since optical fiber fabrication is a highly non-equilibrium process and so achieving high degrees of crystallinity is very counterintuitive and offers new insight into crystal growth mechanisms. This talk will review progress in glass-clad fibers possessing cores of highly crystalline silicon and germanium including anomalies in Si and Ge that may benefit fiber fabrication as well as paths forward to optimization of fiber design and performance.

7598-41, Session 10

Microfiber-coupled photonic crystal resonators

M. Kim, M. Seo, J. Kim, J. Kang, Y. Lee, Korea Advanced Institute of Science and Technology (Korea, Republic of)

The photonic crystal semiconductor microcavity [1] having wavelength-scale volume and high quality factor enables us to study cavity quantum electrodynamics in miniature semiconductor material systems. Recent incorporation of quantum dot into PhC microcavity [2] reported meaningful, but limited success. These trials exposed a couple of critical problems. The first issue is related to the spatial and spectral overlaps of two relevant resonances, the cavity resonance and the quantum dot resonance. In order to meet these challenges, one needs to control the emission wavelength of a quantum dot on the order of nanometer. At the same time, this right-size quantum dot should be placed at the anti-node of the resonant mode with precision on the order of nanometers. The issue of efficient collection and delivery of photons should also be addressed.

We claim that the incorporation of highly-curved micro-fiber is one of the most competitive ways to answer the above mentioned problems. The microfiber-coupled ‘reconfigurable’ resonator demonstrates repeatable formation of the cavity’s physical position. One can utilize this reconfigurability to place the quantum dot of ‘right’ emission spectrum placed at the ‘right’ physical position of a resonant mode. And efficient out-coupling into the tapered single mode optical fiber follows naturally. In this scheme, spatially-reconfigurable Gaussian-shaped photonic well [3] is generated by contacting a curved tapered micro-fiber onto a photonic crystal waveguide. We confirm the photon trapping in this re-locatable well in 1-D and 2-D fashions by observing lasing action slightly below the corresponding band edge.

References

[1] O. Painter et al., Science 284, 1819 (1999)

[2] A. Badolato et al., Science 20, 1158 (2005)

[3] M. K. Kim et. al., Opt. Express 15, 17241 (2007).

7598-42, Session 10

Pulse amplification in semiconductor optical amplifiers with ultrafast gain-recovery times

P. P. Baveja, A. M. Kaplan, Univ. of Rochester (United States); D. N. Maywar, Rochester Institute of Technology (United States); G. P. Agrawal, Univ. of Rochester (United States)

This paper presents detailed numerical and experimental studies of SPM in semiconductor optical amplifiers (SOAs) with ultrafast gain-recovery times. These SOAs have a range of gain-recovery speed which is a function of drive current. At increased drive current, the amount of internal ASE in the SOA increases, which causes the small-signal gain to saturate and reduce the gain-recovery time. The nature and extent of pulse amplification is thus different at different drive currents. We suitably modify the standard propagation equations to include the small-signal gain saturation and recovery-time speed-up to theoretically calculate the evolution of output spectrum as a function of drive current. We calculate the evolution of output spectrum for unchirped-gaussian pulses, chirped-gaussian pulses, and super-gaussian pulses.

We verify these theoretical predictions by performing experiments in which we propagate pulses inside three commercially available SOAs having gain-recovery times of 9, 16, and 100 ps at their maximum drive current. We use pulses with 57 ps full-width at half-maximum, at 1 GHz repetition rate, obtained by gain-switching a semiconductor laser diode.

Understanding of different amplification regimes in these commercial SOAs, punctuated by different drive currents, is important for optimizing the performance of SOA-based optical regenerators, wavelength converters, and amplitude limiters. Our study addresses the full range of gain-recovery times in commercial SOAs extending from less than 10 ps to >100 ps.

7598-43, Session 10

High-temperature stability of lasing wavelength in GaAsSb/GaAs double quantum wells lasers

H. Yu, C. Wan, Y. Su, R. W. Chuang, W. Chen, C. Huang, W. Lin, M. H. Pilkuhn, National Cheng Kung Univ. (Taiwan)

High-temperature stability of lasing wavelength of GaAsSb/GaAs quantum well (QW) lasers grown by metal-organic vapor phase epitaxy (MOVPE) will be demonstrated. The GaAsSb/GaAs double QW (DQW) lasers grown by MOVPE using triethylgallium (TEGa) and TMGa as the Ga source for low-temperature (525oC) and high-temperature (600oC) QW epitaxial growth, respectively. The d /dT of the laser grown at high temperature was 0.36nm/K. Lasers with a lower active layer growth temperature have very low d /dT values, which are in the range from 0.24 to 0.287 nm/K. To the best of the our knowledge, this range represents the best ever reported thermal stability of broad area lasers that use an as-cleaved facet as a Fabry-Perot cavity without any external coupled cavity. And this is also the first trial of using triethylgallium (TEGa) as the precursor to grow QW at low temperature (525oC). The lasing wavelength ranges from 1117 to 1144 nm. The QW grown at high temperature (600 oC) by using trimethylgallium (TMGa) is also examined. The lasing wavelength is 1125.6 nm at room temperature and d /dT is 0.36 nm/K, which is higher than those lasers grown at lower temperature. The Sb compositions of the lasers with d /dT values equal to 0.240 and 0.287nm/K are 0.23 and 0.26, and Jth values are 697 and 1193 A/cm2, respectively. And the characteristic temperature (T0) values are 116 and 109 K below 60oC. The low d /dT values show that the GaAsSb/GaAs QW has potential application in the fabrication of temperature-insensitive VCSELs.

7598-44, Session 10

1.54 µm emitters and amplifiers based on Er-doped III-nitrides

R. P. Dahal, H. Jiang, J. Lin, Texas Tech Univ. (United States); J. Zavada, North Carolina State Univ. (United States)

Er doped III-nitride semiconductors have been a major field of research aiming to achieve photonic devices with multiple functionalities, which are not possible with either Er doped silica glasses or narrow band gap semiconductors like InGaAsP. Due to the large bandgap energy and low thermal quenching, emitters and optical amplifiers operating at 1.54 m based on Er doped GaN and InGaN are expected to be electrically pumped, integratable, temperature insensitive and high signal gain with low noise. These properties are very attractive for next generation optical network system where multiple amplification steps are required. We will discuss here on the metal organic chemical vapor deposition (MOCVD) growth of Er doped GaN and InGaN epilayers and the influence of growth parameters (temperature, pressure, NH3 etc) on the crystalline quality and 1.54 µm emission intensity of these epilayers. We will also report on the fabrication of a chip size current injected 1.54 m emitters and optical amplifiers by heterogeneously integrating MOCVD grown Er doped GaN and InGaN with 365 nm nitride light-emitting diodes. The emitted intensity at 1.54 m varied almost linearly with input forward current. Moreover, the propagation loss and the amplification characteristics at 1.54 m of Er doped nitride waveguide amplifier will be presented. The feasibility of electrically pumped optical amplifiers for photonic integrated circuits with advantages of both semiconductor optical amplifiers and Er-doped fiber amplifiers will also be discussed.

7598-45, Session 11

Near- and medium-infrared optical fiber lasers and emerging applications

F. Prudenzano, L. Mescia, L. A. Allegretti, M. De Sario, A. D'Orazio, A. Di Tommaso, T. Palmisano, V. Petruzzelli, Politecnico di Bari (Italy)

Optical fiber and planar waveguide lasers based on rare earth-doped glasses, are competitive with respect to the other light sources, such as solid-state ion-doped crystal and glass lasers, optical parametric oscillators, semiconductor and gas lasers. They exhibit high conversion efficiency, excellent beam quality, compactness of optical cavities, good heat dissipation capability. Laser sources based on rare earth doped glasses are used in material processing, medical and surgical applications, generation of ultrafast pulses by exploiting the glass nonlinearity, remote sensing, spectroscopy and so on. Moreover, high power fiber lasers can be coherently or incoherently combined to form directed high-energy laser systems having high efficiency, compactness, robustness and long operating lifetime.

The paper reviews the novel strategies pursued to obtain laser sources based on rare earth doped glasses, even with reference to the host materials and the dopants employed for their construction, and the corresponding applications. An example of infrared wavelength range (IR) chalcogenide glass laser is illustrated. The chalcogenide glass potentials which have attracted a great interest in the optical amplification and laser generation, such as high transparency, mechanical and chemical durability and low phonon energy are underlined. To conclude, another example of near infrared (NIR) fiber optic laser fabrication is shown point by point.

7598-46, Session 11

Chromium-doped zinc selenide gain media: from synthesis to pulsed mid-infrared laser operation

A. Sennaroglu, Koç Univ. (Turkey); U. Demirbas, Koç Univ. (Turkey) and Massachusetts Institute of Technology (United States); H. Cankaya, N. Cizmeciyan, A. Kurt, M. Somer, Koç Univ. (Turkey)

Chalcogenides doped with divalent (Cr2+) chromium ions such as Cr2+:ZnSe posses many favorable spectroscopic characteristics that enable efficient generation of laser radiation in the mid-infrared region around 2.5 um. These include high luminescence quantum efficiency at room temperature, absence of excited-state absorption, and availability of broad emission band for the generation of femtosecond pulses. In this presentation, we will review the state-of-the-art in the development of chromium-doped chalcogenide lasers and focus on the work carried out in our group on the synthesis and laser operation of Cr2+:ZnSe. By using diffusion doping, 40 polycrystalline Cr2+:ZnSe samples with ion concentrations in the range of 0.8 × 1018 to 66 × 1018ions/cm3 were prepared. Absorption/emission spectra, and the concentration dependence of luminescence quantum efficiency were experimentally measured. During continuous-wave operation, the samples were placed inside an x-cavity and pumped with a 1800-nm thulium-doped fiber laser. At an incident pump power of 2.1 W, the optimum concentration for lasing was determined to be 8.5 × 1018 ions/cm3. During gain switched operation, intracavity pumping with an optical parametric oscillator operating at 1570 nm resulted in the demonstration of record tuning range between 1880 and 3100 nm. By employing dispersion compensation with a MgF2 prism pair, Kerr-lens mode-locked operation was also demonstrated at 2420 nm, resulting in the generation of 95-fs pulses with an average output energy of 40 mW and spectral bandwidth of 69 nm. The time-bandwidth product of the pulses was further measured to be 0.335.

7598-47, Session 11

Pulsed cladding-pumped large mode area Raman fiber amplifier

J. Ji, C. A. Codemard, J. K. Sahu, J. Nilsson, Univ. of Southampton (United Kingdom)

Cladding-pumped fiber Raman devices are attractive for beam clean-up of multimode beams and for wavelength conversion. To date, however, demonstrations have been limited to devices with relatively small inner claddings and cores. These require pumping with high-brightness pump sources because of the small inner cladding, and are limited in power scalability by a relatively low damage threshold because of the small core. Here, we demonstrate a pulsed cladding-pumped fiber Raman amplifier based on a large mode area fiber with a 20 μm diameter, 0.06 NA, core and a 50 μm diameter, 0.2 NA, inner cladding. With these fiber dimensions, it is possible to efficiently convert the pump at 1545 nm into the signal at the 1st-Stokes (1660 nm), without undesired higher-order Raman scattering, provided that the fiber length is matched to the pump power. In a 700 m long fiber, a 105 mW seed is amplified to 664 W of peak power, by a Raman pump with 1.72 kW of peak output power. Without the Raman seed, the peak power at 1660 nm can be 1.16 kW at the output under 3.7 kW pump peak output power. Both were limited by the appearance of 2nd-order Raman scattering in the relatively long fiber. The M2 of the output signal was ~1.6.

The core and inner-cladding areas are five times higher than that of previously reported cladding-pumped fiber Raman amplifiers. Results with even larger cores as well as shorter fibers, which both promote power scalability, will be reported at the conference.

7598-49, Session 12

Rogue waves in femtosecond supercontinuum generation

M. Erkintalo, G. Genty, Tampere Univ. of Technology (Finland); J. M. Dudley, Univ. de Franche-Comté (France)

Recently, significant results showed that the shot-to-shot statistics of the broadband supercontinuum spectra are associated with the excitation of a small number of statistically-rare “rogue” soliton events associated with an enhanced red-shift and increased temporal intensity. Because these experiments were carried out in a regime where the spectral broadening was seeded by modulation instability, there has been wide interest in drawing analogies with mechanisms potentially underlying the formation of oceanic rogue waves and the way in which large amplitude nonlinear waves can appear from low amplitude perturbations.

The initial work on optical rogue waves was performed in the context of SC generated in the picosecond regime where the spectral broadening was seeded by the spontaneous growth of MI sideband components. In this paper, however, we report experimental results showing that the characteristic features of the rogue wave statistics in supercontinuum generation can also be observed using input pulses in the femtosecond regime. We show that the statistical distribution of the time-series corresponding to the long wavelength edge of the supercontinuum spectrum exhibits the L-shape signature of rogue events. Furthermore, we study how the statistical distribution of the time-series amplitude changes as a function of filtered spectral position and bandwidth, showing that the histogram evolves towards a quasi-Gaussian distribution for shorter wavelength cutoffs. Finally, we show that the intensity histograms obtained from spectrally filtering the supercontinuum on the short wavelength edges of the spectrum also exhibit the L-shaped characteristics typical of extreme-value phenomena due to cross-phase modulation soliton-dispersive wave coupling.

7598-50, Session 12

Terrace-microsphere lasers: spherical cavity lasers for multiwavelength emission

H. Uehara, T. Yano, S. Shibata, Tokyo Institute of Technology (Japan)

We have successfully made terrace-microspheres for laser emission: micrometer size spherical cavity laser having terrace shaped pumping light entrance. “Terrace-microsphere” is a high refractive index glass sphere (nD=1.93) of 30μm in diameter with terrace portion of organic-inorganic materials. The glass sphere is in BaO-SiO2-TiO2 glass system and contain a few ppm of Nd3+. In our previous works, stimulated Raman emission of whispering gallery modes (WGMs) was demonstrated with low threshold by pumping the terrace portion with CW Ar+ laser (514.5nm wavelength). Organic-inorganic hybrid materials of refractive index nD=1.45 were prepared by sol-gel technique using 3-methacryloxypropyltrimethoxysilane and tetramethoxysilane as starting materials. To make terrace portion, a picoliter of sol droplet was supplied with a micro-capillary into the boundary between a glass sphere and a Teflon sheet. The sol-derived part attached to a sphere showed the flat portion like a terrace structure. The terrace-microspheres were pumped with a tunable CW Ti:Sapphire laser (wavelength region is 700nm~850nm) for choosing the suitable pumping wavelengths to WGMs. Pumping the terrace portion at around 800nm wavelength, strong resonances due to WGMs were demonstrated. The resonances originated from Raman scattering and Nd3+ fluorescence were observed at 840~880nm and 880~940nm wavelength region respectively. Consequently, we can show the potential application for a multi-wavelength laser (about 100 lines) at the extended wavelength range (840~940nm) in the near-infrared. Stimulated Raman emission of WGMs was performed with threshold of 3mW.

7598-51, Session 12

From multicolor to white light by upconversion in Tm3+-Ho3+-Yb3+ co-doped tellurite glasses

H. Desirena Enrriquez, Ctr. de Investigaciones en Óptica, A.C. (Mexico); E. De la Rosa, Centro de Investigaciones en Optica (Mexico)

Several Yb3+-Tm3+-Ho3+ co-doped transparent TeO2-ZnO-Na2O-La2O3 glasses were prepared and luminescence properties characterized. Simultaneous red (660 nm), green (546 nm) and blue (480 nm) (RGB) emission were obtained after excitation of 970 nm. The blue emission was produced by Tm3+ (1G4 -- 3H6), green by Ho3+ (5F4 + 5S2 -- 5I8) and red by both codopants (1G4 -- 3F4, 5F5 -- 5I8) as a result of the energy transfer process from Yb3+. Color was tuned from multicolor to white light by varying the intensity ratios between emission bands. Such tunability were produced by both changing the dopant concentration and the excitation pump power. The calculated color coordinate for white emission is x=0.30 and y=0.33 that match the reference white in 1931 CIE chromaticity diagram (x=0.33, y=0.33). Color tunability and high intensity of the signal emitted promise potential application in the photonics field.

Conference 7599: Organic Photonic Materials and Devices XII

Tuesday-Thursday 26-28 January 2010 • Part of Proceedings of SPIE Vol. 7599

Organic Photonic Materials and Devices XII

7599-01, Session 1

Status of photonics polymer and face-to-face communication (Keynote Presentation)

Y. Koike, Keio Univ. (Japan)

No abstract available

7599-02, Session 1

Control of the birefringence dispersion of polymer film by a birefringent crystal

K. Shikama, Keio Univ. (Japan); A. Tagaya, Y. Koike, Keio Univ. (Japan) and Japan Science and Technology Agency (Japan)

We proposed a method to control birefringence dispersion of polymer film by doping with an inorganic birefringent crystal. In this method, a strontium carbonate (SrCO3) crystal was chosen that has a large birefringence and a needle-like shape that was successfully oriented in film-forming of the solvent casting. In order to design birefringence dispersion of polymer films by this method, we measured the birefringence dispersion of a SrCO3 crystal itself by doping this crystal into poly(methyl methacrylate / benzyl methacrylate =81/19 (w/w)) exhibiting almost zero birefringence in the visible region. By using the obtained birefringence dispersion of the SrCO3 crystal, we designed a polymer film with reverse birefringence dispersion, and thus combination of cyclo-olefin polymer (COC) containing 5 wt.% SrCO3 crystals was chosen. A film of COC containing 5 wt.% SrCO3 crystals was fabricated by using the solvent casting. Then, uniaxial heat-drawing of the film was carried out by tensile machine at a draw temperature of 195 oC. As a result, a polymer film with reverse dispersion was successfully fabricated. In addition, retardation of the obtained film with reverse dispersion was 50 nm at a wavelength of 548.9 nm and at a film thickness of 37 m. The control of birefringence dispersion by this method is potentially applicable to fabrication of retardation film with reverse dispersion that is used for improving image quality of liquid crystal displays (LCD), especially for higher contrast in wide viewing angle range in LCD.

7599-03, Session 1

Fluorescent block copolymers prepared by atomic transfer radical polymerization

J. You, Yonsei Univ. (Korea, Republic of); J. Yoon, Carnegie Mellon Univ. (United States); J. Kim, Yonsei Univ. (Korea, Republic of); C. Juang, K. Matyjaszewski, Carnegie Mellon Univ. (United States); E. Kim, Yonsei Univ. (Korea, Republic of)

Well defined fluorescent block copolymers bearing pyrene or anthracene block, P(MMA-b-PY) or P(MMA-b-Ant), respectively, were prepared by the atom transfer radical polymerization (ATRP) using methyl methacrylate and pyrene or anthracene methacrylate, respectively. These block copolymers were responsive to external stimuli such as heat and light. The effect of nanoscale confinement of the polymers at glass transition temperature on fluorescence property was investigated by spectroscopic method in combination with a microscopic imaging. A dramatic change of the fluorescence intensity and emission wavelength were observed and could be attributed to the rearrangement of the fluorescent block. Upon UV exposure the fluorescence of the block copolymers were quenched to allow a direct photo patterning. It was found that the fluorescent polymer experience interesting morphology as well as chemical change upon UV exposure.

7599-04, Session 1

Complementary grating dynamics in photorefractive polymers with Alq3

C. Christenson, J. Thomas, P. Blanche, R. A. Norwood, N. N. Peyghambarian, College of Optical Sciences, The Univ. of Arizona (United States)

The electron transporting molecule tris(8-hydroxyquinoline) aluminum (Alq3) was introduced into a photorefractive composite at 1% by weight to study the effects of electron traps on the performance. Compared to a control sample, the two-beam coupling (TBC) net gain at 60 V/µm was observed to increase by more 20% with 532nm excitation and more than 200% with 633nm excitation. Steady-state four-wave mixing (FWM) measurements showed over-modulation at a reduced voltage. Both of these results are consistent with previous studies and presumably the result of increased effective charge generation from reduced recombination. Transient FWM experiments demonstrated an increased writing speed and longer persistency. For writing times of several minutes, the efficiency increased after the writing beams were blocked, which is indicative of grating revelation via decay of a competing grating. This behavior was not evident for writing times on the order of 10 seconds. A composite with Alq3 and C60 exhibited similar effects evident of competing gratings, with further increases in the speed. All FWM data fit well to a standard bipolar two-species charge transport model, and the relative strength and speed of the competing gratings were extracted. Additionally, samples with Alq3 exhibited increased dielectric breakdown strength compared to control samples, typically surviving several minutes of continuous 500 mW/cm2 illumination at 90 V/µm, making them promising composites for applications such as holographic display and beam clean-up.

7599-05, Session 2

Optical polymer nanocomposites: designer materials for nanophotonics

R. A. Norwood, College of Optical Sciences, The Univ. of Arizona (United States)

The combination of the emergence of high performance linear and nonlinear optical polymer materials and the availability of techniques for making nanoparticles that provide tight control over their size and surface chemistry has led to a unique opportunity to develop optical polymer nanocomposites with unique optical properties that are not otherwise attainable. We will discuss recent progress we have made in the development of polymer nanocomposites for both linear optics and nonlinear optical functions, such as electro-optics, magneto-optics and third order processes.

7599-06, Session 2

Refractive engineering via super-hybrid technology for polymer optical waveguide applications

T. Kaino, O. Sugihara, Tohoku Univ. (Japan)

Refractive index control of polymers is a critical issue for polymer device applications. For that, refractive engineering is of special concern. Using a super hybrid technology, we had controlled polymer refractive index higher than 1.9 with large Abbe number simultaneously. This technology includes a surface treatment of metal oxide nano particles through milling

method as well as two step polymerization technique.

Detail of polymer optical waveguide application will also be presented.

7599-07, Session 2

Solar absorbance and thermal emittance characterization of nanostructured materials

J. H. Kang, National Institute of Aerospace (United States)

Materials with tailored solar absorptivity and thermal infrared emissivity constitute an attractive approach for solar (photonic) energy control in space applications. Numerous solar absorbance/thermal emittance control materials currently available include CuCrOx or FeMnCuOx, transparent metal coatings of copper and silver, wide band gap semiconductors of SnO2, indium tin oxide (ITO) and ZnO, and multilayer coatings of dielectric/metal/dielectric structure. However, conventional metal oxides for solar absorbance/thermal emittance coatings are brittle and too heavy for deployable space structures. The multilayer dielectric/metal/dielectric coatings approach also has limited utility due to problems resulting from delamination of layers, high residual stress from different thermal expansion coefficients of the layers and a complicated fabrication process. In this presentation, an alternate approach based on in-situ polymerization of nanoparticle filled polyimides to afford a tailorable, lightweight, durable, thermally emissive and solar absorptive polymeric material will be reported. This study presents characterization results of the thermal emissivity and solar absorptivity of these tailored multifunctional materials. The thermal emissivity and solar absorptivity were measured for different nano inclusions such as carbon nanotubes (CNT), noble metal, transition metal, or mixtures of these fillers at different concentrations. Adding CNTs or metal salts, such as Fe- or Cu-salts increases the solar absorptivity and thermal emissivity while adding zinc- or indium salts decreases the thermal emissivity. This presentation will address potential terrestrial applications as well as space applications.

7599-08, Session 2

Nanoparticle electroluminescence: controlling emission color through Foerster resonance energy transfer in hybrid particles

C. Huebner, S. H. Foulger, Clemson Univ. (United States)

Electroluminescent polymers are attractive for developing all-organic light-emitting devices due to the potential advantages that polymeric systems may offer in the large-scale manufacturing of electronics. Nonetheless, many of these electroluminescent π-conjugated polymers are inherently insoluble in the solvents employed in the intended solution-based manufacturing processes. One such polymer is poly(2,5-dioctyl-1,4-phenylenevinylene) (POPPV), where the inherent lack of solubility of POPPV in organic solvents has frustrated its widespread application in devices and no organic light emitting devices (OLED) have been presented that exploit its electroluminescence characteristics. In this effort, a unique strategy is presented for the preparation of hybrid nanoparticles composed of POPPV, a green emitter (em = 505 nm), and poly(9,9-di-n-octylfluorenyl-2,7-diyl) (PFO), a blue emitter (em = 417 nm). The aqueous-based nanoparticle dispersion composed of these hybrid particles was stable to aggregation and employed in the construction of OLEDs. The color characteristics of the electroluminescence for the devices could be tuned by exploiting the Forster resonance energy transfer between the polymers within a particle, while suppressing energy transfer between particles. These aqueous-based nanoparticle dispersions are amenable to being printed into devices through high-throughput manufacturing techniques, for example, roll-to-roll printing.

7599-09, Session 2

Piecewise fabrication of click functionalized core-shell particles

R. D. Roeder, Clemson Univ. (United States); D. D. Evanoff, Jr., Western Carolina Univ. (United States); V. Tsyalkovskyy, P. Rungta, S. H. Foulger, Clemson Univ. (United States)

The surface functionalization of colloidal particles is an ongoing interest among materials scientists due to unique physical and chemical properties a colloidal-based system offers. Current research into surface modified colloids cover a variety of applications including drug delivery, sensors, colloidal inks and optical arrays. Recently, the use of click chemistry, specifically the Huisgen 1,3-dipolar cycloaddition between azides and alkynes, has garnered a lot of attention in the colloidal field due to the simplicity and high-yielding nature of the reaction. Azides and alkynes can act as unique chemical handles allowing different materials to covalently attach to a variety of surfaces.

Herein, the synthesis of a core-shell polymer colloid through emulsion polymerization is described as a building block to create diverse-functional particles. The polystyrene seed particle is polymerized and thoroughly cleaned before the addition of the methyl acrylate-co-propargyl acrylate shell. The shell contains surface alkyne units capable of undergoing Huisgen 1,3-dipolar cycloaddition. The colloids are subjected to a click reaction with an azide functionalized poly(ethylene glycol) or anthracene small molecule which results in direct covalent attachment to the particle surface. The success of the click reaction is monitored with photoluminescence spectroscopy, zeta potential analysis, x-ray photoelectron spectroscopy, gel permeation chromatography and contact angle measurements. The piecewise structure of the particle and versatility of the click reaction allows a variety of materials to attach to the shell and has potential use in many optical applications such as sensors (fluorescent materials), ink-jet printing (toner) or organic light-emitting devices (charge transport materials).

7599-10, Session 3

Non-classical properties of phase conjugate light in bacteriorhodopsin

Y. Okada-Shudo, Y. Zhang, M. Watanabe, The Univ. of Electro-Communications (Japan)

The human eye is very sensitive but we cannot see a single photon because several numbers of photons required triggering a conscious response. It seems that there is a threshold number of incident photons to pass a signal to the brain. However, it has been confirmed by many experiments that the sensors in the retina (rhodopsin) can respond to a single photon. High performance of these biological photon counters, low dark noise and high quantum efficiency, have been applied to detection of single-photon and entanglement state in recent years.

On the other hand, we have demonstrated the generation of phase and polarization conjugate light using photo-induced anisotropy of photochromic protein bacteriorhodopsin to date. Bacteriorhodopsin is rerated to the human visual pigment. Lately several experimental observations of slow light and superluminal light in the bacteriorhodopsin solution or thin film have been presented. Its excellent properties of such rod photoreceptor, high stability and light polarization discrimination, make it a potential candidate for quantum information processing.

Our aim is generation of non-classical light using biomaterial bacteriorhodopsin. We generated the phase-conjugate light with four-wave mixing at the wavelength without absorption, and investigated the non-classical properties of phase conjugate light.

7599-11, Session 3

Organic nonlinear optical crystals for electro-optics and THz generation

B. Ruiz, Z. Yang, S. Kwon, O. Kwon, M. B. Stillhart, F. Brunner, A. Schneider, C. Medrano, M. Jazbinsek, P. P. Günter, ETH Zürich (Switzerland)

Organic materials exhibiting second-order nonlinearity are very promising for applications such as broadband THz-wave generation and high-speed electro-optic applications. This is because of their low dielectric dispersion, which allows for velocity matching between the optical and electric, as well as THz waves. Opposed to polymers, organic single crystals do not require poling and also their thermal and photochemical stability is considerably improved, which is of particular importance for applications where high-power short-pulse lasers are used.

The organic stilbazolium salt DAST (4-N,N-dimethylamino-4'-N'-methyl-stilbazolium tosylate) has been shown to be a very efficient material for electro-optic and THz-wave applications. We have developed an optimized solution-growth technique, which resulted in size-tailored high-optical quality DAST crystals, which have been successfully used for THz generation and integrated electro-optic structures. Additionally, we developed several novel organic crystals, based on either stilbazolium salts or hydrogen-bonded molecular crystals. Very high electro-optic figures of merit n3r and nonlinear optical susceptibilities (2) of above 500 pm/V at 1.5 µm have been measured in these crystals. We present the stilbazolium salt DSTMS (4-N,N-dimethylamino-4'-N'-methyl-stilbazolium 2,4,6-trimethylbenzenesulfonate) and the hydrogen-bonded crystal OH1 (2-(3-(4-hydroxystyryl)-5,5-dimethyl-cyclohex-2-enylidene)malononitrile), for which high-quality and large-size bulk crystals can be readily grown from solution, and their absorption in the THz range is considerably reduced compared to DAST. Broadband THz-wave generation by optical rectification of femtosecond laser pulses with record-high figures of merit has been demonstrated in DSTMS and OH1.

7599-12, Session 3

Polarization/depolarization processes in NLO side-chain polymers doped with push-pull chromophores

H. Ibn El Ahrach, A. Barsella, J. Vola, L. Mager, A. F. Fort, Institut de Physique et Chimie des Matériaux de Strasbourg (France); W. Bentoumi, Y. Bretonniere, C. Andraud, Ecole Normale Supérieure de Lyon (France)

In the past decades, a lot of different strategies have been attempted to fabricate an efficient organic electro-optic material. Starting from the work on the non linear optical (NLO) chromophore itself (calixarene, octupoles...) and going to the synthesis of complex structures (crystals, grafted polymers, mesoporous matrix, dendrimeres...), a large number of alternative options have been tested. But one of the first and the simplest structure considered, a polymer matrix doped with a push-pull chromophore, remains one of the most efficient. Recently, the doping of a functionalized NLO polymer with a high efficiency push-pull chromophore has resulted in huge electro-optic response. Here, we present such a material using an heptamethine cyanine chromophore (CPO1) to dope a side chain NLO polymer (PMMA-co-DR1). The very high quadratic nonlinear optical properties (µ (@1.9µm) = 30 000 10-48 esu) of the chromophore yields a electro-optic coefficient r33 of up to 70 pm/V at the telecommunication wavelength of 1550 nm while showing good temporal stability. The presence in the same material of these two different NLO dipolar chemical species leads to an original behaviour when one observes the thermally induced relaxation of the chromophore orientation in the material. We present our findings on the polarization/depolarization processes of this material observed via absorption, electro-optic, and dielectric spectroscopy. The depolarization currents in thermally stimulated relaxation have also been measured. Our results allow a better understanding of the individual and collective behaviours of the different molecular species present in the material.

7599-13, Session 3

Characterization of the nonlinear optical response of collagen

A. Deniset-Besseau, Ecole Polytechnique (France); J. Duboisset, Univ. Claude Bernard Lyon 1 (France) and CNRS (France); P. De Sa Peixoto, Univ. Pierre et Marie Curie (France); M. Strupler, Ecole Polytechnique (France); E. Benichou, C. Loison, Univ. Claude Bernard Lyon 1 (France); F. Hache, Ecole Polytechnique (France); G. Mosser, Univ. Pierre et Marie Curie (France); P. Brevet, Univ. Claude Bernard Lyon 1 (France); M. Schanne-Klein, Ecole Polytechnique (France)

Collagen is a major protein of the extracellular matrix that is characterized by triple helical domains. Fibrillar collagens (type I, III, V...) form nanometer-scale fibrils that further assemble in micrometer-scale fibers and show a hierarchical organization in tissues (skin, cornea, bone, tendons...). Other collagen types form microfibrillar networks, basement membranes as well as other tissue-specific structures.

Remarkably, fibrillar collagen exhibits intrinsic Second Harmonic Generation (SHG) signals and SHG microscopy proved to be a sensitive and reproducible technique to characterize collagen three-dimensional distribution during tissue remodeling. However, quantitative nonlinear data are required to further process SHG images. We therefore performed Hyper-Rayleigh Scattering experiments and measured a second order hyperpolarizability of 1.25 10-27 esu for rat-tail type I collagen. This value is surprisingly large considering that the collagen presents no strong harmonophore in its amino-acid sequence. We therefore inferred that the collagen large nonlinear optical response originates in the tight alignment of a large number of weakly efficient harmonophores, presumably the peptide bonds, resulting in a coherent amplification of the nonlinear signal along the triple helix. This mechanism was confirmed by HRS measurements after denaturation of the collagen triple helix and for a collagen-like short model peptide [(Pro-Pro-Gly)10]3.

To illustrate this coherent nonlinear optical process, we successfully recorded SHG images in collagen liquid solutions by achieving liquid crystalline ordering of the collagen triple helices. It demonstrated the ability of SHG microscopy to monitor the organization processes involved in the synthesis of biomimetic collagenous matrices.

7599-14, Session 4

New frontiers of organic electro-optic materials and devices: from molecular engineering to technological innovation (Keynote Presentation)

A. K.-Y. Jen, J. Luo, X.-H. Zhou, Z. Shi, S. Huang, S.-H. Jang, B. Polishak, L. Dalton, and M. Hochberg, Univ. of Washington (United States); M. Hayden, University of Maryland (United States); R. Norwood and N. Peyghambarian, University of Arizona (United States); B. Block, T. Younkin, and P. Chang, Intel Corporation (United States)

The ultimate goal for research in organic electro-optic (E-O) materials is to develop highly efficient and processible materials that can modulate optical signals with large bandwidth, low power consumption, and excellent operational reliability. Through the combined approaches of molecular engineering, self-assembly, and controlled lattice hardening, the activity of organic E-O materials have been elevated to an unprecedented level (>500 pm/V @1310nm). In this talk, the progress of developing E-O materials with ultrahigh activity while possessing good thermo-, photo-, and electro-stability will be discussed. These results have inspired the vigorous development of innovative photonic devices, such as ultralow drive voltage polymer modulators, polymer-silicon hybrid devices, broadband terahertz generation and detection, and advanced CMOS/photonic interconnects.

7599-15, Session 4

Hyperbranced polymers for electro-optic (EO) and photonic crystal applications

S. Yokoyama, X. Piao, A. Inoue, X. Zhang, S. Inoue, Kyushu Univ. (Japan)

We synthesized hyperbranched polymers used for the host materials of EO chromophores. Synthesized hyperbranched polymers have poly(ethyl ether) or PMMA based branched chain, so that their optical losses at the telecommunication wavelength are measured less than 1 dB/cm. Their refractive indices can be varied from 1.45 to 1.70. We found that hyperbranched polymers became a good host of EO chromophores such as well-known FTC derivatives. Polymer films showed EO coefficients higher than 100 pm/V. This is the highest level of polymer EO activity for the conventional host-guest systems. We used hyperbranched polymers for the application of one dimensional polymeric photonic crystal with EO defect layers. Polymer EO layer was inserted in the reflection-type planar microcavity, and the EO response of the poled polymer was measured at telecommunication wavelength. We designed and fabricated the microcavity with an enhanced local field in the EO polymer layer, and measured reflection band centered at 1300 nm. Enhancement of the phase sensitivity by the multiple reflections in the microcavity was evaluated by the refractive-index changes of the incident light at the same wavelength. The enhanced refractive-index change was about 90 times larger than the vale obtained at the off-resonance wavelength.

7599-16, Session 4

EO polymer modulators reliability data

R. Dinu, GigOptix Corp. (United States)

Although many photonic devices have been demonstrated using EO polymers, the lack of industry standard lifetime testing has hindered commercial adoption, which is especially important for low driving devices having chromophores with more intricate and potentially more susceptible structures. In particular, thermal instability of r33 is a long-recognized issue in EO polymers due to the dependence of poled chromophore orientation on the glass transition temperature (Tg) of the polymer. Additionally, the chromophore can be damaged on exposure to light that may decrease r33 and increase optical loss since light must pass through the EO polymer during operation. We report on low driving voltage Mach-Zehnder modulators fabricated using high performance, photostable and thermally stable electro-optic polymers. The device key parameter, driving voltage, directly related to EO coefficient, r33, and it was monitored for thousands of hours at 65, 85, 90, and 100C. The relaxation time constants and activation energy that have direct impact on device stability were obtained by fitting experimental data with polymer system specific Arrhenius equation. The obtained time constants were applied to predict lifetime of devices for up to 25 years.

7599-17, Session 4

High-performance electro-optic modulators realized with commercial side-chain electro-optic copolymer DR1-PMMA

S. Michel, J. Zyss, Ecole Normale Supérieure de Cachan (France); I. Ledoux-Rak, C. T. Nguyen, École Normale Supérieure de Cachan (France)

Several high-performance polymeric electro-optic modulators have been demonstrated in the last ten years. Most of these modulators were realized with specific high-performance electro-optic polymers which had been designed and synthesized in molecular engineering research laboratories. In this paper we report the high-performance of electro-optic modulators realized with the commercial side-chain electro-optic copolymer DR1-PMMA as a core material and passive epoxy polymer NOA73 as cladding material. The electro-optic polymer used in ours modulators is disperse red 1- methyl-methacrylate (DR1-MMA) based side-chain copolymer with relative molar concentration of MMA substituted and MMA unsubstituted groups equal to 30/70. We examine the phase modulator, the push-pull Mach-Zehnder modulator and the loop structure push-pull Mach-Zehnder modulator in order to optimize their figure of merit represented by the product half-wave voltage by electrode length (Vpi.L). A push-pull Mach-Zehnder modulator with a 2 cm-long electrode and an inter-electrode distance of 8.8 µm demonstrated a half-wave voltage of 2.6 V at 1550 nm, corresponding to a figure of merit of 5.2 V.cm. This result was obtained with a moderate push-pull poling voltage of ± 280 V with respect to 0 V, corresponding to a estimated poling electric field of 75 V/µm in the core of the modulator waveguide. We achieved the best figure of merit which has never been observed in a modulator realized with a commercial side-chain electro-optic polymer.

7599-18, Session 5

Electro-optic modulator with exceptional power-size performance enabled by transparent conducting electrodes

S. Ho, F. Yi, F. Ou, B. Liu, Y. Huang, T. J. Marks, J. Liu, Y. Wang, Northwestern Univ. (United States); A. K. Y. Jen, S. Huang, J. Luo, Univ. of Washington (United States); R. Dinu, D. Jin, GigOptix Inc. (United States)

Low-voltage high-speed electro-optic modulator is of great interest. We demonstrate that a new modulator structure utilizing transparent conducting oxide (TCO) electrodes with appropriate electrical and optical loss characteristics, dramatically lowers the required switching power and enables very compact device structures. Initial results for an indium oxide-based phase modulator using a high-r33 organic polymer achieve a power-length product equivalent to only 7.2mW-cm2 --about 100-fold lower than that of current organic EO modulator designs. High-frequency simulation of the modulator performances and application of TCO based structures to both organic and semiconductor based EO modulators will be discussed.

7599-19, Session 5

Hybrid organic crystal/silicon-on-insulator integrated electro-optic modulators

M. Jazbinsek, C. Hunziker, S. Kwon, H. Figi, O. Kwon, P. P. Günter, ETH Zürich (Switzerland)

Organic electro-optic materials are very attractive candidates for future high-speed optical switches and modulators with bandwidths beyond 100 GHz, since their inorganic counterpart electro-optic materials like LiNbO3, as well as silicon modulators based on free-carrier effect have already approached their intrinsic bandwidth limits. Compared to the more widely studied poled polymers, organic electro-optic crystals present important advantages due to their stable chromophore orientation, superior photochemical stability, and do not require complicated poling procedures. However, thin-film processing possibilities of crystals are usually limited with respect to polymers, and therefore only few examples of integrated optical devices based on organic crystals have been reported up to now.

We have recently developed a very promising organic crystal OH1 (2-(3-(4-hydroxystyryl)-5,5-dimethyl-cyclohex-2-enylidene)malononitrile) with high electro-optic figures of merit, n3r=530 pm/V at 1319 nm. The processing possibilities of OH1 are considerably improved compared to previous high-nonlinearity organic crystals. We have developed an epitaxial-like solution growth technique that allows fabrication of high-quality OH1 films with single-crystalline domains of more than 2 cm2 area and 0.1-4 µm thicknesses on various substrates, which is of particular importance for integrated optics. We have demonstrated

highly-efficient electro-optic modulation in OH1 waveguides, as well as in silicon-on-insulator (SOI) waveguides, functionalized by single crystalline OH1 grown directly on top of the silicon structures. This is the first demonstration of the compatibility of organic crystalline materials with silicon photonics technology. Silicon nanowire waveguides with OH1 cladding offer a great potential for high-bandwidth, sub-1-V half-wave voltage, hybrid SOI/organic electro-optic modulators with highly stable chromophore orientation.

7599-20, Session 5

Organically enabled silicon-based photonic/ RF-photonic applications

A. S. Sharkawy, O. Ebil, P. Yao, EM Photonics, Inc. (United States); M. Zablocki, Univ. of Delaware (United States); E. J. Kelmelis, EM Photonics, Inc. (United States); D. Prather, Univ. of Delaware (United States)

Optical control of RF-signal transmission presents an attractive avenue for processing and transmitting RF information using various optical components, as opposed to electronic control, where metallic wires/cables are required. Optical waveguides, switches, high-speed modulators, filters, etc. offer a reduction of the physical size and hence weight of the overall RF-System and the advantage of high power handling capability with picosecond timing precision. Optical components for RF-photonic applications such as communication satellites, avionics, optical networks, sensors and phase array radar will require high speed, high capacity and low power. Due to the nature of crystalline electro-optic materials (LiNbO3, GaAs, InP, etc.) today's commercial electro-optical devices do not perform well above 40 GHz. This limitation can be circumvented by utilizing the unique properties of organic materials (Nonlinearity, electro-activity, conductivity and electro-opticity). Since amorphous polymers do not have lattice mismatch problems, incorporation of organic (polymeric) materials with conventional materials like Si, SiGe, GaAs, InP and GaN should open up multiple possibilities of achieving high-frequency, high-bandwidth applications such as high-capacity optical networks, THz and mmW imaging, wireless communication, phase array radar and antennae, lightweight broadband avionics etc. Several RF applications will also benefit from the development of such technology, including high-speed switching and gating of RF signals, the development of optically reconfigurable multifunctional antennas, and high speed EO-modulators. Organically-enabled silicon-based RF Photonic applications are sought to effectively process an RF signal using macro- and microscopic optical components with high linearity and low optical loss.

7599-51, Session 5

Numerical model of multilayer organic emitting light devices

Y. Hu, H. Rao, J. Ju, Y. He, Univ. of Electronic Science and Technology of China (China)

A numerical model of multilayer organic light-emitting devices is presented which include charge injection, transport, space charge effects, transport in heterojunction interface, recombination process and exciton diffusion. The model is based on the drift-diffusion equations. The device structure in simulation is ITO/CuPc(30nm)/NPD(40nm)/Alq3(60nm)/LiF/Al. Instead of using the thermionic emission current in the interface, the current across internal interfaces is in analogy to the hopping process of transport. The mobilities are expected to be field dependent in the amorphous organic materials and given by Poole-Frenkel form. The recombination rate of free carrier is given by the Langevin form. The density of singlet exciton is calculated by considering their generation, diffusion, and decay. The I-V characteristics, carrier distribution, electronic field, exciton density of a device are calculated. Electronic is injected from the cathode and hole from the anode. There are accumulations of hole and electron at the heterojunction (30nm and 70nm) due to the barrier between different materials. Recombination rate is biggest in the interface between Alq3 and NPD as electron and hole are both highest in the interface. The exciton density decreased rapidly near the cathode with the influence of electrode quenching. The Electronic filed distribution are smart change in the first interface (30nm) and distinct increase in other interface (70nm). The simulation results and measured data are in good agreement. The current is accompanied with a much stronger dependence on the applied voltage compared to the ideal SCLC dependence when the applied voltage is bigger than 2.5V.

7599-21, Session 6

Degradation of biopolymer-based thin films

I. Rau, R. Popescu, M. Moldoveanu, A. Meghea, Polytechnical Univ. of Bucharest (Romania); J. G. Grote, U.S. Air Force Research Lab. (United States); F. Kajzar, Univ. d'Angers (France)

An attractive alternative to common organic polymers used in photonics applications is presently represented by the biopolymers, obtained from biological waste. Two biopolymers: collagen and DNA, abundant and renewable attract particular interest. However for practical applications in photonics they have to be functionalized in order to obtain desired properties. Therefore it is necessary an extensive material and optical characterization of pure DNA and collagen, as well as their functionalization with active molecules to get desired linear optical, thermal, photoconducting nonlinear optical properties. The obtained materials require appropriate physical chemical characterization. One of the important factors governing their use is the chemical and photochemical stability.

In this paper we will discuss our results concerning the photo, thermal and chemical stability of thin films made from pure and functionalized biopolymers. The results will be compared with similar studies on synthetic polymers.

7599-22, Session 6

Full-color sensitive photorefractive polymers and compositions

M. Kathaperumal, T. Gu, B. Rachwal, J. Tillema, W. Hsieh, Z. Jiang, O. Siddiqui, D. Flores, D. Padiyar, W. Lin, P. Wang, M. Yamamoto, Nitto Denko Technical Corp. (United States); R. Norwood, N. Peyghambarian, College of Optical Sciences, The Univ. of Arizona (United States)

An abstract will be submitted after getting clearance from our top management at Nitto Denko Technical Corporation. Actually, we were invited to make a INVTIED Presentation at the conference OE103 by one of the program Committee members Prof. Robert Norwood.

7599-23, Session 6

Enhancement of electroluminescent property of ITOLEDs with transparent WO3/Ag/WO3 multilayer anode

K. Hong, S. Kim, K. Kim, J. Lee, Pohang Univ. of Science and Technology (Korea, Republic of)

In this work, we report the enhancement of electroluminescent property of ITOLEDs by using tin oxide (SnO2) buffer layer and transparent WO3/Ag/WO3 (WAW) multi-layer anode. The transmittance of WAW anode as a function of wavelength and sheet resistance with various thickness (10 ~ 25 nm) of Ag layer were investigated by UV-monochromator and 4-point probe. Compare to the 30 nm-thickness Au anode (42 %), the WAW structure showed high optical transparency over 75 % in visible region. When Ag with a thickness of 15 nm is used, the sample (94.5 %)

showed higher transparent property than any other samples. The WAW multi-layer showed low sheet resistance of about 10 Ω/sq. To evaluate the electrical and optical properties of ITOLEDs with SnO2 buffer layer and WAW anode, the L-I-V characteristics was measured. The turn-on voltage decreased from 10.5 to 8.1 V when SnO2 buffer layer was used. The luminance is promoted from 74.5 to 99.8 cd/m2 when Au anode was replaced by WAW multi layers. It is thought that when the SnO2 buffer layer and WAW multi-layer anode was used, holes were effectively injected from anode to organic layer and more light could be extracted through the anode, promoting the internal and external quantum efficiency.

7599-24, Session 6

Electro-optic modulation in optical waveguides written by quasi-solitonic propagation in functonalized photopolymers

H. Ibn El Ahrach, Institut de Physique et Chimie des Matériaux de Strasbourg (France); S. Kamoun, Ecole Nationale Supérieure de Chimie de Paris (Tunisia); A. Jemal, Faculté des sciences de Sfax (Tunisia); J. Vola, L. Mager, A. Fort, Institut de Physique et Chimie des Matériaux de Strasbourg (France)

The Light Induced Self Written (LISW) waveguide propagation in photopolymerizable materials has allowed the fabrication of permanent optical waveguides with lengths up to a few millimetres. This process has been applied to the fabrication of tips for Scanning Near Field Microscopy (SNOM) or to the connexion of optical fibers and integrated optical waveguides (SOLNET process). The great advantage of this technique is that the connexion problem is greatly simplified. Up to now, the demonstrated devices have only been passive ones. But, the photopolymerizable material can be easily functionalized by the simple addition of small molecules with specific properties (fluorescence, non linear optical responses...). It is therefore possible to insert an arbitrary function in an optical circuit by through a proper formulation of a connecting part and then built an active device. We present here the functionalization of the LISW waveguide by 4'-n-pentyl-4- cyanobiphenyl (5CB). This molecule is a nematic precursor, but here the amount of 5CB as been kept in the solubility limits to avoid phase separation and light diffusion. The molecule exhibits a permanent dipole and a linear polarization anisotropy enabling the modulation of the guest/host material birefringence by the application of an electric field. The efficiency of the material and the performance in terms of phase modulation are measured in an interferometric setup. This demonstration of phase modulation opens the path to other devices such as TE-TM mode converters and polarization based electro-optic intensity modulators.

7599-25, Session 6

Optical, photoluminescent, and photoconductive properties of functionalized anthradithiophene and benzothiophene derivatives

W. E. B. Shepherd, A. D. Platt, G. Banton, Oregon State Univ. (United States); M. A. Loth, J. E. Anthony, Univ. of Kentucky (United States); O. Ostroverkhova, Oregon State Univ. (United States)

We present optical, photoluminescent (PL), and photoconductive properties of functionalized anthradithiophene (ADT) and benzothiophene (BTBTB) derivatives and their composites. Solution-deposited ADT films exhibit charge carrier mobilities of over 1.5 cm^2/(Vs), high PL quantum yields, and high photoconductivity at room temperature. We show molecular arrangement and intermolecular interactions significantly contribute to (opto)electronic properties of thin films of these pi-stacked materials. In addition, these properties can be effectively manipulated through the addition of guest molecules to a host material. In particular, exciton and charge carrier dynamics can be varied, even at picosecond time-scales after photoexcitation, using a competition between photoinduced charge and energy transfer in a guest-host system.
To better understand these processes at a molecular level, we apply single-molecule fluorescence spectroscopy (SMFS) to probe effects of intermolecular interactions and external parameters on the molecular properties. In particular, we demonstrate that ADT molecules exhibit high enough quantum yields and photostability to be imaged on a single-molecule level at room temperature. Moreover, we show that brightness and stability of single ADT molecules depend on the host matrix (for example, brightness improves in a crystalline BTBTB, as compared to poly(methyl)methacrylate (PMMA), thin film) and are comparable to those of the best fluorophores utilized in SMFS. Finally, we analyze performance of individual ADT molecules depending on their local nanoenvironment (which includes arrangement of the surrounding host molecules and the presence of other guest molecules in the vicinity of the molecule under study), at various temperatures and applied electric fields.

7599-26, Session 7

Polymer nanofibers and nanowires for VLSI photonic circuit application

E. Lee, OPERA (Korea, Republic of) and Inha Univ. (Korea, Republic of)

We report on the design and fabrication of polymer-based nanofibers and nanowires for VLSI photonic integrated circuit applications. We fabricate them either by conventional batch process or by imprinting technique. They are made in different cross-sectional shapes and sizes of different optical and physical properties. We examine and characterize how the lightwave propagates through the nanofibers and nanowires by using near-field scanning microscopic (NSOM) method. For the study of VLSI photonic integration application, polymer wires are coupled with various nano-scale wires and devices, such as directional couplers, photonic crystals, micro-rings, and micro-disks, made of silicon and plasmonics. We analyze the lightwave propagation characteristics and examine the optical mismatch problems between each coupled wires or devices. We analyze the effective index of the nanowires and calculate the mode field of the individual nano-waveguide. We also calculate the coupled eigen-modes of even and odd eigen-modes directly to analyze the coupling between two nano-wires. Using these results, we have designed and fabricated some of the basic functional and integrated devices, such as directional couplers, MMI devices, optical filters, wavelength splitters, power splitters, triplexers, and sensors. We also fabricated some light-emitting polymer nanofibers and nanowires and will discuss their characteristics and functionalities in the presentation.

7599-27, Session 7

Development print-like-fabrication techniques for distributed feedback solid state dye lasers with multiple-layered structure

S. Omi, Kyushu Univ. (Japan)

Novel fabrication technique of organic solid state waveguide dye laser has been developed for easy fabrication that and integration on surface. Solid state dye lasers have advantages such as easy fabrication and wide coverage in visible/NIR spectral region.

Houever, the spin-coating technique adopted generally for integration is not suitable for hybrid and mulple-layered dye doped organic waveguide. Our group has studied fabrication technique of polymer waveguides based on dispensing and drawing scheme.

Recent technique can fabricate qualified and multiple-layered waveguides with refractive index controlling of 0.001 resolution just in the limited area.

It can make more complicated laser system possible in comparison with our previous technique, and, 4-layered waveguides with methacrylate co-polymers were fabricated, and this Quasi-Mode-Coupled DFB laser array demonstrated improved performances.

The QMC laser has dual-cores structure that consists a dye doped core with higher index and a non-doped core with lower index.

QMC can control coupling coefficient between the pump and the laser waveguide, so the absorption length can be optimized to the waveguide length by not only the dye concentration but also other parameters such as the thickness of laser/pump layers and the refractive index.

7599-28, Session 7

The effect of trans-stilbene unit in the compensation of birefringence of poly(methyl methacrylate) in the random copolymerization method and anisotropic molecule dopant method

H. Shafiee, A. Tagaya, Y. Koike, Keio Univ. (Japan)

No abstract available

7599-29, Session 8

Synthesis of donor-acceptor-donor two-photon absorbing fluorene derivatives

S. Yao, H. Ahn, K. D. Belfield, Univ. of Central Florida (United States)

Both the magnitude and the wavelength of two-photon absorption (2PA) need to be taken into account for developing materials for 2PA applications, such as two-photon fluorescence imaging, because the most efficient output wavelength of the Ti:sapphire laser source is around 800 nm. However, there are not many fluorene derivatives reported to have peak 2PA at ca. 800 nm. One approach to achieve large two-photon absorptivity near this wavelength involves donor-acceptor-donor (D-A-D) type chromophores. However, the effective acceptor groups in this chromophore type are quite limited. Here a series of donor-acceptor-donor (D-A-D) type fluorene derivatives were synthesized with acceptors that have not been reported before. The linear and nonlinear optical properties, including UV-vis absorption spectra, fluorescence spectra, fluorescence anisotropic spectra, and two-photon fluorescence exciation spectra of these D-A-D compounds were determined and compared with their donor-acceptor counterparts. These compounds show much higher 2PA cross sections, with the highest 2PA cross section >3000 GM at ca. 800 nm excitation wavelength. Further structure-property relationships of these chromophores will be discussed according to these results.

7599-30, Session 8

Maximizing two-photon absorption cross section within few essential state models

A. K. Rebane, M. Drobizhev, N. Makarov, E. Beuerman, Montana State Univ. (United States)

Increasing the efficiency of instantaneous two-photon absorption (2PA) of organic chromophores in a broad range of laser irradiation wavelengths is an important task for a number of practical applications including biological imaging, optical data storage and optical power limiting. It is well known that 2PA cross sections depend on the molecular parameters such as transition dipole moments, permanent dipole moments and transition frequencies. In practice, however, such exhaustive information is hardly available, at least not for all energy levels. So-called few essential energy level models are applied when lowest excited energy levels contribute the most part of the nonlinear response, and the higher energy levels can be neglected.

Here we validate the few essential energy level approach by collecting absolute 2PA spectra of a broad variety of chromophores, including substituted stilbenes, porphyrins, phthalocyanines, corroles, Pt-acetylides, and compare the experimental values with those estimated based on two- or three essential state model. The lowest dipole-allowed transition is most cases well quantitatively described by two-level model. In case of strongly dipolar molecules, e.g. some charged dyes, the cross sections can be as large as 1000 GM in rather broad (several thousand cm-1) bands. Here we extend current study to include higher electronic transitions. To apply quantitative three-level model, we measure transition dipole moments between excited states by using femtosecond transient absorption technique.

We show that even under conditions, when only one or two lowest excited energy levels contribute the essential part of the nonlinear absorption, it is possible to achieve high 2PA cross sections values in broad range of wavelengths, from visible to near-IR.

7599-31, Session 8

Justification of two-level approximation for description of two-photon absorption in oxazine dyes

E. B. Beuerman, N. S. Makarov, M. Drobizhev, A. Rebane II, Montana State Univ. (United States)

High demand in efficient two-photon chromophores requires better understanding of how the structure-to-property relations can be applied for two-photon absorption (2PA). It is usually assumed that for a lowest energy pure electronic transition of non-centrosymmetrical dipolar molecules the maximum 2PA cross section is quadratically related to the permanent dipole moment difference between ground and excited states (DM).

Here we present a systematic approach comparing experimental values of the DM obtained from 2PA cross sections, solvatochromic shifts, and hole burning Stark spectroscopy in a series of Oxazine molecules with slight variations in chemical structure.

We show that the DM values obtained from 2PA cross sections using two-level approximation coincide within the margins of experimental error with those measured previously with Stark spectroscopy. This justifies the two-level approximation for 2PA. However, the values of the permanent dipole difference measured using solvatochromic shifts are systematically larger even considering hydrogen bonding as a cause of additional spectral shifts. The uncertainty in molecular shape, specific associations, major geometric reorganizations of the molecules in the excited state, or quadrupolar effects might be responsible for the disagreement. All abovementioned reasons except for the corrections to the molecular shape are important in the case of low intrinsic permanent dipole differences (DM<5 D), as in the case of Oxazines.

The analysis of few-level model approximation for description of 2PA cross sections allows better insight into the influence of the dipole moments on the strength of 2PA as well as the influence of molecular substituents on the dipole moments

7599-49, Poster Session

Synthesis and photovoltaic properties of a low band-gap polymer based on soluble dithienothiophenes

K. Kim, K. Lee, Hannam Univ. (Korea, Republic of)

Dithieno[3,2-b:2 3 -d]thiophene (DTT) based materials are of particular interest in recent years as active materials in various optoelectronic devices because of their planar geometry and high mobility. However, the drawback on the use of these materials is the poor solubility. In this

context, we synthesized a soluble DTT derivative, 3,5-dioctyldithieno[3,2-b:2 3 -d]thiophene, and prepared a low-band gap conjugated polymer by alternating with 2,1,3-benzothiadiazole derivatives. Due to the long alkyl chains on the DTT backbone, the polymer was solution processable for the fabrication of photovoltaic devices. The synthesis, optical and electrochemical properties and photovoltaic device performance will be presented.

7599-50, Poster Session

Molecular orientation of discotic molecules controlled via self-assembly monolayer films

C. Chiang, Y. Hu, W. Zheng, C. W. Ong, National Sun Yat-Sen Univ. (Taiwan)

Discotic Liquid Crystalline materials have attracted considerable attention due to their sufficiently high carrier mobility, and have been used in many photonic and electric devices such as organic light emitting diodes, photovoltaic cells and organic thin film transistors. To take the devices into practical use, it is critical to control the molecular orientation of discotic liquid crystals (DLCs). In our previous studies, we revealed that surface free energy of the substrate has significantly effects on the molecular stack of discotic molecules when stacking on a solid-state surface. Recently, we have investigated the molecular stack of DLCs on surfaces which were coated with the self-assemble monolayers (SAMs). The DLC used in this study was an in house synthesized compound 2,3,6,7,11,12-hexaoctyloxy-dibenzo[a,c]phenazine (DBP-8), and the silane materials were octadecyltrichlorosilane (OTS) and 3-aminopropyltriethoxysilane (APS). In the present study, SAMs were formed on the clean glass substrates, and the surface energies of substrates were found to be varied greatly. On the substrates modified by APS-SAMs, which possess higher surface free energy, discotic molecules assemble with disk-face-on anchoring; whereas molecules assemble with disk-edge-on anchoring when stacking on the OTS-SAMs, which possess lower surface free energy. The initial observation also revealed the capability to imprint specific patterns of discotic molecular orientation on the substrate surfaces via silanes modifications.

7599-52, Poster Session

Luminance and heat uniformities of large-area OLED light sources

J. Park, J. Jang, C. Park, J. Lee, G. Kim, Korea Institute of Industrial Technology (Korea, Republic of)

Recently, white organic light-emitting diodes (WOLEDs) have attracted much attention for their potential applications in flat panel lightings and backlight units of flat panel displays. For those applications, the fabrication of large-emission-area WOLED panels is essential. However, many issues are involved in the fabrication of large-area OLED panels such as a short circuit, hot spot, heat generation, low luminous intensity, non-uniformity of light emission, etc. In this work, we have investigated the effect of an auxiliary metal (chrome) electrode in association with a device configuration on the luminance and heat uniformities of a large-area (15×15cm2) white OLED. It has been found that the auxiliary metal grids make the current distribution highly homogeneous over a large area. Even so, however, the luminance uniformity has been shown to be significantly degraded when the vertical resistance of OLEDs is relatively low, demonstrating that the ratio between the device thickness (i.e., vertical resistance of OLEDs) and the width of the auxiliary metal lines (i.e., effective horizontal resistance of TCO anode) is the key design parameter. Though the luminance uniformity is shown to be degraded with increasing bias current (namely, the OLED panel with the 200-µm-wide metal lines exhibits the luminance uniformity as high as 90% at 200mA and 85% at 500mA), an OLED panel with wider auxiliary metal lines exhibits higher luminance uniformity at higher bias current and generates higher luminance over a large area. Moreover, the heat uniformity is shown to be enhanced by optimizing an array of the auxiliary metal grids. In design of large-emission-area OLED panels, however, much care is taken on the selection of the width of the auxiliary metal lines since the gross emission area is decreased with increasing metal coverage.

7599-53, Poster Session

Synthesis and electroluminescent characteristics of carbazole-based copolymers

S. Nam, Pusan National Univ. (Korea, Democratic Peoples Republic of); I. H. Jung, Korea Advanced Institute of Science and Technology (Korea, Democratic Peoples Republic of); E. Jeong, W. Lee, S. Choi, H. Y. Woo, Pusan National Univ. (Korea, Democratic Peoples Republic of)

Continuous attention has been paid to polymeric light-emitting diodes (PLEDs) due to their good processability, flexibility, low power consumption, fast response time, and facile color tenability, etc.

Especially, polycarbazoles are under extensive investigations for PLEDs applications because of their good hole-transporting property, low-highest occupied molecular orbital (HOMO) level, thermal-, chemical stabilities, and good solubility in common organic solvents. The facile substitution at N-position of the carbazole moiety provides easy control and improving the solubility and processability of the polymers.

Five Carbazole-based copolymers were synthesized and their detailed light-emitting characteristics were studied. The emission color was fine-tuned over the entire visible region by incorporating narrow bandgap comonomers into the polycarbazole backbone. Synthetic approach involves the Suzuki copolymerization of 9-(1-octyl-nonyl)-2,7-bis-(4,4,5,5-tetramethyl-[1,3,2]dioxaborolan-2-yl)-9H-carbazole and electron deficient units such as 4,7-bis(2-thienyl)-2,1,3-benzothiadiazole (DBT), 2,1,3-benzothiadiazole (BT), 2,1,3-benzoselenadiazole (SeBT), 2,5-bis(4-hexyl-thiophen-2-yl)-thiazolo[5,4-d]thiazole (TZ) and 9,9-dioctyl-9H-fluorene (Fl).

By changing the comonomers, the bandgap of the carbazole-based copolymers were changed. As a result, PL emission was successfully fine-tuned from red, orange, yellow, green to blue by modifying intramolecular change transfer interaction. The number-average molecular weights (Mn) of the synthesized carbazole-based polymers were determined to be 8,600 g/mol (PDI=2.07) for PC-DBT, 20,000 g/mol (PDI=2.05) for PC-SeBT, 24,000 g/mol (PDI=1.22) for PC-BT, 3,500 g/mol (PDI=1.23) for PC-TZ and 15,000 g/mol (PDI=1.51) for PC-Fl by gel permeation chromatography (GPC) with a polystyrene standard. They show good solubility in common organic solvents such as chloroform, THF, toluene, etc. Their optical, photophysical, electronic properties and EL characteristics of the resulting copolymers will be discussed in detail.

7599-54, Poster Session

Triplet energy transfer and exciton dissociation in phosphorescent dye blended polymer photovoltaic devices

L. Chang-Lyoul, B. Clare Chisu, S. Duk-Il, Gwangju Institute of Science and Technology (Korea, Republic of); S. Han, Mokpo National Maritime Univ. (Korea, Republic of); N. C. Greenham, Y. Xudong, Univ. of Cambridge (United Kingdom)

The triplet exciton dynamics of conjugated polymer in phosphorescent dye blended polymer films has been investigated by photo-induced absorption spectroscopy. The effect of triplet excitons on the photovoltaic performance is also investigated. The 2,3,7,8,12,13,17,18-octaethyl-21H,23H-phophineplatium (II) (PtOEP) was used as a phosphorescent dye, poly[2-methoxy-5-(2'-ethyl-hexyloxy)-1,4-phenylene vinylene] (MEH-PPV) and poly(3-hexylthiophene-2,5-diyl) (P3HT) were used as the conjugated polymer and 1-(3-methyloxycarbonyl) propy(1-phenyl [6,6]) C61 (PCBM) was

used as an electron acceptor. Steady-state photoluminescence spectra and photoinduced absorption of PtOEP blended MEH-PPV films show that PL quenching of the MEH-PPV and PtOEP phosphorescence is originated from the exciton dissociation and triplet-triplet energy transfer from PtOEP to MEH-PPV. However, the PtOEP blended P3HT film shows no PL quenching of P3HT and PtOEP and no change of photoinduced absorption spectrum shape and intensity. The MEH-PPV : PCBM photovoltaic device with PtOEP shows the better device performance than that without PtOEP. The enhancements in quantum efficiency and overall device performance are mainly originated from the increase of photocurrent, attributed to the longer lived triplet excitons. The results suggest that triplet excitons can be used for improving the efficiency of polymer photovoltaic devices.

7599-55, Poster Session

Molecular weight dependence on bandgap tuning of PS-P2VP photonic

S. Shin, S. Kim, D. M. Shin, Hongik Univ. (Korea, Republic of)

Photonic crystals with tunability in the visible or near-infrared region have drawn increasing attention for controlling and processing light for active components of future display. To compare the molecular weight effect on band gap, we prepared polystyrene-b-poly(2-vinyl pyridine) (PS-b-P2VP) lamellar films which are hydrophobic block-hydrophilic polyelectrolyte block polymer among them the one have 190 kg /mol-b-190 kg/mol and the other have 57 kg /mol-b-57 kg/mol. The result of UV-visible absorption spectra and polarizing microscopy supported that molecular weight dependence on band gap tuning of PS-P2VP photonic gel.

7599-56, Poster Session

The study of photosensitive polyimide containing cinnamate derivatives on photo-alignment of liquid crystal

S. Kim, S. Shin, D. Shin, Hongik Univ. (Korea, Republic of)

Polyimide film containing cinnamate groups was investigated for photo-alignment of liquid crystal (LC) by irradiation of linearly polarized ultraviolet lights. We study the effects of the methoxy cinnamate groups on photo-alignment of LC. The anisotropy of the polyimide film induced by irradiation of linearly polarized UV light. 4-Methoxy cinnamic acid, 2-methoxy cinnamic acid and 2,5-dimethoxy cinnamic acid were irradiated and the absorption spectra were obtained with irradiation time in solubilized in chloroform to understand the effect of the structural difference in photo-reactivity. 4-Methoxy cinnamic acid and 2-methoxy cinnamic acid have different isosbestic points 268 and 250nm, respectively and 2,5-dimethoxy cinnamic acid has no isosbestic point. LCD device was fabricated and UV-visible spectroscopy was used to confirm direction of alignment.

7599-57, Poster Session

Improvement in life time of green-organic light-emitting device

H. Ki, S. H. Kim, D. G. Kim, H. J. Kim, M. Han, H. Kim, Korea Photonics Technology Institute (Korea, Republic of); K. J. Hong, Gwangju Univ. (Korea, Republic of)

Organic Light Emitting Device (OLED) has a characteristic to change the electric energy into the light when the electric field is applied to the organic material. OLED is currently employed as a light source for the lighting tools because research has extensively progressed in the improvement of luminance, efficiency, and life time. OLED is widely used in the plate display device because of a simple manufacture process and high emitting efficiency. In this research, we have proposed a novel encapsulation method with simple process in comparison with conventional encapsulation technique. Here, the encapsulation film of silicon dioxide is steady for external environment because this can be designed to cover the emitting organic material from air. Silicon dioxide of 220 nm was deposited by Plasma Enhanced Chemical Vapor Deposition and etched by Reactive Ion Etching system. Then, Alq3 was used as a material to emitting layer in the green OLED and TPD in the Hole Transportation Layer was used for the harmonious transportation of Hole. Also, LiF metal was utilized for Electron Transportation Layer. Operating voltage of green OLED with encapsulation film was 5.5 V and luminance was 7.370 cd/m2 at the applied voltage of 14.5 V. Luminance was measured with 40 hour intervals at the air-exposed condition. After 400, 1,000, 1,600, and 2,000 hours, luminance of green OLED were 7,366, 7,200, 6,210, and 5,100 cd/m2, respectively. Luminance of green OLED doesn't decrease until 2,000 hours. As a results, proposed encapsulation technique can increase the life time of green OLED.

7599-58, Poster Session

Integrated electro-optic devices of melt-processable single-crystalline organic films

H. Figi, M. Jazbinsek, C. Hunziker, M. P. Koechlin, P. P. Gunter, ETH Zürich (Switzerland)

Organic electro-optic materials are the materials of choice for high speed optical modulators with modulation frequencies greater than 100 GHz. This is due to the large electro-optical effects observed and a low material dispersion of the dielectric constant resulting in a very small velocity mismatch between the optical and electrical waves. However, the implementation of organic materials into real devices has been hindered by several factors such as an insufficient long-term thermal and photochemical stability of the widely investigated poled polymers or the lack of available structuring techniques for the inherently superior organic electro-optic crystalline materials. Here we report on the realization of integrated organic electro-optic single-crystalline Mach-Zehnder modulators by a recently developed melt based channel growth technique. The main fabrication concept is to grow the organic electro-optic single-crystals from the melt directly in pre-structured and electroded waveguide channels, which were obtained by standard optical lithographic techniques and wafer bonding. By this method single crystal structure details with a size below 30 nm have been achieved and the growth of single-crystalline Mach-Zehnder modulators has been successfully demonstrated, where we have chosen DAT2 (2-(3-(2-(4-dimethylaminophenyl)vinyl)-5,5-dimethylcyclohex-2-enylidene) malononitrile) as electro-optic material. The half-wave voltage x length product determined in the DAT2 based Mach-Zehnder modulators has been found to be 78 +/- 2 Vcm for TE-modes and 60 +/- 1 Vcm for TM-modes at a wavelength of 1.55 um. The accuracy and reproducibility of the process allowed also for the realization of the first electro-optic single-crystalline microring resonator in an organic material.

7599-59, Poster Session

Picosecond and nanosecond third order nonlinear optical characterization of Cu and Ni phthalocyanines using Z-scan technique

V. R. Soma, Univ. of Hyderabad (India); A. K. Prasad, Cochin Univ. of Science & Technology (India); T. Surya Prakash, Univ. of Hyderabad (India); G. Lingamallu, Indian Institute of Commerce and Trade (India)

Phthalocyanines and their derivatives are macromolecules with large number of delocalized electrons possessing attractive third-order nonlinear optical (NLO) properties with outstanding applications in the areas of optical limiting and ultrafast all-optical switching [1-4]. For optical limiting applications the potential molecules should possess important qualities such as (1) small linear absorption (2) strong nonlinear (excited-state/reverse saturable) absorption (3) broad spectral

response (d) ability to be doped in glasses/polymers for devices (e) cost-effectiveness and (f) robust design/synthesis strategies. Many of the phthalocyanines investigated recently possess only a mishmash of these characteristics. However, the advantage with these classes of molecules is the versatility with which one can tailor their optical properties. The efforts from material scientists, chemists, and physicists are ensuing for establishing competent molecules with better figures of merit. It is essential that any new molecule should be tested under rigorous conditions with laser pulses of various energies and durations to arrive at the exact figures of merit in each domain. Herein we present our results on the picosecond and nanosecond nonlinear optical studies of Cu(SO3Na)pc and Ni(SO3Na)pc using the Z-scan technique.

7599-60, Poster Session

Pump-probe experiments with 40 femtosecond pulses for characterizing the excited state dynamics of phthalocyanine thin films

V. R. Soma, D. Swain, T. Surya Prakash, Univ. of Hyderabad (India)

Phthalocyanines and their derivatives are macromolecules with large number of delocalized electrons possessing attractive third-order nonlinear optical (NLO) properties with outstanding applications in the areas of optical limiting and ultrafast all-optical switching [1-5]. The advantage with these classes of molecules is the versatility with which one can tailor their optical properties. We have been evaluating the nonlinearities magnitude for a new class of phthalocyanines [1-5]. We are also trying to comprehend the time-response of the nonlinearity in these molecules. A combination of huge nonlinearity and an ultrafast response time is required for translating the materials into devices. Here, we present results on the studies of ultrafast dynamics in phthalocyanine thin films achieved using the pump-probe technique

1. R.S.S. Kumar, S. Venugopal Rao, L. Giribabu, D. Narayana Rao, Chem. Phys. Lett. 447 (2007) 274.

2. S. Venugopal Rao, Proc. SPIE 7197 (2009) 719715.

3. S.J. Mathews, S. Chaitanya Kumar, L. Giribabu, S. Venugopal Rao, Mat. Lett. 61 (2007) 4426.

4. S.J. Mathews, S. Chaitanya Kumar, L. Giribabu, S. Venugopal Rao, Opt. Commun. 280 (2007) 206.

5. R.S.S. Kumar, S. Venugopal Rao, L. Giribabu, D. Narayana Rao, Opt. Mat., 31 (2009) 1042.

7599-61, Poster Session

Improvement of two-photon absorptivities of diarylethene derivatives for two-photon 3D data storage

G. Luchita, S. Yao, H. Ahn, K. D. Belfield, Univ. of Central Florida (United States)

Photochromic diarylethene derivatives are promising candidates for rewritable two-photon 3D data storage application. However, the two-photon absorption (2PA) cross sections of the known diarylethene compounds are very low (<50 GM) and further improvement is highly desired. One approach to improve the 2PA cross section of the photochromic compounds is to increase the conjugation length and introduction of an electron donating end group. In this work, a new, fully conjugated diarylethene derivative possessing a fluorenyl group as π-bridge and diphenylamino group as donor was successfully synthesized and characterized by UV-vis and fluorescence emission, resulting in a much high 2PA cross section (1500 GM at 700 nm). Another approach to improve the two-photon absorptivity of a diarylethene compound is through Förster resonance energy transfer (FRET). Previously, FRET has been observed in a physical mixture of a 2PA chromophore and a commercial diarylethene. However, the distance between two components was not optimized. Here, a 2PA chromophore was closely brought together with a diarylethene derivative through strong H-bonding to increase the efficiency of the energy transfer. The H-bonded self-assembly was characterized by NMR by following the chemical shift change of the H-bond forming protons at different concentrations and photophysical properties were measured. The effect of the hydrogen bonding in the complex upon the ring opening and closing quantum yields, conversions at photostationary state, extinction coefficients, and photoisomerization reaction rates of the diarylethene compound were determined.

7599-62, Poster Session

Comparative study on the effect of thermal annealing on polymer/small molecule blend and copolymer light-emitting devices

P. Rungta, V. Tsyalkovskyy, Y. P. Bandera, M. A. A. Daniele, S. H. Foulger, Clemson Univ. (United States)

The intrinsic deterioration in device performance of polymeric single layer OLEDs that were doped with either a fluorescent or phosphorescent emitter was studied. The specific focus was on the role that thermal aging, at sub-glass transition temperatures of the polymeric layer, has on the phase separation of the active layer. This was accomplished by the rational design of an oxadiazole-containing methylacrylate monomer that was energetically similar to the technological important electron transporting small molecule 2-biphenyl-4-yl-5-(4-tert-butylphenyl)-1,3,4-oxadiazole (tBu-PBD). This monomer was copolymerized with a carbazole containing hole-transporting monomer 2-(9H-carbazol-9-yl) ethyl 2-methylacrylate and the resulting copolymer was utilized as the active layer, with either coumarin 6 or tris(2-phenylpyridine) iridium (III). With both the fluorescent and phosphorescent emitter, the devices exhibited a stable mean luminance of ca. 400 cd/m2 (Coumarin 6) and 800 cd/m2 (iridium) with thermal aging at temperatures ranging from 23 °C to 130 °C, while a comparable poly(9-vinyl-9H-carbazole)/tBu-PBD blend device exhibited a drop from an initial mean luminance of 2500 cd/m2 to 1.6 cd/m2. In addition, with the phosphorescent emitter, the blend devices exhibited a single order reduction in luminance efficiency from 5.26 cd/m2 over the temperature studied; while the comparable copolymer devices exhibited a stable value of 11 cd/m2. The reduction in luminance and luminance efficiency for the blend system was attributed to phase separation in the blend and verified with optical microscopy.

7599-63, Poster Session

Synthesis and characterization of two-photon absorbing organic materials for bio-imaging applications

J. A. Park, T. Kim, K. Lee, Hannam Univ. (Korea, Republic of)

Two-photon absorbing (TPA) materials have attracted considerable attention over the past decade due to the potential use in various applications such as bio-imaging, photodynamic therapy, 3-D microfabrication, etc. The TPA materials to be able to use for bio-imaging, they should contain fluorescent labels with a large two-photon cross-section and high quantum efficiency to enable detection and sensitivity. In the present report, TPA chromophores based on donor-pi-donor system have been synthesized. These materials are designed to be miscible in biological environments. The synthesis, linear and nonlinear optical properties and fluorescent behavior in a living cell membrane will be reported.

7599-32, Session 9

Photonic nanostructures: combined molecular and plasmonic effects (Keynote Presentation)

F. Charra, Commissariat à l'Énergie Atomique (France)

The exploitation of plasmonic local field enhancements to promote the interaction between conjugated molecules and optical fields motivates intensive researches. The objectives are to understand the mechanisms of plasmon-mediated interactions, and to realize molecularly- or atomically-precise nano-structures favouring such phenomena. We have developed a local-probe-free experiment (M-PEEM [1]) to map the electromagnetic field at the nanoscale close to metal structures. We have analyzed the optical response of various metal nano-objects and evidenced strongly coupled modes.[2] A particularly interesting geometry is that of a nano-scale gap between two metallic objects, as present between the tip and the sample in STM.[3] Such a geometry is ideally suited to exhibit simultaneously field enhancement and antenna effects. Moreover, it permits to insert molecular systems in the junction, in particular through self-assembly. The analysis of current- or field-induced photonic processes in the junction of a STM operating in an organic environment offers new insights into elementary mechanisms. We have studied the response of self-assembled metal particles [4] and -conjugated organic systems [5]. Time-resolved [6] or nonlinear [7] processes may be exploited.

1. Douillard et al, J. Appl. Phys. 2007.
2. Douillard et al., Nano Letters 2008.
3. Kusovaet al, Surf. Science 2008.
4. Silly et al, Phys. Rev. Lett. 2000.
5. Perronet, Ann. Phys. Fr. 2005.
6. Perronet et al, Europhys. Letters 2006.
7. Berline et al, J. Appl. Phys. 2008.

7599-33, Session 9

Symmetry breaking in metamaterials and its optical implications

J. Wu, B. Kang, J. H. Woo, E. Y. Choi, H. Lee, Ewha Womans Univ. (Korea, Republic of); T. Hwang, Y. Park, D. Kim, Yeungnam Univ. (Korea, Republic of)

Systematic symmetry breaking in metamaterials renders the metamaterial a rich system to explore nano-structure of photonic organics.Control of coherent coupling between the closed and open modes allows for a high sensitive monitoring of surfaces. Chiral metamaterials are fabricated and its optical activity characteristics are investigated. In the transmission spectra, there exit two resonances, namely, plasmonic resonance and meta resonance. The meta resonance associated with the chirality exhibits optical activity property such as circular dichroism. Femto-second nonlinear optical response of chiral metamaterials also will be discussed.

7599-34, Session 9

Photonic crystals in photosensitive polymers: fabrication techniques and optical transfer function

A. Schlösser, C. Müller, F. Büchau, S. Emec, S. Orlic-Elschner, Technische Univ. Berlin (Germany)

A new approach for the generation of light-induced three-dimensional photonic crystals is presented. Using a holographic volume recording technique up to six collimated laser beams generate three-dimensional interference patterns. These are transferred into periodic 3D structures in an organic photopolymer layer. The use of holographic multiplexing techniques allows the realization of any crystal configuration.

We present a holographic exposure setup for flexible fabrication of various types of photonic crystals. Transmission of light through the generated photonic crystals and optical transformations are investigated in an appropriately designed analysis setup.

The novel fiber based recording setup features 405nm laser wavelength and variable interference geometry, therefore allowing for a wide range of crystal symmetries and periodicities. Applying multiplex exposure techniques and optimized scheduling photonic crystals with fcc symmetry have been realized in commercial photopolymers with thicknesses up to 300 µm.

Upon exposure to light these crystals show Bragg-selective response. Far-field diffraction patterns correspond to spatial and spectral optical filtering functions of the photonic crystal.

For characterization of different 3D photonic crystals regarding their basic diffraction properties a versatile optical imaging system has been designed. Based on CCD-camera imaging this setup produces the full 4D optical transfer function via angular and spectrally resolved measurement of transmitted and diffracted light. Results from these analyses are presented for different 3D photonic crystals. The results are also used in optimizing the exposure process and parameters.

7599-35, Session 9

Rational design of molecular self-assemblies on surfaces: towards applications in nanophotonics

A. Attias, D. Bléger, F. Mathevet, D. Kreher, Univ. Pierre et Marie Curie (France); G. Metgé, L. Douillard, C. Fiorini-Debuisschert, F. Charra, Commissariat à l'Énergie Atomique (France)

In order to create surface patterns, we developed an original approach allowing the exact positioning of (photo)active molecules on the substrate. We have realized subwavelength-sized photon sources. Here we present a strategy aimed at the decoupling of molecules from the surface, by lifting photoactive entities a few Å above the surface while maintaining the lateral organization of the array. This is achieved by using 2-level based building blocks. While the first level allows the precise organization of the building blocks on HOPG at the solid-liquid interface at room temperature, the second level is a photoactive compound, namely a chromophore. This strategy results in the precise organization of chromophores arrays a few Å above the conducting surface, as determined by scanning tunneling microscopy (STM), opening interesting perspectives for applications in nanophotonics.

7599-36, Session 9

Novel cyanoporphyrazine ytterbium and vanadium complexes for photonic and biophotonic applications

L. G. Klapshina, Razuvaev Institute of Organometallic Chemistry (Russian Federation); W. E. Douglas, Univ. Montpellier II (France); I. S. Grigoryev, E. Y. Ladilina, Razuvaev Institute of Organometallic Chemistry (Russian Federation); M. V. Shirmanova, Nizhny Novgorod State Medical Academy (Russian Federation); A. I. Korytin, Institute of Applied Physics (Russian Federation)

A series of new vanadyl and ytterbium(III) cyano-substituted porphyrazine complexes has been developed. The vanadyl octacyanoporphyrazine complex was found to be a rare example of a highly-absorbing dye combining significant electron-acceptor properties with a band gap unusually narrow for an organic semiconductor (ca. 1.1 eV). A novel highly emissive ytterbium complex forming a disordered polynuclear coordination polymer network including a macrocyclic structure and metal cations bridged through the nitrile nitrogen atoms has been prepared. It is readily soluble and is compatible with a variety of polymeric matrices giving doped polymeric glasses and films which are highly luminescent in the biologically relevant optical window covering the visible and NIR range (640-1000 nm). In addition, doped polymeric glasses and films highly emissive at the telecommunication wavelength (1540 nm), including a composition cconsisting of an equimolar ratio of the novel ytterbium complex and a per se non-luminescent erbium chelate, have been obtained. The complex is found to be an extraordinarily strong sensitizer of NIR Er3+ emission. Furthermore, it was tried as a fluorescent marker in a mouse tumor model. By using a fluorescence transilluminative imaging setup, planar images of mice were obtained in vivo and the distribution of the complex in the living organism over time was shown. We demonstrated selective complex accumulation in the tumor. The materials developed based on novel porphyrazine vanadyl and ytterbium complexes have promising potential in modern photonic and optoelectronic devices such as photovoltaic cells, IR amplifiers in photonic integrated circuits, NIR emission sources in telecommunication defence applications and bio-imaging.

7599-37, Session 10

Femtosecond two-photon absorption measurements based on accumulative photo-thermal thermal effect and the Rayleigh interferometry

L. Rodriguez, H. Ahn, K. D. Belfield, Univ. of Central Florida (United States)

The high repetition rate (HRR) of a laser causes an accumulative heating in the sample. This heating can be produced by absorption of one or two photon, generating a distribution of temperatures that consequently produces a change in the spatial distribution of the refractive index. The induced thermal lensing (TL) distorts the wave front of the laser beam at the exit plane of the sample. By measuring this distortion the nonlinear absorbance can be estimated. Despite its intrinsic sensitivity and experimental simplicity, the TL technique requires accurate data on geometrical parameters in order to estimate . In addition to TL, interferometry provides accurate measurements of linear or nonlinear optical properties with knowledge of fewer experimental parameters. Hereby, we propose an approach that combines the sensitivity of TL and the accuracy of the interferometry. It is based on a modified Rayleigh interferometer and the accumulative photo-thermal effect induced by a HRR laser. The proposed technique consists of determining beta from the sample by inducing an accumulative TL and measuring its effect on the phase shift of an interference pattern. The technique has the following advantages: a) simple experimental setup, b) total absence of mechanical movements of the sample during the measurement, c) fast recording and processing of the experimental data, and d) good sensitivity in the measurement of small phase shifts in fluorescent or non-fluorescent media.

7599-38, Session 10

Photostability enhancement studies on zwitterionic chromophores for nonlinear optics

S. G. Raymond, S. Janssens, M. Do, G. V. M. Williams, D. Bhuiyan, A. J. Kay, Industrial Research Ltd. (New Zealand)

Nonlinear optical chromophores are promising materials for a variety of applications ranging from optical communication to THz generation and detection. [1-3]. They offer a number of advantages over inorganic compounds (e.g. LiNbO3) including much higher electro-optic coefficients [4], lower drive voltages, lower refractive indices and the ability to be processed into a variety of geometries for applications such as wave-guiding. The photostability of the active polymer materials is a crucial factor as photo-degradation occurs when organic NLO polymers are exposed to light for long periods of times. It is important to understand the different photodegradation processes and to be able to develop strategies to reduce the photodegradation quantum efficiency.

We report in this paper the results from optical measurements and modelling of host-guest films containing amorphous polycarbonate and an organic chromophore, which has a high 2nd order nonlinear optical figure of merit [5]. The main photodegradation process in these materials is oxygen-mediated and the photodegradation quantum efficiency depends strongly on the oxygen concentration.[6] We have comprehensively studied the effect of incident power on the stability of these thin films. We will also present the results for incorporating singlet oxygen quenchers within the polymer matrix.

References

[1] Y. Shi, C. Zhang, H. Zhang, J. H. Bechtel, L. R. Dalton, B. H. Robinson, and W. H. Steier, Science 288, 119 (2000); H. Ma, A. K.-Y. Jen, and L. R. Dalton, Adv. Mater. 14, 1339 (2002).

[2] A. Schneider, M. Neis, M. Stillhart, B. Ruiz, R. Khan, and P. Günter, J. Opt. Soc. Am. B 23, 1822 (2006)

[3] A. M. Sinyukov, M. R. Leahy, L. M. Hayden, M. Haller, J. Luo, A. K-Y. Juen, and L. R. Dalton, Appl. Phys. Lett. 85, 5827 (2004).

[4] Hu Kang et al., J. Am. Chem. Soc. 129, (2007), 3267; Tae-Dong Kim et al., Adv. Mater. 18, 2038 (2006).

[5] A. J. Kay and A. D. Woolhouse, Y. Zhao, and K. Clays, J. Mater Chem. 14, 1321 (2004).

[6] S. G. Raymond, G. V. M. Williams, B. Lochocki, M. D. H. Bhuiyan, A. J. Kay, and J. W. Quilty, J. Appl. Phys. 105, 113123 (2009).

7599-39, Session 10

Nonlinear transmission using highly nonlinear Bragg mirrors

X. Zhu, College of Optical Sciences, The Univ. of Arizona (United States); J. Wang, College of Optical Sciences, The Univ. of Arizona (United States) and TIPD LLC (United States); P. Lau, D. Nguyen, College of Optical Sciences, The Univ. of Arizona (United States); R. A. Norwood, College of Optical Sciences, The Univ. of Arizona (United States) and TIPD LLC (United States); D. Steeves, B. R. Kimball, U.S. Army Soldier Systems Ctr. (United States); N. N. Peyghambarian, College of Optical Sciences, The Univ. of Arizona (United States) and TIPD LLC (United States)

Nonlinear transmission upon the formation of an optically induced photonic band gap (PBG) is demonstrated by using periodic layers of optical polymers doped with highly nonlinear transition metal oxides. The refractive indices of the alternating layers are designed to be close and no PBG is formed at low power density. Under high power illumination, the index difference becomes large because of the high optical nonlinearities of the transition metal oxides. Consequently, nonlinear transmission is accomplished with the formation and the broadening of the PBG. Compared to typical optical limiters based on a PBG approach, our devices provide a large dynamic range and a broad operation wavelength range. The experiments on a nonlinear Bragg mirror consisting of only 4 pairs of PVA:Co3O4-PVK, each with a layer thickness of 90 nm, show a linear transmittance of greater than 50% throughout the visible, and nonlinear transmission for a 10 ns laser pulse at 523 nm with a threshold of 30 mJ/cm2 and a minimum transmission of about 10%. The minimum transmission reduces to 5% for a 12-pair device. Improving the uniformity of each layer and adding more pairs can result in even lower transmission at high intensities. The threshold can be further reduced through precise design and control of the thickness of each layer. The device and material approach is promising for applications such as protection for broadband detectors and human eyes. This work is supported by the US Army Natick Center and the US Army Research Office MURI through the University of Central Florida under contract/grant 50372-CH-MUR.

7599-40, Session 10

Symmetry controlled resonance in terahertz anisotropic planar metamaterials

B. Kang, J. H. Woo, E. Y. Choi, H. Lee, Ewha Womans Univ. (Korea, Republic of); T. Y. Hong, J. H. Kim, Yonsei Univ. (Korea, Republic of); J. Wu, Ewha Womans Univ. (Korea, Republic of)

Two dimensional arrays of ring resonators with double splits are prepared to examine the symmetry dependent resonances. The anisotropic resonance of planar metamaterials can be controlled by imbedding a symmetry breaking line in the two dimensional array. The resonance spectrum shows that there exist distinct angular domains in the metamaterials structure. Anisotropic two dimensional oscillator model is introduced to clarify the symmetry dependent resonaces.

7599-41, Session 11

Novel probes for biphotonic bio-imaging

C. Andraud, Y. Bretonnière, O. Maury, Ecole Normale Supérieure de Lyon (France)

We present two different approaches for the design of novel fluorescent probes featuring high two-photon absorption (TPA) cross-sections :

-using the unique luminescence properties of LnIII ions (sharp emission, large Stockes shift, insensitivity to oxygen, and their long excited state lifetime), which triggered the development of time-resolved microscopy for applications in biological imaging, we designed a new family of ligands-based chromophores inducing lanthanides emission by two-photon antenna effect1. Tuning the strength of the donor as well as the length of the -conjugated backbone allowed to optimize 2.

The description of the first two-photon scanning microscopy bio-imaging experiments using these complexes led to consider these complexes as a new generation of molecular probes 3.

-in order to develop efficient probes combining both second-harmonic imaging and two-photon excited fluoresecence microscopies, we proposed a series of novel neutral push-pull probe molecules4, fulfilling the right balance between hydrophobicity and hydrophilicity and for which a good membrane staining, compared to existing probes, could be observed.

1. A. D'Aléo, A. Picot, A. Beeby, J. A. G. Williams, B. Le Guennic, C. Andraud, O. Maury, Inorg. Chem.,47, (2008) 10258., 47, 10258-10268.

2. A. D'Aléo, A. Picot, P. L. Baldeck, C. Andraud, O.Maury, Inorg. Chem.,47, (2008) 10269.

3. A. Picot, A. D'Aléo, P. L. Baldeck, A. Grishine, A. Duperray, C. Andraud, O. Maury, J. Am. Chem. Soc., 130, (2008) 1532.

4. C. Barsu, R. Fortrie, K. Nowicka, J.-C. Vial, P.L. Baldeck, A. Barsella, A. Fort, M. Hissler, Y. Bretonnière, O. Maury, C. Andraud Chem. Comm., (2006) 4744.

7599-42, Session 11

Novel nonlinear transmission of porphyrin complexes containing rhenium selenide clusters

J. Wang, X. Zhu, College of Optical Sciences, The Univ. of Arizona (United States); X. Tu, Z. Zheng, The Univ. of Arizona (United States); R. A. Norwood, College of Optical Sciences, The Univ. of Arizona (United States); D. M. Steeves, B. R. Kimball, U.S. Army Soldier Systems Ctr. (United States); N. Peyghambarian, College of Optical Sciences, The Univ. of Arizona (United States)

Nonlinear transmission is found to be significantly enhanced by introducing heavy metal atoms on the periphery of macrocycle porphyrin complexes via rhenium selenide clusters that are coordinated to four pyridyl groups. Experiments on 5, 10, 15, 20-tetra(4-pyridyl) porphyrin (H2TPyP), Cu(TPyP), [Re6(μ3-Se)8(PEt3)5]4(H2TPyP)(SbF6)8, and [Re6(μ3-Se)8(PEt3)5]4Cu(TPyP)(SbF6)8 using 10 ns laser pulses at 523 nm show that, in contrast to Cu(TPyP) and [Re6(μ3-Se)8(PEt3)5]4(H2TPyP)(SbF6)8 that are saturable absorbers at a low fluence of 1-100 mJ/cm2 and become nonlinear absorbers with a threshold larger than 1000 mJ/cm2 at high fluence, [Re6(μ3-Se)8(PEt3)5]4Cu(TPyP)(SbF6)8 exhibits an excellent nonlinear transmission performance with a threshold as low as 20 mJ/cm2. This work is supported by the US Army Natick Center and US Army MURI through the University of Central Florida

7599-43, Session 11

Numerical modeling of non-Lorentzian two-photon absorption line shape in dipolar chromophore

A. Rebane II, M. Drobizhev, N. S. Makarov, E. Beuerman, Montana State Univ. (United States); C. Nacke, J. Pahapill, National Institute of Chemical Physics and Biophysics (Estonia)

A number of key applications of two-photon absorption (2PA) rely on assumption that the chromophores exhibit practically no one-photon absorption (1PA) at the illumination wavelength, and thus depend on actual line shapes of the 2PA and 1PA transitions. Modeling of realistic (non-Lorentzian) 2PA line shapes is also critical for study of pulse propagation in nonlinear media including optical power limiting.

In this paper we present a new stochastic method, where we numerically solve two-level density matrix equation of motion for the chromophore excited state population with a randomly time-varying transition frequency in external pulse field. As a model compound, we use Styryl 9M, which has high 2PA cross section ~800 GM and where the 1PA and 2PA transitions energies approximately coincide. These known experimental facts indicate large permanent dipole moment difference between the ground and excited states and justify two-level approximation of 2PA.

Our numerical model reproduces quantitatively well both 1PA and 2PA non-Lorentzian line shapes of the lowest dipole-allowed transition of the chromophore. The result is suggesting that the 300 cm-1 spectral shift that is experimentally observed between the 1PA and 2PA maxima is most likely because the permanent dipole moment difference is changing within the electronic transition band.

Our approach can be readily expanded to include three- or more energy levels. The results presented here may be used to explain the line shapes of other third-order nonlinear optical effects.

7599-44, Session 11

Third-order optical nonlinearities and optical limiting properties of triarylmethane dye in liquid and solid media

G. Vinitha, B.S. Abdur Rahman Univ. (India); A. Ramalingam, Anna Univ. (India)

The nonlinear optical response of thermo-optic origin exhibited by Pararosanilin dye at low continuous wave laser powers was studied and optical limiter action based on nonlinear refraction is demonstrated in liquid and solid media. The dye doped polymer (PMMA) films of thickness 0.6 mm and of dye concentrations 0.3 and 0.4 mM were synthesized by thermal bulk free radical polymerization method. The Z-scan technique is used to determine both nonlinear index of refraction n2 and nonlinear absorption coefficient ß. The Z-scan experiments were performed using a continuous wave 532 nm diode pumped Nd:Yag laser beam. The peak followed by a valley-normalized transmittance obtained from the

closed aperture Z-scan data, indicates that the sign of the refraction nonlinearity is negative i.e. self-defocusing. Self-defocusing effect is due to local variation of refractive index with temperature. Hence, origin of the nonlinearity appears to be predominantly thermo-optic. A polarizer -analyzer combination was used to vary the input power for limiting studies. The transmitted output intensity was found to vary linearly with the incident input intensity at very low input intensities, but starts to deviate at high incident intensities. With further increment of the input power, the transmitted intensity reaches a plateau and is saturated at a point defined as the limiting amplitude: (i.e.) the maximum output intensity, showing obvious limiting property. The variation in the output intensity was studied as a function of input intensity for two different aperture sizes, different concentrations, different sample positions and in liquid & solid media and the influence of the aperture size, concentration, sample position and medium on the threshold limit was analyzed.

7599-45, Session 12

Organic-inorganic hybrid materials for photovoltaics

K. Lee, K. K. Jang, P. Prem, S. H. Lee, Hannam Univ. (Korea, Republic of); W. J. Kim, J. Seo, A. N. Cartwright, P. N. Prasad, Univ. at Buffalo (United States)

Quantum dots (QDs) present extremely well defined size dependent spatial quantization, which leads to generation of multiple excitons. When QDs are coupled with efficient charge transfer materials, such as single wall carbon nanotubes (SWCNTs)or polypyrole nanotubes (PPyNTs) or low band gap polymers the exitons can be effectively separated and the electron carried away to harness a current. The versatility of absorption range of quantum dots based on size and material (CdSe, CdTe, CdSe/ZnS)make them ideal choice for charge carrier generation. Low band gap polymers provide excellent conducting domains because of their ability to easily accept and carry charge carriers. The value of the band gap is crucial because it governs the conduction properties of organic materials. These materials have been tested in combination with photo-electron generating components like fullerene derivatives and nanocrystals in conceptual photovoltaic devices and their properties assessed. We continually seek to improve both the material and design side of the devices by improving them from the inputs received from the test devices. Recently we have demonstrated a relative improvement in hybrid polymer composite photovoltaic cells involving P3HT:CdSe nanocrystals by using thermal deprotection processing of t-BOC in the carbamate ligand surrounding the surface of the CdSe nanocrystal. The device performance was investigated as a function of the composition ratio of P3HT/CdSe and the heating temperature. This simple and straight-forward ligand deprotection strategy resulted in almost two orders of magnitude increase in PCE (photo conversion efficiency) due to better charge transport between the closer packed nanocrystals. As this processing could endow totally different solubility of nanocrystals before and after the chemical structural change of the ligand on their surface, this thermal deprotection technique of tBOC moiety in semiconducting nanocrystals can lead to a facile multilayered device fabrication for further photovoltaic device applications.

7599-46, Session 12

Red organic light-emitting devices with low-efficiency roll-off behavior by employing fluorescent-interlayer-phosphorescence emission structure

W. C. Choy, T. Zheng, The Univ. of Hong Kong (Hong Kong, China)

Organic light emitting device (OLED) with a fluorescence-interlayer-phosphorescence emission structure (FIP EML) has been proposed to solve efficiency roll-off issue effectively. Red OLED based on FIP EML exhibiting an improvement more than 20% in luminance efficiency roll-off aspect compared with that of conventional phosphorescent OLED with single EML in 10-500 mA/cm2 range has been demonstrated. Detailed mechanisms have been discussed, and such enhancement should be attributed to the improved balance of charge carriers, the redistribution of excitons in recombination zone, the suppression of non-radiative exciton quenching processes and the elimination of energy transfer loss with the help of FIP EML, which may provide a route to develop efficient OLED for high luminance applications.

7599-47, Session 12

Wavelength resolution improvement on organic photodiodes made by ink-jet technique

Y. Yang, T. Nakamichi, S. Oomi, R. Goto, H. Watanabe, Kyushu Univ. (Japan); M. Era, Saga Univ. (Japan); Y. Oki, Kyushu Univ. (Japan)

In this work, a drop-on-demand piezoelectric ink-jet system has been employed to fabricate a disposable photodiodes as the detectors on the integrated lab-on-chip lasers, due to its advantage as a direct high-precision and cost-effective printing technique for the organic electronic devices. J-aggregated films of 3 cyanine dyes include NK-3989, NK-1952, and NK-2203 doped into a conductive polymer, PEDOT:PSS on the ITO substrate have been made by the ink-jet method. With the thin Al layer on the top of cyanine dye films as the cathode, while ITO substrate as the anode, this orgranic bulk-hetero photodiodes have been demonstrated to be wavelength sensitive under the excitation of a tuneable pico-second laser, which corresponds to the characteristic red-shifted, sharp and narrow J-aggregate absorption peak of each cyanine dye employed. The influence of cyanine dye solution composition, ink-jet fabrication parameters, presence of metal ions and pH value of dye solutions on the J-aggregate formation and also the wavelength sensitivity of the photodiodes have been systematically investigated and the mechanisms involved have been discussed. It is found that by optimizing the dye solution composition and ink-jet fabrication parameters such as UV exposure dose amount, substrate temperature, and pulse voltage, or by introducing ions such as K+ or H+ at the optimized concentration, the wavelength resolution of the photodiodes made by ink-jet method can be improved significantly, for instance, the slope of open voltage as the function of wavelength can be increased from 0.016V/nm to 0.1V/nm and wavelength resolution of less than 0.1nm may be expected.

7599-48, Session 12

Optofluidic distributed feedback dye laser via evanescent gain

W. Song, A. E. Vasdekis, D. Psaltis, Ecole Polytechnique Fédérale de Lausanne (Switzerland)

We demonstrate optofluidic evanescent dye lasers based on two types of solid distributed feedback (DFB) grating cavities- the first order linear DFB gratings which gives in-plane laser emitting and second order circular DFB gratings which gives surface laser emitting. For both of them, the laser mode is confined within the waveguide and experience optical gain via evanescent wave coupling with the dye solution. Benefitting from the solid waveguide cores, stable and narrow linewidth laser output were observed with a large tolerance of fluid refractive indices, which prove the feasibility of integrating fluid evanescent gain dye laser into passive waveguide circuit.

Conference 7600: Ultrafast Phenomena in Semiconductors and Nanostructure Materials XIV

Sunday-Wednesday 24-27 January 2010 • Part of Proceedings of SPIE Vol. 7600

Ultrafast Phenomena in Semiconductors and Nanostructure Materials XIV

7600-02, Session 1

Ultrafast spectroscopy of ensembles and single metal nanoparticles

N. Del Fatti, V. Juvé, H. Baida, D. Christofilos, P. Maioli, A. Crut, F. Vallée, Univ. Claude Bernard Lyon 1 (France)

Ultrafast electron interactions and their modification by size reduction play key roles in the properties of metal nanoparticles. In particular, increase of the electron-lattice energy exchanges have been demonstrated when decreasing the size of noble metal particles. These results were modelled in term of surface-induced modification of the bulk electron interactions for nanoparticles larger than about 3 nm. Investigation of smaller size nanoparticles requires a good control of their interface condition to selectively analyse confinement effects. We will present here ultrafast experiments on noble metal clusters smaller than 2 nm synthesized by laser sputtering. A decrease of the electron-lattice energy exchange rate in the small size regime is observed, in spark contrast with the behavior for large particles. This suggests a change in the nature of electron-lattice interaction, i.e., transition from a solid to a molecular - like behavior.

In these optical studies, particle to particle fluctuations often limit the information extracted from ensemble measurements, especially for non-spherical nanoobjects. With the development of the spatial modulation spectroscopy technique and its coupling with a high sensitivity pump-probe setup, quantitative investigation of the ultrafast response of a single nanoparticle can now be performed. Using this approach we have investigated the ultrafast nonlinear optical response of a single gold nanorod whose geometry is optically characterized via its extinction spectrum. This ultrafast response has been found to be dominated by the optical-Kerr nonlinearity (i.e., the induced change of the nanorod dielectric constant), in full agreement with a theoretical model.

7600-03, Session 1

Ultrafast spectroscopy of phonon dynamics in single-walled carbon nanotubes

J. Kono, Rice Univ. (United States)

Single-walled carbon nanotubes (SWNTs), with their uniquely-simple crystal structures and chirality-dependent electronic and vibrational states, provide a one-dimensional playground for studying the dynamics and interactions of electrons and phonons. During the past several years, a large number of studies have been performed on their basic optical properties through absorption and photoluminescence spectroscopy, both on ensemble and individual SWNT samples, quantitatively elucidating their strongly excitonic optical spectra.

Here, we have studied excited state lattice vibrations in SWNTs with coherent phonon (CP) spectroscopy [1-4]. In CP spectroscopy, CP oscillations are excited by pumping with an ultrafast pump pulse and are detected by measuring changes in the differential transmission using a delayed probe pulse. The CP intensity is then obtained by taking the temporal power spectrum of the differential transmission. The peaks in the power spectrum correspond to CP frequencies [1]. More recently, using femtosecond pump-probe spectroscopy with pulse shaping techniques, we have generated and detected CPs in chirality-specific semiconducting SWNTs [3]. The signals are resonantly enhanced when the pump photon energy coincides with an interband exciton resonance, and analysis of such data provides a wealth of information on the chirality-dependence of light absorption, phonon generation, and phonon-induced band structure modulations.

To explain our experimental results, we have developed a microscopic theory using a tight-binding model for the electronic states and a valence force field model for the phonons [4]. We find that the CP amplitudes satisfy a driven oscillator equation with the driving term depending on photoexcited carrier density. We compared our theoretical results with experimental results on (n,m) mod 3 = -1 nanotubes and found that our model provides satisfactory overall trends in the relative strengths of the CP signal both within and between different mod -1 families. We also find that the CP intensities are considerably weaker in mod 1 nanotubes in comparison with mod -1 nanotubes, which is also in excellent agreement with experiment.

This work was performed in collaboration with J.-H. Kim, K.-J. Yee, Y.-S. Lim, E. H. Hároz, L. G. Booshehri, G. D. Sanders, C. J. Stanton, and R. Saito

References:

1. Y. S. Lim, K. J. Yee, J. H. Kim, E. H. Hároz, J. Shaver, J. Kono, S. K. Doorn, R. H. Hauge, and R. E. Smalley, "Coherent Lattice Vibrations in Single-Walled Carbon Nanotubes," Nano Letters 6, 2696 (2006).

2. J.-H. Kim, K.-J. Han, N.-J. Kim, K.-J. Yee, Y.-S. Lim, G. D. Sanders, C. J. Stanton, L. G. Booshehri, E. H. Hároz, and J. Kono, "Chirality-Selective Excitations of Coherent Phonons in Carbon Nanotubes by Femtosecond Optical Pulses," Physical Review Letters 102, 037402 (2009).

3. J.-H. Kim, J.-G. Park, B.-Y. Lee, D.-H. Lee, K.-J. Yee, Y.-S. Lim, L. G. Booshehri, E. H. Hároz, J. Kono, and S.-H. Baik, "Polarization Anisotropy of Transient Carrier and Phonon Dynamics in Carbon Nanotubes," Journal of Applied Physics 105, 103506 (2009).

4. G. D. SandersG. D. Sanders, C. J. Stanton, J.-H. Kim, K.-J. Yee, Y.-S. Lim, E. H. Hároz, L. G. Booshehri, J. Kono, and R. Saito, "Resonant Coherent Phonon Spectroscopy of Single-Walled Carbon Nanotubes," Physical Review B 79, 205434 (2009).

7600-04, Session 1

Ultrafast carrier-induced change of refractive index in bulk ZnO

M. A. Versteegh, T. Kuis, J. I. Dijkhuis, Utrecht Univ. (Netherlands)

Ultrafast pump-probe reflectivity measurements have been used to study the change in refractive index and carrier relaxation in a bulk ZnO crystal at room temperature for probe energies close to the band-gap and exciton resonance (~3.20-3.45 eV) and a broad range of carrier densities (~1016-1020 cm-3). For high densities, we find that both the exciton and the bandgap resonance disappear from the dielectric function and a maximum observed change in refractive index as large as Δn=-0.44. This demonstrates band-gap renormalization and screening, preventing excitons to form and the creation of an electron-hole-plasma.

Our results are well described by quasi-equilibrium electron-hole plasma theory predicting a strong non-linear dependence of the dielectric function on the carrier density and explaining the observed complex behaviour in the time domain. We find a carrier dynamics that consist of rapid carrier build up during the pump pulse followed by carrier trapping with a time constant of ~0.8 ps and electron-hole recombination decay of ~150 ps. Even better results are obtained taking into account the hot-carriers thermalization in ~1.5 ps. We find the trapping decay to saturate at a density of ~6 1019. This high value is attributed to the large surface to volume ratio in the reflection region and many oxygen surface traps in our sample.

7600-05, Session 1

Optical properties and carrier dynamics of ZnO thin films and quantum structures

Y. Cho, Korea Advanced Institute of Science and Technology

(Korea, Republic of)

Optical properties and carrier dynamics of undoped, p-type doped, and polarity controlled ZnO thin films as well as ZnO-based quantum structures were investigated by photoluminescence (PL), PL excitation, cathodoluminescence (CL), and time-resolved PL spectroscopy. First, we investigated depth-resolved CL properties of excitonic and phonon-assisted transitions in undoped ZnO thin films. A weaker free exciton (FX) emission than its first longitudinal optical phonon replica (FX-1LO) is observed at elevated temperatures (T>150 K) for interior area, while a stronger FX than FX-1LO is seen at all temperatures for top surface area of the sample. The different intensity ratios of FX and FX-1LO depending on the sample depth are strongly associated with extrinsic features of ZnO. Second, optical properties of p-type ZnO epilayers doped with different amounts of phosphorus by radio-frequency magnetron sputtering were investigated. Bound exciton, free electrons-to-acceptors, donor-to-acceptor pair, and deep-level emissions are observed at low temperature for p-type ZnO. We found that phosphorus doping plays an important role in reducing native defects and in generating shallow acceptors in ZnO, leading to good p-type conductivity in ZnO. Finally, we studied optical properties and carrier dynamics of polarity controlled ZnO films grown by Cr-compound intermediate layers. At low temperature, a dominant donor-BX peak at 3.36 eV has been observed in the O-polar ZnO grown on Cr_2O_3 intermediate layer, while a dominant acceptor-BX peak at 3.32 eV has been observed in the Zn-polar ZnO grown on CrN intermediate layer. We also present optical characteristics of ZnO-based quantum structures investigated by linear and nonlinear optical spectroscopic techniques.

7600-06, Session 2

Role of electron-phonon scattering in reducing the LO phonon lifetimes in GaN

J. B. Khurgin, The Johns Hopkins Univ. (United States)

Recent Raman Scattering experiments have show that the lifetimes of optical phonons in GaN gets reduced as the electron concentration increases. Many theries, including LO-phonon - plasmon coupling have been developed to explain this phenomenon, but none of these theories agree very well with the theory. Here we propose an alternative explanation according to which the LO phonons gets scatter by electrons throughout the Brillouin zone where they become Raman inactive. We then examine the implication of these results for the high power GaN transistors.

7600-07, Session 2

Two-photon absorption and multi-exciton generation in lead salt quantum dots

L. A. Padilha, G. Nootz, S. Webster, D. J. Hagan, E. W. Van Stryland, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States); L. Levina, V. N. Sukhovatkin, E. H. Sargent, Univ. of Toronto (Canada)

Understanding the nonlinear optical processes in semiconductor nanostructures leads to possible applications in areas including laser amplifiers, optical switches, and solar cells. Here we present a study of the frequency degenerate two-photon absorption (2PA) spectrum of a series of PbS and PbSe quantum dots (QDs). The influence of the quantum confinement is analyzed using a four-band model which considers the mixing of valence and conduction bands. In contrast to our observations of CdSe QDs, the present results point to an increase of the 2PA cross-section (normalized by the QD volume) as the quantum dot size is made smaller. This is explained by the symmetry between the valence and conduction bands which allows the density of states to remain high even for small QDs.

A detailed study of the ultrafast carrier dynamics of the PbS quantum dots is also presented. Through non-degenerate femtosecond pump-probe experiments we show evidence of multi-exciton generation with quantum yield (number of excitons generated per absorbed photon) over 200% for excitation with hbar.w = 3.1 Eg (where Eg is the bandgap energy).

7600-08, Session 2

Ultrafast dynamics of exciton-polariton condensates in II-VI semiconductor microcavities

K. G. Lagoudakis, B. Pietka, M. Wouters, Ecole Polytechnique Fédérale de Lausanne (Switzerland); M. Richard, Institut NÉEL (France); A. Baas, Ecole Polytechnique Fédérale de Lausanne (Switzerland); R. Andre, D. Le Si Dang, Institut NÉEL (France); B. Deveaud-Pledran, Ecole Polytechnique Fédérale de Lausanne (Switzerland)

Microcavity exciton-polaritons are bosonic quasi-particles with a half-light half-matter nature that occur from the strong coupling between quantum well excitons and cavity photons in semiconductor microcavities. Because of their half-light nature they are four orders of magnitude lighter than the free electrons and can undergo condensation even in temperatures achievable by cryogenic means.

The achievement of polariton condensation has triggered a great interest in the scientific community because of the rich physics of this system and the simplicity of the experimental realization. The short lifetimes of these particles, renders the condensates far out of equilibrium and allows us to probe their behaviour and properties from the emitted luminescence.

Condensation of exciton polaritons in the steady state has been studied in depth by non resonant continuous wave excitation means but the investigation and understanding of the ultrafast dynamics of these systems is still in progress. In the present experimental work, we used the CdTe-CdMgTe microcavity where condensation of exciton polaritons was first reported. This work consists of an ensemble of experimental observations related to the dynamics of population redistribution in real and momentum space, the temporal behaviour of the long range spatial coherence of the polariton condensate and the dynamics of condensed polaritons in a double-well potential. For this purpose we employed non-resonant femtosecond pulsed excitation in combination with an actively stabilized Michelson interferometer and an ultrafast temporal analyser for detection.

7600-09, Session 2

A quantum phase gate via coherent optoelectronic control of an exciton qubit

S. J. Michaelis de Vasconcellos, S. Gordon, D. Mantei, Univ. Paderborn (Germany); D. Reuter, A. D. Wieck, Ruhr-Univ. Bochum (Germany); A. Zrenner, Univ. Paderborn (Germany)

Quantum gates acting on one or more qubits are critical components of quantum processors. As recently shown, excitons in semiconductor quantum dots (QDs) are promising implementations of qubits. In our contribution, we demonstrate the manipulation of the phase of an exciton in a QD by electric signals. Thereby it is possible to implement an optoelectronic one qubit phase gate, controlled by the parameters of a fast electric signal.

We use a single InGaAs/GaAs QD embedded in the intrinsic region of a n-i-Schottky photodiode. The exciton ground state represents a two-level system (i.e. a qubit) and can be coherently prepared by ps laser pulses. The state of the qubit can be determined with high accuracy by photocurrent measurements.

We proof the performance of our quantum gate by a Ramsey-like experiment. Thereby, a coherent state is created by a first laser pulse and probed by a second laser pulse following after a fixed delay time. This setup is highly sensitive to the evolution of the exciton phase between the two optical pulses.

In order to demonstrate the optoelectronic quantum gate operation, we apply a fast electric signal (e.g. a 100 ps pulse) to the photodiode, which manipulates the phase of the exciton coherently. The phase shift depends on the electric pulse area, which is defined as the time integral of the electric gate signal between the ps laser pulse pair. By controlling only the electric signal, we are able to control the quantum phase of the exciton qubit.

7600-10, Session 3

Transient optical gain and carrier dynamics in Ge/SiGe quantum wells

S. Chatterjee, C. Lange, N. S. Köster, Philipps-Univ. Marburg (Germany); H. C. Sigg, Paul Scherrer Institut (Switzerland); G. Isella, D. Chrastina, Politecnico di Milano (United States); H. von Känel, EpiSpeed AG (Switzerland); M. Schäfer, M. Kira, S. W. Koch, Philipps-Univ. Marburg (Germany)

One of the most eagerly sought goals of semiconductor technology is the monolithic integration of photonics and microelectronics on silicon. Intense research efforts are made towards the realization of a laser on Si, amonst them on group IV semiconductors because of their compatibility with Si processing. However, none of the many availible concepts for lasing in silicon are close to beeing commercially availible to date. Here, we demonstrate transient optical gain by population inversion on a sub-100 fs time scale.

We perform pump-probe experiments on a 50x Ge/SiGe multi quantum well structure held at room temperature using tuneable 80fs pulses emitted by an opto-parametric amplifier as a pump and white-light supercontinuum generated directly from a 1kHz Ti:sapphire regenerative amplifier system. The transmitted probe light is spectrally dispersed and detected using a liquid-nitrogen-cooled (GaIn)As photodiode array. The resulting spectro-temporal response shows three distinct temporal regimes. Coherent oscillations dominate at negative times yielding a well-defined time zero. Shortly and during excitation dynamics are observed within the direct conduction band valley while carriers are also scattered towards the indirect minima. After several hundreds of fs to a few ps the carriers decay out of the L valleys on a timescale longer than several 10's of ns. During the first ps, carrier inversion is obtained for significantly strong pumping due to faster intra-valley than inter-valley scattering. The obtained gain values are similar in magnitude to those observed in typical III-V compound semiconductors.

7600-11, Session 3

Localization of photo-excited carriers in semiconductor nanoparticles investigated by time-resolved THz spectroscopy

P. Kuzel, H. Nemec, Z. Mics, Institute of Physics of the ASCR, v.v.i. (Czech Republic)

The optical pump-THz probe spectroscopy provides a sub-picosecond time resolution and a convenient access to the spectral part of the conductivity spectra where the responses of free and localized charge carriers usually fundamentally differ. Up to now the majority of these experiments in semiconductor nanoparticles have been interpreted within the frame of Drude-Smith conductivity model which mimics the carrier localization by introducing predominant backscattering of carriers. However, this model is purely phenomenological and it suffers from internal inconsistencies. We propose a microscopic model of far-infrared conductivity based on realistic physical assumptions. The response of carriers in nanoparticles comprises two contributions which we address separately: the contribution of local (depolarization) fields (accounted for by Maxwell-Garnett or Bruggeman effective medium model) and that directly related to the localization and scattering of carriers. We employ a Monte Carlo method to simulate the carrier motion within nanoparticles and, subsequently, we use the Kubo formula to calculate the far-infrared conductivity. The character of the complex conductivity spectrum is essentially determined by the probability of the inter-particle transport of carriers and by the ratio of the nanoparticle size and the bulk carrier mean free path. We demonstrate our approach on the interpretation of experimental results we obtained with TiO2, ZnO and CdS nanoparticles with various sizes.

7600-12, Session 3

Ultrafast transient absorption studies of single metal and semiconductor nanowires

G. V. Hartland, C. R. Carey, H. Staleva, Univ. of Notre Dame (United States)

Samples of nanomaterials are typically very heterogeneous, with different dimensions, morphologies (branched and unbranched nanowires, for example), and even crystal structures present. This makes single particle spectroscopy a vital technique for studying nanomaterials. In this paper we report the results of single particle transient absorption experiments on metallic and semiconducting nanowires. These experiments are performed by focusing pump and probe beams from an ultrafast Ti:Sapphire laser to a diffraction-limited spot at the sample, and detecting the change in the probe intensity with a lock-in amplifier. The low-noise of Ti:Sapphire lasers makes it possible to detect single nanoparticles. The transient absorption traces for metal and semiconductor nanowires show different photophysics. For the metal wires we observe modulations due to the breathing mode, which is coherently excited by laser induced heating. The vibrational periods depend on the width of the nanowires, whereas, the damping times depend on how the nanowires interacts with their environment. Transient absorption images also provide information about the optical absorption properties of these materials, specifically, the relative intensity of the surface plasmon polariton modes compared to the antenna modes of the wire. For the semiconductor wires the experiments provide information about charge carrier dynamics. CdTe nanowires show fast dynamics, which are attributed to charge carrier trapping at the surface of the wire. In contrast, CdSe wires show almost no dynamics on the time scale of our measurements. The difference between the two materials is consistent with the higher emission quantum yield of CdSe nanowires compared to CdTe nanowires.

7600-13, Session 3

Fast carrier dynamics in new GaAs deep-center laser for 1.3µm-1.5µm fiber optics

J. L. Pan, M. Gupta, Yale Univ. (United States)

INVITED: The ongoing quest for semiconductor lasers with low threshold current has led to the development of new materials (e.g., quantum wells, wires, and dots) and new optical resonators (e.g., microdisks and photonic bandgap crystals). In a novel approach to ``thresholdless" lasers, we have developed a new growth technique for self-assembled deep-centers in the technologically important semiconductor gallium-arsenide. We recently demonstrated the first gallium-arsenide deep-center laser. These lasers, which intentionally utilize gallium-arsenide deep-center transitions, exhibit a threshold current density of less than 2A/cm2 in continuous-wave mode at room temperature at the important 1.54um fiber-optic wavelength. We studied the fast carrier dynamics in the new GaAs deep-center laser. We found that the low threshold current was made possible by fast subpicosecond capture of free holes onto deep-centers. This fast capture of free holes onto deep-centers allowed a fast depopulation of electrons out of the lower energy level of the optical transition. We demonstrated laser action at many wavelengths between 1.2um and 1.6um, which includes fiber-optic wavelengths. The significance is that it has been a long-sought goal to tune the stimulated-emission from the same semiconductor over a wide wavelength range. A semiconductor source of tunable coherent infrared radiation would have many applications, such as fiber-optics, spectroscopy, lab-on-a-chip, chemical species identification, medicine, and dentistry.

7600-14, Session 4

Ultrafast terahertz response of optically excited semiconductor heterostructures

S. W. Koch, M. Kira, Philipps-Univ. Marburg (Germany)

Time resolved terahertz (THz) spectroscopy provides a powerful method to characterize different quasiparticles in optically excited semiconductors. If the central frequency of a strong THz pulse is resonant with the excitonic 1s-to-2p transition, extreme nonlinear effects are observed [1,2] including Rabi flopping, THz high harmonics, and the excitonic dynamical Franz-Keldysh effect. Comparing the THz absorption and transmission spectra of intersubband transitions in semiconductor quantum wells, we clearly identify Fano-like signatures due to the coherent superposition of ponderomotive and THz-current contributions [3] .

[1] J. R. Danielson et al. , Phys. Rev. Lett. 99, 237401 (2007).

[2] S. Leinß et al., Phys. Rev. Lett. 101, 246401 (2008).

[3] D. Golde et al. , Phys. Rev. Lett. 102, 127403 (2009).

7600-15, Session 4

Recent progress on parametric generation and amplification of monochromatic and broadband THz pulses

Y. J. Ding, Lehigh Univ. (United States)

During this presentation, we will review our recent progress on parametric generation and amplification of monochromatic and broadband THz pulses in stacked GaAs plates, GaSe, GaP, periodically-poled $LiNbO_3$, InGaN/GaN quantum wells, InN, GaAs, and InP. We will also illustrate some important applications being realized by using these THz pulses.

7600-16, Session 4

Time-resolved terahertz spectroscopy of hybrid conjugated polymer/CdSe nanorod films

D. G. Cooke, Technical Univ. of Denmark (Denmark); J. Y. Lek, Y. M. Lam, Nanyang Technological Univ. (Singapore); F. C. Krebs, P. U. Jepsen, Technical Univ. of Denmark (Denmark)

Semiconducting conjugated polymers are extremely promising materials for cheap and flexible photovoltaic cells that can be mass produced by inkjet printing techniques. The primary photoexcitation is thought to be a neutral exciton that must undergo dissociation at an interface with a material of higher electron affinity to produce useful charge carriers. In bulk heterojunction (BHJ) films, the polymer and an acceptor material are intermixed such that an exciton meets an interface within its diffusion length. Recently, blends of conjugated polymers and CdSe nanorods have shown promise for hybrid polymer solar cells due to the enhanced mobility of the inorganic nanorods compared to an organic acceptor molecule.

In this work we report time-resolved terahertz spectroscopy measurements of ultrafast carrier dynamics on hybrid CdSe nanorod / poly(3-hexylthiophene) (P3HT) BHJs and compare these to the most commonly used blend of P3HT / phenyl-C61-butyric acid methyl ester (PCBM). Following femtosecond excitation at 400 nm, well above the P3HT π-π^* transition, both films show an improved photoconductivity compared to P3HT alone, consistent with efficient charge transfer. The photoconductivity dynamics show fast, picosecond trapping or recombination in the hybrid blend while the all-organic shows no such loss of mobile charge over ns time scales. The ac conductivity spectra reveals disordered transport consistent with a Drude-Smith model up to 6 THz. We briefly discuss the implications of the Drude-Smith model and its fitting parameters.

7600-17, Session 4

Terahertz and mid-infrared ultrafast spectoscopies for measuring carrier dynamics in nanophotonic materials and molecular switches

E. J. Heilweil, O. Esenturk, T. T. To, National Institute of Standards and Technology (United States); J. S. Melinger, P. A. Lane, U.S. Naval Research Lab. (United States); K. Mosley, C. B. Duke III, T. J. Burkey, The Univ. of Memphis (United States)

Ultrafast pump-probe methods are useful tools for investigating transient electronic and vibrational states of conducting materials and molecular photochemistry. Ultraviolet and visible excitation pulses (<150 fs, <20 uJ, 266-800 nm) with time-delayed broadband terahertz (~500 GHz to 3 THz) and mid-infrared probing pulses (<500 fs, <100 nJ, 5 mm wavelength with ~ 250 cm-1 FWHM) are used to measure linear spectroscopic absorption changes in carrier population signal intensity or frequency shifts of molecular vibrational modes. Picosecond timescale exciton geminate recombination and longer-time free-carrier conduction in semiconductor polymers and nanolayered donor-acceptor films are first discussed. Systems investigated with terahertz probe pulses include thiophene polymers (P3HT, PbTTT) studied as drop and spin-cast films on transparent quartz substrates. The relative conductivity of these films increases with increasing P3HT polymer molecular weight and structural regularity, and the fused rings in PbTTT further increases conduction. Recent studies of nanolayered films containing alternating Zn-pthalocyanine and C60 also yield high conduction since it scales linearly with the number of interfaces and total film thickness.1 These findings parallel results for FET polymer transistor devices pointing to the advantage of optically measuring material properties before device test. Novel molecular structural designs, synthetic routes and detailed dynamical mid-infrared studies of organo-metallic “picometer” optical switches (MnCpR and related Cr(arene)R’ derivatives with pendant bifunctional ligands) undergoing photoinduced dynamics with picosecond response times will also be presented.2

1) O. Esenturk, et al, Polymer Preprints 49(2), 1026 (2008).

2) T. T. To, et al, J. Phys. Chem. A, 113(12), 2666-2676 (2009).

7600-18, Session 4

THz spectroscopy as a new tool to probe hydration dynamics

M. Havenith, Ruhr-Univ. Bochum (Germany)

Hydration water makes comparable contributions to the structure and energy of proteins. A controversial discussion in protein folding concerns the question whether the picosecond dynamics of the hydration water profoundly affects the slower but larger-scale protein motions. In return it is also unclear whether the protein influences the structure and dynamics of surrounding water molecules.

Terahertz spectroscopy is shown to provide a new tool to directly probe the fast sub-psec solvation dynamics, and is able to determine the width of the dynamic hydration layer. For example for the five helix bundle protein lambda repressor we found dynamical hydration layers which extend over more than 20 Å. This is greater than the static structural correlation length as observed by X-ray and NMR techniques. THz studies are able to show the onset of long range water network motions upon dilution of a peptide in water. Further studies revealed that the changes in the absorption coefficient are determined by the hydrophobic or hydrophilic nature of the solute.

Recently we have introduced time resolved monitoring of changes in THz absorption during a biological process such as protein folding: Kinetic Terahertz Absorption spectroscopy (KITA). We found that the rearrangement of the protein-water network motions as probed by Terahertz spectroscopy is participating in the initial steps during protein folding. Furthermore we are now carrying out KITA studies during

enzymatic reaction of MMP with substrates. These studies along with time resolved X-ray studies in the group of Irit Sagi show the importance of the solvent for the initiation of enzymatic reactions.

7600-19, Session 5

Ultrafast hybrid plasmonics

G. P. Wiederrecht, Argonne National Lab. (United States)

Nanoscale materials absorb, propagate, and dissipate energy very differently than their bulk counterparts. Furthermore, hybrid nanostructures consisting of molecular and plasmonic materials with strongly coupled electronic states can produce new optical states and energy flow pathways that provide additional means to controllably delocalize optical energy flow in complex nanostructured systems. In this talk, we discuss our recent studies of electromagnetic coupling and associated temporal dynamics of molecular excitations with plasmonic resonances supported by either localized or extended planar geometries. Recent experimental results and theoretical analysis for observing coherences between molecular excitations and plasmonic polarizations are shown. Advances will explore new directions in ultrafast flow processes in hybrid plasmonic structures, as well as ultrafast addressing of plasmonics-based circuit architectures. Also discussed are recent synthetic advances in the creation of hybrid materials. Ultimately, these studies may impact a range of next-generation optical materials and devices, of relevance to new energy conversion materials, nanoscale photocatalysis, or plasmon-enhanced sensors.

7600-20, Session 5

Ultrafast coherent control of hybridized plasmon polaritons in metallic nanostructures

T. Utikal, Univ. Stuttgart (Germany); M. I. Stockman, Georgia State Univ. (United States); A. P. Heberle, Univ. Stuttgart (Germany); M. Lippitz, Max-Planck-Institut für Festkörperforschung (Germany); H. W. Giessen, Univ. Stuttgart (Germany)

We present a new technique to coherently control ultrafast nonlinear plasmonic effects on a nanometer scale. By using a nonlinear four-photon process (third-harmonic generation) our detection is not limited to the local optical intensity in the system, but additionally supports phase information. The nanostructure under investigation consists of a 1-D gold wire grating on top of a dielectric slab waveguide. The coupling of particle plasmons, optically excited in the wires, to photonic waveguide modes leads to plasmon-polaritonic eigenstates, characterized by long dephasing times [1], whose dynamics can be coherently controlled on a femtosecond timescale.

In the experiment one polaritonic eigenstate is excited by a first sub-8 fs laser pulse (start pulse). A subsequent second pulse (control pulse) follows the start pulse after a few tens of femtoseconds. Dependent on the exact phase delay, the control pulse either stops the polariton oscillation or re-excites it again. A third pulse (probe pulse), which is aligned at a small angle to the start and control pulse, is continuously shifted in time. Photons of the probe pulse together with photons of the start and control pulse create a nonlinear third-harmonic signal depending on the coherently controlled polarization of the polariton.

In addition the experimental data is qualitatively very well reproduced by numerical simulations.

[1] T. Zentgraf et al., Phys. Rev. Lett. 93, 243901 (2004).

7600-21, Session 5

Evidence of terahertz emission from a particle plasmon Schottky barrier

A. Y. Elezzabi, C. Baron, C. J. Straatsma, M. Egilmez, J. A. Jung, Univ. of Alberta (Canada)

It is a well-known consequence of Maxwell's equations that an accelerating/decelerating electron or oscillating space-charge results in the emission of electromagnetic radiation. In this work, we provide evidence that it may be possible to induce a radiating space charge at the Schottky barrier that exists between a metal and a semiconductor. To explore this possibility, we exploit the plasmonic enhanced transmission of terahertz radiation through random ensembles of subwavelength metallic micro-particles. We partially coat Cu particles that have a native oxide on the surface with an Au layer. A semiconductor-metal interface is created on each particle since CuO and CuO2 are p-type semiconductors. For comparison, another sample is prepared where there is no native oxide present between the Cu and Au. The relatively large skin depth of Au at THz frequencies (~ 100 nm) ensures that the external electric field interacts with the interface provided that the Au layer is not too thick. While the physics should be observed in a single metallic interface, the utilization of many particles (and interfaces) allows any electromagnetic effects arising from the interface to accumulate. It is found experimentally that the presence of the oxide layer results in lower transmission losses for the terahertz pulses, suggesting that the semiconductor-metal interface provides additional electromagnetic transport mechanisms. Accordingly, this preliminary work provides strong evidence that a Schottky space charge region can radiate in the terahertz regime.

7600-22, Session 5

Terahertz plasmonics: from surface plasmon polaritons to metamaterials

O. Paul, B. Reinhard, P. Weis, M. Rahm, Technische Univ. Kaiserslautern (Germany); R. Beigang, Fraunhofer-Institut für Physikalische Messtechnik (Germany)

Electromagnetic materials composed of metallic elements which are comparable in size to the operating wavelength or even smaller, have gained a lot of attraction during the last decade. Whereas for structures comparable in size plasmonic effects dominate their properties materials with substructures below the wavelength offer the possibility of creating an effective medium with controllable permittivity and permeability leading to metamaterials with designable properties [1]. In particular, in the terahertz (THz) spectral region such structures can easily be fabricated and the additional losses caused by the metallic elements are still small enough for device applications, like manipulation of the state of polarization of electromagnetic waves or fast switching[2]. These materials pave the way to a wide field of applications from high-sensitive spectroscopy to short-range secure THz communication. From a scientific point of view media not naturally occurring are of interest, in particular, those with a negative index of refraction leading eventually to the perfect lens [3], capable of focusing electromagnetic waves beyond the diffraction limit.

In this contribution we present plasmonic materials as well as metamaterials designed for the construction of highly sensitive sensors and electrically tuneable devices for applications in the THz spectral region. Typical examples for sensitive detectors, materials with a negative refraction and electrically tuneable switches for the THz spectral range will be demonstrated both theoretically and experimentally.

[1] J. B. Pendry, D. Schurig, and D. R. Smith, "Controlling Electromagnetic Fields," Science 312, 1780-1782 (2006).

[2] H.-T. Chen, W. J. Padilla, J. M. O. Zide, A. C. Gossard, A. J. Taylor, and R. D. Averitt, "Active terahertz metamaterial devices," Nature 444, 597-600 (2006).

[3] J. B. Pendry, "Negative Refraction Makes a Perfect Lens," Phys. Rev. Lett. 85, 3966-3969 (2000).

7600-23, Session 5

Metactronics: a new paradigm for optical nanocircuitry

N. Engheta, Univ. of Pennsylvania (United States)

The two fields of metamaterials and plasmonic optics may provide road maps for novel futuristic nanocircuits and wireless nanosystems and sensors that will provide information processing with night at the nanoscale. These may include circuit elements that will work with light instead of drifts of charged particles -- circuits so small that you will be able to fit many of them in a tiny microscale volume (e.g., a cell). What could you do with such optical nanocircuits? Would you be able to use them in wireless gadgets at nanoscales, like a “nanoradio”, that may connect our nanoworlds? Could these tiny optical nanocircuits be coupled with biological entities and thus provide nanoscale sensors? In my group, we have been developing and investigating some of the fundamental concepts and theories, and key features of such metaplasmonic structures, devices, and circuits. These circuit elements and components may be envisioned as a tapestry of nanostructures of sizes much smaller than the wavelengths of light. This field, for which I have coined the term metactronics, addresses metamaterial-inspired optical nanocircuits and nanosystems (N. Engheta, Science, 317, 1698-1702, 2007). . In my group, a variety of ideas and paradigms for nanocircuit functions, optical antennas and sensors for beam shaping and photonic wireless at the nanoscale, optical nanoscopy, nanospectrometer for molecular spectroscopy, cloaking of particles, nanotagging and barcodes based on these optical circuits are being studied. In this talk, I will give an overview of these studies in the field of metactronics, present insights into these findings, and forecast future ideas and road maps in these areas.

7600-24, Session 5

Determination of the polarity of InN by terahertz radiation

J. Hwang, K. Lin, National Cheng Kung Univ. (Taiwan); C. Chang, Chinese Military Academy (Taiwan)

Indium nitride (InN) is an important component of the group-III nitride system and has recently received con- siderable attention due to the lowest effective mass, the highest mobility, and the highest saturation velocity of the group-III nitrides. Recently, many reports in-dicate that the terahertz (THz) generation mechanism in InN is dominated by the photo-Dember effect.This work investigates the polarity of THz radiation from InN excited by femtosecond optical pulses with a central wavelength of around 790 nm is measured. The InN epilayers are grown by metalorganic chemical vapor deposition on sapphire and silicon substrates. The polarity of the THz radiation field from InN is opposite to that from p-InAs whose radiation mechanism is dominated by the photo-Dember effect indicating that the dominant radiation mechanism in InN is the drift current induced by the internal electric field at low-density excitation below 590 nJ/cm2. The internal electric field consists of the surface accumulation field and the spontaneous polarization induced electric field. In addition, since no azimuthal angle dependence of the THz radiation is observed, the optical rectification effect is ruled out. By comparing the wave forms of THz radiation from the front and the back of the InN sample grown on sapphire in reflection geometry, the N polarity of the InN sample is confirmed.

7600-25, Session 6

Imaging the spin hall effect of light in a semiconductor

H. M. van Driel, Univ. of Toronto (Canada)

The spin Hall effect of Light (SHEL), historically referred to as the Federoff-Imbert effect, refers to the lateral separation, perpendicular to the plane of incidence, of right and left circularly polarized components of an optical beam when it crosses an optical interface at non-normal incidence. Unlike previous methods that emphasized far-field observations of SHEL and transparent media we observe this effect via absorption in a semiconductor. In particular spin angular momentum from the light beam is transferred to electrons in GaAs using 100 fs pulses. By performing spatially resolved circular dichroism measurements by a probe beam at delay times less than the spin relaxation time (50 ps) , we can directly image in situ the spin Hall effect of light and obtain the nm scale separation of right and left circularly polarized beam components. Other types of ultrafast beam interaction can be used to generalize this imaging technique.

Peformed with Adam Mattacchione, Jean-Michel Ménard and Markus Betz.

Financial support provided by NSERC.

7600-26, Session 6

Ultrafast dynamics and optical spin-control in single magnetic quantum dots

V. M. Axt, Univ. Bayreuth (Germany)

Only a few years ago the fabrication and optical investigation of a single quantum dot with an embedded single Mn atom has become feasible. Such systems effectively realize a nanometer-sized magnet located inside a nanostructure that supports discrete electron-hole excitations with well defined spin properties. Even though there is no direct optical coupling to the Mn spin, such a structure opens up promising perspectives for all-optical magnetization control schemes. The control may be achieved by the optical excitation and manipulation of spin polarized carriers that couple to the Mn spin via the exchange interaction. In this talk manipulation schemes are discussed suitable for the all-optical Mn spin control in neutral or charged CdTe quantum dots. It is shown that the Mn spin can be selectively driven into each of its available spin eigenstates on a picosecond timescale. By suitably chosen pulse sequences also the preparation of well defined superposition states is possible. The influence of external static magnetic fields is analyzed. It turns out that for well chosen magnetic fields the number of pulses needed to realize the magnetization switching protocol as well as the total switching time can be substantially reduced.

7600-27, Session 6

Microscopic analysis of injection currents in semiconductor quantum wells

T. Meier, J. Förstner, H. T. Duc, Univ. Paderborn (Germany)

In unbiased solid state systems it is possible to excite currents on ultrafast femtosecond time scales using optical laser pulses. Here, we present and analyze a microscopic theory that is capable of describing the generation of injection currents in GaAs quantum wells. The band structure and the wave functions are computed via 14x14 band k.p theory. This approach includes the anisotropy of the dispersion and the spin-orbit interaction. Using the k.p band structure and wave functions, the optical matrix elements are computed and inserted into the semiconductor Bloch equations, i.e., the equations of motion of the optically induced polarizations and carrier occupations. Injection current transients are obtained via numerical solutions of the semiconductor Bloch equations including heavy- and light-hole transitions. Depending on the growth direction of the considered quantum well system and the propagation and polarization directions of the incident light beam, it is possible to generate charge and/or spin photocurrents in GaAs quantum wells on ultrashort time scales. The dependence of the injection currents on the excitation conditions is computed and discussed. We find that the strength of the electron, heavy- and light-holes contributions and thus that of the total currents depends on the excitation frequency. Interestingly, also the excitation intensity influences the magnitude and the direction of the photocurrents via Rabi flopping. Furthermore, we

evaluate the Terahertz emission arising from the transient charge current and compare to experimental data.

7600-28, Session 6

Spin dynamics and manipulation in (Ga,Mn)As alloys

X. Liu, Univ. of Notre Dame (United States)

The study of spin excitation and manipulation in ferromagnetic (FM) semiconductors (such as GaMnAs) can tell us a great deal about spin dynamics in these new systems. Spin dynamics in GaMnAs has been studied by two complementary approaches -- by frequency-domain techniques, such as ferromagnetic resonance (FMR) and Brillouin light scattering; and by optical real time techniques, such as ultrafast pump-probe magneto-optical spectroscopy. Using the FMR approach, multi-mode spin wave spectra have been observed, whose analysis provides new information on magnetic anisotropy, dynamic surface spin pinning (surface anisotropy), and the value of the exchange stiffness constant. A very different approach to the problem is the study of photo-induced complex spin dynamics using time-resolved magneto-optical Kerr effect (MOKE). Here the observed coherent magnetic precessions provide a measure of ultrafast changes in the in-plane orientation of magnetization in a given ferromagnetic domain due to laser induced transient changes of the magnetic anisotropy of GaMnAs. This approach provides real-time confirmation of the properties of spin excitations observed by the frequency-domain FMR-like measurements already mentioned. Since the photo-induced magnetization changes have the characteristic speed of semiconductor processes, the real-time studies thus illustrate a combination of magnetism and semiconductor physics that is unique to magnetic semiconductors. In addition, the photo-induced femtosecond magnetization manipulation in GaMnAs will also be discussed.

Collaborators: J. K. Furdyna, N. Tolk, J. Qi, J. Wang, D. S. Chemla, R. Merlin, D. M. Wang, K. C. Hall, J. P. Zahn, L. E. McNeil and E. Harley

7600-29, Session 7

Interplay between disorder and Coulomb interactions in semiconductors

X. Li, Z. Sun, T. Jarvis, The Univ. of Texas at Austin (United States); M. Erementchouk, M. Leuenberger, Univ. of Central Florida (United States)

The interplay between disorder and Coulomb interactions ubiquitously affects properties of condensed matter systems. We examine its role in the nonlinear optical response of semiconductor quantum wells. In particular, we investigate the coherent coupling strength between spectrally resolved exciton resonances due to interface fluctuations. Previous studies yielded conflicting results, which can be summarized as two main schools of opinion, both supported by some experimental observations. Some researchers believe that coherent coupling exists between spatially separated excitons based on observation of oscillatory signals in time-resolved or spectrally resolved four-wave-mixing (FWM) experiments. Others believe that there is no coherent coupling, but there might be incoherent transfer among localization sites. In view of rising interest in semiconductor devices that rely on spatial and/or temporal coherence, we revisit this problem by applying a newly developed spectroscopy method: electronic two-dimensional Fourier transform spectroscopy (2DFTS). 2DFTS is a powerful technique for revealing the presence of coupling and for distinguishing the (coherent or incoherent) nature of such coupling, especially in complex systems with several spectrally overlapping resonances. Even the most basic information about such complex systems, including homogeneous and inhomogeneous linewidths of various resonances, cannot be extracted reliably using conventional spectroscopy methods. In the new measurements based on 2DFTS, we did not observe clear cross peaks corresponding to coherent couplings between either heavy-hole or light-hole excitons. A modified mean-field theory reveals a simple yet important relation which determines how the coherent coupling strength depends on the disorder correlation length and Coulomb interaction length.

7600-30, Session 7

Multimode instabilities and modelocking phenomena in quantum cascade lasers

F. Capasso, Harvard Univ. (United States)

High power cw Quantum Cascade Lasers (QCL) have led to the observation of remarkably rich spectra with sideband spacing at the Rabi frequency and very large number of longitudinal modes due to spatial hole burning (SHB), in agreement with simulations.1,2 A large Rabi frequency (~ 1 THz) is favored by the large dipole matrix element and high intracavity power. However the short gain recovery time of QCLs, which favors SHB, also impedes the observation of self-modelocking. In suitably designed QCLs active modelocking (AML) is clearly observed in interferometric autocorrelation measurements with a 2-photon quantum well detector by periodically electrically driving with an RF waveform at the roundtrip frequency a short end-of-cavity section 3, however SHB limits the range of observation of AML to a narrow range of drive currents and RF power. Finally the observation of modelocking of transverse modes is discussed which leads to beam steering effects associated with the gain saturation third order nonlinearity, in excellent agreement with theory.4

1. C. Wang et al. Phys. Rev. A Rapid Comm.75, 31802 (2007).

2. A. Gordon et al. Phys. Rev. A 77, 53804 (2008).

3. L L. Kuznetsova et al. CLEO 2009 Technical Digest.

4. N. Yu et al. Phys. Rev. Lett. 102, 13901 (2009).

Collaborators:

C. Y. Wang, A. Gordon; F. Kärtner, L. Diehl, V. M. Gkortsas, A. Belyanin, M. A. Belkin, H. Schneider , H. C. Liu; L. Kuznetsova, N. Yu, E. Cubukcu, A. K. Wojcik, K. B. Crozier, D. Bour, S. Corzine, G. Hofler, J. Faist

7600-31, Session 7

Subfemtosecond and attosecond pulse generation

A. H. Kung, Institute of Atomic and Molecular Sciences (Taiwan)

In this talk I shall describe two effective approaches of producing multi-octave-spanning combs of frequencies in the visible-uv regime that can be used to synthesize subfemtosecond and attosecond pulses. The first is by driving adiabatically a Raman coherence to its maximum that was initially proposed by Harris and Sokolov at Stanford University. By driving the vibrational Raman coherence of H_2 at room temperature we succeeded in generating over 15 orders of intense Stokes and anti-Stokes radiation in H_2. The frequency span of the equally-spaced radiation exceeds 70,000 cm-1. Using a subset of this frequency band we synthesized periodic waveforms consisting of pulses that are 0.83 cycles long and have an electric field FWHM of 0.44 fs. The second approach is by cascaded multiple harmonics generation in a monolithic quasi-phase-matched crystal. Up to seven harmonics have been obtained from a crystal 2 cm in length with a conversion efficiency of nearly 20%. I shall demonstrate that by starting with a single laser beam at a fundamental frequency the electric field waveform of the pulses synthesized from these approaches is stable and can be fully controlled. Since the generated pulses are in the optical region these pulses can be very useful for ultrafast study of electronic and photonic phenomena in condensed matter and semiconductors.

7600-32, Session 7

Temporal femtosecond pulse tailoring for nanoscale laser processing of wide-bandgap materials

M. Wollenhaupt, L. Englert, C. Sarpe-Tudoran, A. Horn, Univ. Kassel (Germany); T. Baumert, Univ.Kassel (Germany)

Ultrashort laser pulses are a promising tool for processing wide band gap materials for applications, ranging from precision micromachining even below the wavelength of light to medical surgery. The transient free-electron density in the conduction band plays a fundamental role for phase transitions when sub-picosecond pulses are used. We employ temporally asymmetric femtosecond pulses of identical fluence and statistical pulse duration in order to control two distinct ionization processes (photo-ionization and electron-electron impact ionization). Control leads to different final electron densities / energies as the temporal intensity-profile and its time inverted counterpart address the two ionization processes differently. This results in different thresholds for material modification in fused silica as well as in reproducible lateral structures being an order of magnitude below the diffraction limit (down to 100 nm at NA0.5) being robust with respect to laser fluence variations [1] [2]. Employing chirped pulses with comparable pulse duration, we observed that asymmetric temporal frequency ordering had no significant influence on the ablation thresholds. Currently, we extend our studies on time resolved plasma dynamics [3] to spectral interference measurements with shaped laser pulses.

1. Englert etal. “Control of ionization processes in high band gap materials via tailored femtosecond pulses,” Optics Express 15, 17855-17862 (2007).

2. Englert etal., “Material processing of dielectrics with temporally asymmetric shaped femtosecond laser pulses on the nanometer scale,” Appl. Phys. A 92, 749-753 (2008).

3. Sarpe-Tudoran etal., “Plasma dynamics of water breakdown at a water surface induced by femtosecond laser pulses,” Appl. Phys. Lett. 88, 261109-261109-3 (2006).

7600-33, Session 8

Ultrafast optical control of electron spins in quantum wells and quantum dots

S. G. Carter, S. E. Economou, T. A. Kennedy, A. S. Bracker, T. L. Reinecke, Naval Research Lab. (United States); A. Shabaev, George Mason Univ. (United States); Z. Chen, National Institute of Standards and Technology (United States) and JILA, Univ. of Colorado (United States); S. T. Cundiff, JILA, Univ. of Colorado (United States) and National Institute of Standards and Technology (United States)

Optical control of spins is attractive for applications in spintronics and quantum information since spins can be manipulated on picosecond or shorter timescales, allowing many operations before spin dephasing or relaxation can occur. Using two-color time-resolved Faraday rotation and ellipticity, we demonstrate ultrafast optical control of electron spins in GaAs quantum wells and InAs quantum dots. In quantum wells, a magnetic-field induced electron spin polarization is manipulated by off-resonant pulses. By measuring the amplitude and phase of the spin polarization as a function of pulse detuning, we observe the two competing optical processes: real excitation, which generates a spin polarization through excitation of electron-hole pairs; and virtual excitation, which can manipulate a spin polarization without exciting electron-hole pairs.

In InAs quantum dots, the spin coherence time is much longer, so that the effect of many repetitions of the pump pulses must be considered. Through real excitation, the pulse train efficiently polarizes electron spins that precess at multiples of the laser repetition frequency, leading to a “mode-locking” phenomenon. Through virtual excitation, the spins can be partially rotated toward the magnetic field direction, leading to a sensitive dependence of the spin orientation on the precession frequency and detuning. The electron spin dynamics strongly influence the nuclear spin dynamics as well, leading to directional control of the nuclear polarization distribution. These results can be used to coherently control the electron spin polarization, the nuclear spin polarization, and to minimize fluctuations in the nuclear spin polarization.

7600-34, Session 8

Ultrafast optical nonlinearities in hybrid metal-J-aggregate nanostructures

C. Lienau, Carl von Ossietzky Univ. Oldenburg (Germany)

The strong coupling between excitons and surface plasmon polaritons (SPP) in metal-semiconductor and metal-dye nanostructures are interesting because in analogy to semiconductor microcavities may be of importance in designing novel nano-optic devices. So far, however, very little is known about such nonlinearities and rather weak effects have been observed. Here, we report the first observation of ultrafast optical nonlinearities in metal-J-aggregate hybrid nanostructures.

We investigate a metal-J-aggregate, hybrid nanostructure consisting of an aggregated cyanine dye-polymer film on a gold grating. Strong, linear exciton-SPP coupling in these nanostructures is verified by angle-resolved, p-polarized reflectivity measurements, revealing significant bending due to the SPP-exciton polariton formation. These linear spectra are well understood within a coupled oscillator model with a coupling strength of ~20 meV.

For investigating the nonlinearity, an angle-resolved, low-temperature non-collinear pump-probe setup is used. 30 fs pump pulses centered at 670 nm excite the dye slightly above the exciton resonance. Angle-resolved differential probe reflectivity spectra are recorded for probe incidence angles of 15-50 deg., which show the expected dispersive nonlinearity of uncoupled excitons arising from excited state and bleaching of the ground state absorption. Near the SPP resonances, we observe a surprisingly strong polariton nonlinearity having a dispersive lineshape even at probe wavelengths which are strongly detuned from the exciton-SPP crossing, accompanied by significant changes in the dynamics of the polariton nonlinearity.

Experiments to investigate the role of polariton-phonon scattering and/or polariton-polariton scattering as in microcavities, are currently underway. Our results show that in strongly-coupled exciton-SPP systems optical nonlinearity is efficiently transferred from excitons to otherwise linear metal SPP resonances which is of considerable interest for various future applications like SPP amplification, lasing, or ultrafast switching.

7600-35, Session 8

Enhancement of optical emission and absorption by metal nanoparticles

G. Sun, Univ. of Massachusetts Boston (United States)

A simple, analytical, yet rigorous theory is presented for treating the modification of optical properties induced by metal nanoparticles that are placed in the vicinity of optically active objects of similar dimensions. The theory takes into account the radiative decay of the surface plamon mode supported by the metal nanospheres - a basic phenomenon that has been ignored in electro-static treatment. Specifically, enhancement of optical emission and absorption of molecules by metal nanoparticles is studied, which has important implications on efficiencies of optical devices that reply on absorption, electroluminescence or photoluminescence process. Using the example of Ag nanospheres embedded in GaN dielectric, it can be shown that enhancement for each case depends strongly on the nanoparticle size enabling optimization for each combination of absorption cross section, original radiative efficiency, and separation between the object and metal sphere. The enhancement effect is most significant for relatively weak and diluted absorbers and rather inefficienct emitters that are placed in close proximity to the metal nanoparticles.

7600-36, Session 8

Multiple exciton generation and carrier dynamics in electronically coupled PbSe quantum dots

M. C. Beard, A. G. Midgett, B. Hughes, J. Luther, National Renewable Energy Lab. (United States); H. W. Hillhouse, Purdue Univ. (United States); A. J. Nozik, National Renewable Energy Lab. (United States)

Recently, absorption of a single photon with an energy n times the quantum dot (QD) bandgap has been shown to produce f*n excitons where f is the multi-exciton conversion efficiency. This process is termed multiple exciton generation (MEG) in semiconductor QDs and is a way to bypass wasteful heat generation that occurs via phonon emission. Using ultrafast transient absorption spectroscopy we studied MEG in two series of chemically-treated PbSe QD films. We find that the average number of excitons produced per absorbed photon varies between 1.0 and 2.4 at a photon energy of ~4Eg for films consisting of 3.7 nm QDs, and between 1.1 and 1.6 at hν ~5Eg for films consisting of 7.4 nm QDs. The variations in MEG depend upon the size of the QDs and the chemical treatment used to electronically couple the QDs in each film. The single and multi-exciton lifetimes also change with the chemical treatment: biexciton lifetimes increase with stronger inter-QD electronic coupling and exciton delocalization, while single exciton lifetimes decrease after most treatments relative to the same QDs in solution. MEG is a hotly debated subject in the scientific literature with varying results for similar QD systems. We studied MEG in static and as a function of flow rate of two sized PbSe QDs with and without a Cd-oleate surface treatment. Addition of Cd-oleate increases the PLQY of the QD colloids from ~10% to ~90%. The apparent MEG efficiency of the untreated PbSe QDs decreases by ~ 10-15% when flowing, while no decrease is observed when the QDs are treated with Cd-oleate. Our results show that the MEG efficiency is sensitive to the condition of the QD surface as well as to QD size, and suggest that the wide range of MEG efficiencies reported in the recent literature may be a result of uncontrolled differences in QD surface chemistry.

7600-37, Session 9

Coherently coupled plasmonic and magnetic array antennas

A. F. Koenderink, I. Sersic, M. Frimmer, FOM Institute for Atomic and Molecular Physics (Netherlands)

Nanoscale, ultrafast optics requires the strongest interaction strength per volume of matter with electromagnetic fields. Because the interaction of dielectrics with light vanishes as dimensions are shrunk to the nanoscale, one really requires resonant nanoscatterers, such as plasmonic and metamaterial objects. These resonant nanoobjects have a strong resistive, capacitive or inductive response to incident light, allowing to realize analogs of microwave circuits at optical frequencies. To create such complex nanocircuits, one needs to understand the coupling mechanisms between resonant components. To this end, we study coupled plasmon nanoparticles (resonant response to electric fields) and coupled metamaterial particles (resonant response to magnetic fields) in waveguide and antenna configurations, as well as in 2D arrays. We lithographically fabricated Ag and Au resonant scatterer arrays with pitches down to a fifth of the wavelength. We present angle and frequency resolved extinction measurements that show strong dipole-dipole coupling both in plasmon chains, and in inductively coupled metamaterial systems. These couplings imply that electric and magnetic collective delocalized modes are formed. We demonstrate that two types of modes form: modes with ultrafast superradiant damping, and modes that are strongly confined and subradiant. These collective modes open new perspectives for active devices, such as metamaterial lasers, and optical antennas similar to 'Yagi-Uda' radio-antennas. Such antennas can be tailored to have very large overall optical extinction crosssection, while providing field concentration in nanoscale volumes. We show that coupling active media to subradiant modes gives rise to directional single-photon sources and efficient polariton sources with high Purcell factor.

7600-38, Session 9

Ultrafast silicon-plasmonic modulators

M. S. Sederberg, Z. Han, V. Vien, A. Y. Elezzabi, Univ. of Alberta (Canada)

The recent advances of silicon-based photonic devices have demonstrated the potential for large-scale all-optical integrated circuitry on this platform. The field of plasmonics has seen the development of numerous passive devices, but an appropriate platform showing potential for large-scale active integrated circuitry has not yet been demonstrated. In this work, we investigate a unique silicon-based platform for plasmonic devices. The design and fabrication of devices will be discussed and the performance of a variety of key optical components including waveguides, focussing elements, splitters, couplers, Mach-Zehnder interferometers and microring resonators will be discussed and results from fabricated devices will be presented. The integration of silicon-based plasmonic devices with the existing silicon-photonics platform will be demonstrated. The potential for development of cascaded logic gates and all-optical active plasmonic circuitry on this platform will be assessed.

7600-39, Session 9

Ultrafast electron emission from metals: the role of surface plasmons

P. Dombi, P. Rácz, M. Lenner, Research Institute for Solid-State Physics and Optics (Hungary); S. E. Irvine, A. Y. Elezzabi, Univ. of Alberta (Canada)

We investigated few-femtosecond electron emission from thin metal films induced by surface plasmons. In this unprecedented temporal regime (laser pulse length <7 fs), we observed novel surface plasmon dynamics as well as the broadband coupling of light to surface plasmon oscillations, and as a result, the generation of ultrashort plasmons. These phenomena were observed with the help of surface plasmon induced electron emission from the metal. Spectral analysis of the emitted electron beam reveals novel ultrafast acceleration mechanisms in the evanescent electromagnetic field in the vicinity of the metal surface. As a result, we generated electrons with hundreds of eV kinetic energy without the application of dc fields. Moreover, we observed the transition between multi-photon-induced and field emission from the surface. This was made possible by the inherent, unique field enhancement in plasmonic fields. To our knowledge, these results are the first fundamental studies of surface plasmon dynamics on such ultrashort time-scales and at such high field strengths. These experiments can provide a basis for the further development of new methodologies where ultrashort electron pulses are needed, such as ultrafast electron diffraction and microscopy.

7600-40, Session 10

Correlated ultrafast electron and proton translocation processes in bacteriorhodopsin monitored by time-resolved terahertz radiation

E. Riedle, Ludwig-Maximilians-Univ. München (Germany); J. Hebling, Univ. of Pécs (Hungary); G. I. Groma, Biological Research Ctr. (Hungary); J. Hauer, Univ. Wien (Austria); G. Váró, Biological Research Ctr. (Hungary)

The light-induced proton pumping function of bacteriorhodopsin consists of a chain of charge translocation processes which is well studied by direct electric methods in a wide range of time-scales. However, due to the lack of proper detection technique available in the 0.1-20 THz region, the experimental study of the ultrafast phases of the charge motion related to the energy conversion process has remained unfeasible. The fundamental concept of Hertzian dipole emission dictates that the charges motion in the above ultrafast region generates coherent electromagnetic radiation, detectable by the current methods of THz spectroscopy, provided that the emitting molecules are ordered both at the microscopic and the macroscopic level. By a simple experimental realization of this idea, for the first time we observed light-induced coherent terahertz radiation from bacteriorhodopsin with fs time-resolution. The detected THz signal was analyzed by numerical simulation, considering several possible models for the molecular polarization processes. We find that the major component of the emission originates from excited-state intramolecular electron translocation within the retinal chromophore. The response of this component to the varied wavelength and intensity of the pump pulse corresponds to a resonant second-order optical rectification processes, in accordance to this model. An additional slower phase of the radiation was also well described if the contribution of an early step of the proton motion - kinetically correlated to the formation of the K intermediate of the bacteriorhodopsin photocycle - was included in the model. This step could be attributed to the redistribution of a H-bond near the retinal.

7600-41, Session 10

New phenomena in interaction of intense ulrashort light pulses with transparent materials: from 3D self-assembled nanostructures to quill writing and nonreciprocal photosensitivity

P. G. Kazansky, M. Beresna, Univ. of Southampton (United Kingdom); Y. Shimotsuma, K. Hirao, Kyoto Univ. (Japan); Y. P. Svirko, Univ. of Joensuu (Finland)

Modification of transparent materials with ultrafast lasers has attracted considerable interest due to a wide range of applications including laser surgery, integrated optics, optical data storage, 3D micro- and nano-structuring [1].Three different types of material modifications can be induced with ultrafast laser irradiation in the bulk of a transparent material, silica glass in particular: an isotropic refractive index change (type 1); a form birefringence associated with self-assembled nanogratings and negative refractive index change (type 2) [2,3]; and a void (type 3). In fused silica the transition from type 1 to type 2 and finally to type 3 modification is observed with an increase of fluence. Recently, a remarkable phenomenon in ultrafast laser processing of transparent materials has been reported manifesting itself as a change in material modification by reversing the writing direction [4]. The phenomenon has been interpreted in terms of anisotropic plasma heating by a tilted front of the ultrashort laser pulse. Moreover a change in structural modification has been demonstrated in glass by controlling the direction of pulse front tilt, achieving a calligraphic style of laser writing which is similar in appearance to that inked with the bygone quill pen [5]. It has also been a common belief that in a homogeneous medium, the photosensitivity and corresponding light-induced material modifications do not change on the reversal of light propagation direction. More recently it have observed that in a non-centrosymmetric medium, modification of the material can be different when light propagates in opposite directions (KaYaSo effect) [6]. Non-reciprocity is produced by magnetic field (Faraday effect) and movement of the medium with respect to the direction of light propagation: parallel (Sagnac effect) or perpendicular (KaYaSo effect). Moreover a new phenomenon of ultrafast light blade, representing itself the first evidence of anisotropic sensitivity of isotropic medium to femtosecond laser radiation has been recently discovered [7]. We anticipate that the observed phenomena will open new opportunities in laser material processing, laser surgery, optical manipulation and data storage.

References

1. R. R. Gattas and E. Mazur, “Femtosecond laser micromachining in transparent materials,” Nature Photonics 2, 219-225 (2008).

2. Y. Shimotsuma, P. G. Kazansky, J. Qiu and K. Hirao, “Self-organized nanogratings in glass irradiated by ultrashort light pulses,” Phys. Rev. Lett. 91, 247705 (2003).

3. V. Bhardwaj, E. Simova, P. Rajeev, C. Hnatovsky, R. Taylor, D. Rayner and P. Corkum, “Optically produced arrays of planar nanostructures inside fused silica,” Phys. Rev. Lett. 96, 057404-1 (2006).

4. P. G. Kazansky, W. Yang, E. Bricchi, J. Bovatsek, A. Arai, Y. Shimotsuma, K. Miura and K. Hirao,”Quill” writing with ultrashort light pulses in transparent materials,” Appl. Phys. Lett. 90, 151120 (2007).

5. W. Yang, P. G. Kazansky, Y. Shimotsuma, M. Sakakura, K. Miura and K. Hirao, “Ultrashort-pulse laser calligraphy,” Appl. Phys. Lett. 93, 171109 (2008).

6. W. Yang, P. G. Kazansky and Yu. P. Svirko, “Non-reciprocal ultrafast laser writing,” Nature Photonics, 2, 99-105 (2008).

7. P. G. Kazansky, Y. Shimotsuma, J. Qiu, W. Yang, M. Sakakura, M. Beresna, K. Miura and K. Hirao, “Ultrafast light blade: Anisotropic sensitivity of isotropic medium to femtosecond laser radiation”, submitted to PRL(2009).

7600-42, Session 10

Probing H2O molecular layering structures at solid-water interfaces by femtosecond acoustic pulses

Y. Wen, National Taiwan Univ. (Taiwan); V. Gusev, Univ. du Maine (France); Y. Huang, National Taiwan Univ. (Taiwan); S. Chin, C. Chang, Y. Chang, Academia Sinica (Taiwan); C. Sun, National Taiwan Univ. (Taiwan)

Hydration force between water and solid surfaces is origin of many natural phenomena and at the core of many areas of research, including solute adsorption, wetting properties, and electrochemistry. One important phenomenon inherent at interfaces with other media is the network structure of water molecules, which makes the behaviors of interfacial water drastically different from that of the bulk liquid. Knowledge about the structure and the microscopic interactions of the interfacial molecule network is thus crucial for clarifying many important questions involving water. In this talk, we will present a novel resonance phenomenon induced by the collective dynamics of interfacial water network. The experimental observation is achieved by shaking the interfacial water structure and measuring its energy absorption. This concept is analogy with the absorption of earthquake by natural vibration of architectures, while the frequency of the adopted “nano-earthquake” is in the THz range. Detailed experimental observations and the theoretical interpretation will be given in the talk.

7600-43, Session 10

Development and application of plasma-waveguide based soft x-ray lasers

J. Wang, Academia Sinica (Taiwan); S. Chen, Institute of Atomic and Molecular Sciences (Taiwan); J. Lin, National Chung Cheng Univ. (Taiwan); H. Chu, National Central Univ. (Taiwan); M. Chou, P. Lin, Institute of Atomic and Molecular Sciences (Taiwan)

In the development of soft x-ray lasers, we achieved dramatic enhancement of optical-field-ionization collisional-excitation x-ray lasing by using an optically preformed plasma waveguide. With a 9-mm-long pure krypton plasma waveguide prepared by using the axicon-ignitor-heater scheme, lasing at 32.8 nm is enhanced by 400 folds. An output level of 8*10^10 photon/shot is reached at an energy conversion efficiency of 2*10^-6. The same method is used to achieve x-ray lasing in a gas jet for the high-threshold low-gain transition at 46.9 nm in neon-like argon. We have also demonstrated seeding of Ni-like Kr lasing at 32.8 nm by high harmonic generation. Comparing with the same laser seeded only with spontaneous emission, seeding with high harmonics yields much smaller divergence, enhanced spatial coherence, and controlled polarization. The integration of high harmonic seeding, optically preformed plasma waveguide, and optical-field-ionization pumping forms an optimal archetype of ultrashort-pulse soft x-ray lasers. In application, we demonstrated single-shot digital holographic microscopy with an adjustable field of view and magnification by using a tabletop 32.8-nm soft x-ray laser. The holographic images were reconstructed with a two-dimensional fast Fourier-transform algorithm, and a new configuration of imaging was developed to overcome the pixel-size limit of the recording device without reducing the effective numerical aperture. The image of an atomic-force-microscope cantilever was reconstructed with a lateral resolution of 480 nm, and the phase contrast image of a 20-nm carbon mesh foil demonstrated that profiles of sample thickness can be reconstructed with few-nanometers uncertainty. The ultrashort x-ray pulse duration combined with single-shot capability offers great advantage for flash imaging of delicate samples.

7600-44, Session 10

Up on the Jaynes-Cummings ladder of a quantum dot-microcavity system

J. Kasprzak, Cardiff Univ. (United Kingdom); S. Reitzenstein, C. Kistner, C. Schneider, M. Strauß, S. Höfling, A. W. B. Forchel, Univ. Würzburg (Germany); W. W. Langbein, Cardiff Univ. (United Kingdom)

In optical microcavities light and matter can be fused under the strong coupling regime resulting in the formation of superposition states, often referred as dressed states or polaritons. Strong coupling is an essential ingredient in the research spanning from many body quantum coherence phenomena, like Bose condensation and superfluidity, to cavity quantum electrodynamics (cQED). The elementary description in cQED is the Jaynes-Cummings (JC)model that mimics interaction of a single two-level system with a single radiation mode. In the limit of few photon numbers and for fermionic coupling, an anharmonicity is predicted for the ladder-like spectrum of dressed states and demonstrated for atomics systems and superconducting qbits. As concerns semiconductor nanostructures, direct signatures of few-photon states and related transitions occurring between neighbouring rungs of the Jaynes-Cummings ladder have not been reached yet, primarily due to fast dephasing occurring in a solid state environment within a ps timescale. In this work, we have employed heterodyne spectral interferometry to perform four-wave mixing (FWM) spectroscopy on a strongly-coupled quantum dot-microcavity system. By extracting the FWM response in both amplitude and phase we retrieve the signal both in temporal and spectral domain. In time domain we observe Rabi-like coherent oscillation between a single exciton and a photon mode. The spectrum is decomposed into the parts originating from one- and two-photon transitions. Coherent dynamics of one- and two-photon transitions is identified. Fermionic quantum strong coupling regime is demonstrated and the results are compared with the predictions of the Jaynes-Cummings model.

7600-45, Session 11

Ultrafast optical manipulation of electron spins in quantum dots

A. Greilich, Technische Univ. Dortmund (Germany)

Currently, the most attractive quantum bit (qubit) candidate in semiconductors is an electron spin in a quantum dot. Due to confinement the spin is largely protected from relaxation mechanisms, leading to decoherence times in the µs-range. This time has to be contrasted with the time to perform coherent manipulations on the qubit, which should be orders of magnitude shorter for useful implementations. A tool which has the potential to reach this goal is pulsed optical excitation, which has been shown to generate/initialize a fast and efficient spin polarization using ps-laser pulses. Here, we use an ensemble of quantum dot electron spins focused into a small number of precession modes about a magnetic field by periodic optical pumping. We demonstrate ultrafast optical rotations of spins about arbitrary axes of the Bloch sphere on a picosecond timescale using laser pulses as control fields. We also observe, for the first time, optically stimulated spin echoes. They validate that the spin rotations are robust, and open an opportunity to lengthen spin coherence times by decoupling the spins from the nuclear system. The results are supported by the theoretical analysis. In collaboration with Sophia E. Economou, S. Spatzek, D. R. Yakovlev, D. Reuter, A. D.Wieck, T. L. Reinecke and M. Bayer.

7600-46, Session 11

Spin manipulation and generation with spin orbit interaction in semiconductor heterostructures

M. Kohda, J. Nitta, Tohoku Univ. (Japan)

Spin orbit interaction (SOI) plays a significant role for the fundamental physics as well as the realization of spin based functionalities in semiconductors [1]. This is because the SOI provides momentum-dependent effective magnetic fields and spin-dependent orbital modulations for electrons, and these properties are essential for utilizing spin degree of freedom in semiconductors. Here, we investigated electrical spin manipulation and spin generation induced by the SOI.

For electrical control of spin precession, we measured gate bias dependence of spin interference effect based on InGaAs mesoscopic ring structures with high-k Al_2O_3 gate insulator. Al'tshuler-Aronov-Spivak (AAS) oscillations were clearly observed with negative and positive phases at zero magnetic fields by applying gate bias voltages. It corresponds to the electrical control of spin precession due to the modulation of effective magnetic fields. Spin precession angle of 6π is achieved by applying the gate bias [2].

For electrical spin generation, we investigated spin dependent current induced by the spatial gradient of Rashba SOI in Y-branch shaped narrow wire structures [3]. At Y-branch junction, independently controlled side gates are formed for controlling spin dependent force induced by the SOI. We observed the different branch currents depending on the injected spin directions. It indicates that spin polarized currents are generated in each branches with opposite spin orientation.

References:

[1] M. Kohda et al., J. Phys. Soc. Jpn. 77, 031008 (2008). [2] M Kohda et al., ECS transactions 16, 39 (2008). [3] J. Ohe et al., Phys. Rev. B 72, 041308 (R) (2005).

7600-47, Session 11

Electron-spin beat susceptibility of excitons in semiconductor quantum wells

N. Kwong, College of Optical Sciences, The Univ. of Arizona (United States); S. Schumacher, Heriot-Watt Univ. (United Kingdom); R. H. Binder, College of Optical Sciences, The Univ. of Arizona (United States)

The long-lived electron-spin coherence of excitations in semiconductor quantum wells has been intensively investigated recently. In one experimental configuration, excitons are created by a pump pulse in a pure spin state aligned with the quantum well's growth axis in the presence of a weak magnetic field applied along the well's plane (Voigt geometry). In the subsequent evolution, the excitons dephase to an optically incoherent population and the hole spin also decoheres. The electron spin typically remains coherent over hundreds of picoseconds and precesses around the magnetic field's direction. Probe pulses sent in at various delay times then generate time-resolved DT and FR signals that oscillate at the electron spin precession frequency. In recent experiments in such a configuration, the oscillation amplitudes and phases of the DT and FR signals show some interesting dependencies on the probe center frequency, which could provide information on the many-body physics involved in the measurement and manipulation of these electron spins. To understand these dependencies, we have formulated, with the help of real-time Green's functions and diagrammatic perturbation methods, a general microscopic theory of the optical response of a quantum well which carries a population of electron-spin-coherent excitons. A spin susceptibility is derived which yields predictions for the DT and FR signals. The theory has been evaluated to linear order of the exciton density. Our results explain the basic features of the measured frequency dependencies as outcomes of interference among various exciton-exciton scattering processes.

7600-48, Session 11

Theory of ultrafast spin dynamics in bulk semiconductors: a microscopic picture

H. C. Schneider, Technische Univ. Kaiserslautern (Germany)

This talk presents recent theoretical results on spin dynamics in bulk III-V semiconductors. We study in particular nonequilibrium carrier dynamics after ultrafast-pulse excitation using a microscopic approach, and compare with recent experimental results wherever possible. By computing the microscopic dynamics of the momentum-resolved spin-density matrix and including the relevant interaction mechanisms at the level of Boltzmann scattering integrals, new insights beyond the spin relaxation-time (or dephasing-time) approximation are obtained. Two examples will be discussed in detail. The first one is electron-spin dephasing due to the Dyakonov-Perel mechanism under high excitation conditions at low temperatures. It is shown that the microscopic calculation yields accurate spin dephasing times over a wide range of doping densities including the occurrence and breakdown of motional narrowing for the spin dephasing. A maximum of the spin-dephasing time is achieved around the same densities as at low temperature. In the low-temperature case this behavior is due to a metal-insulator transition. However, at high excitation conditions, the maximum is exclusively due to the combined influence of screening and scattering on the spin-dynamics of the excited electrons, and not a signature of a metal-insulator transition. We also discuss hole-spin relaxation dynamics in bulk GaAs. Due to the p-like character of the hole bands, this is a model system of spin relaxation in the presence of strong spin-orbit interaction. Different measures for the polarization in the hole system exist, and, unlike the electronic case, their dynamics are different.

7600-49, Session 12

Advances in optical two-dimensional spectroscopy applied to the study of semiconductor and atomic systems

A. D. Bristow, D. Karaiskaj, X. Dai, G. A. Moody, S. T. Cundiff, JILA, Univ. of Colorado at Boulder (United States)

Electronic structure and dynamics of a material can be determined through optical spectroscopy. Optical two-dimensional Fourier-transform (2DFT) spectroscopy uses a sequence of laser pulses to generate coherent signals in a material. The phase evolutions of these signals are recorded as a function of time delays between various pulses in the multi-pulse excitation sequence. The signals are converted to a two-dimensional spectrum with a Fourier transform. These spectra unfold the complex nonlinear signals, separating and isolating spectrally overlapping signatures due to the electronic interaction.

We have developed an ultra-stable platform for 2DFT spectroscopy, which consists of nested interferometers with active phase control. The platform allows complete phase and time control of the excitation sequence to explore both single and two-quantum coherences in semiconductors and atomic vapors. In addition, the "global" phase, associated with the induced nonlinear polarization, is determined by all-optical means, and allows capture of the real part of the complex signals for any excitation configuration.

In GaAs quantum wells the coherent response is dominated by many-body effects and is sensitive to the confinement potential. These competing contributions can only be unambiguously isolated using 2DFT spectroscopy. Polarization-dependent measurements have confirmed the suppression of many-body interactions for cross-linear excitation, and revealed a spin-dependence for circular-polarized excitation configurations. Many-body two-quantum coherences are separated from biexciton contributions. We also demonstrated noise suppression using phase cycling while examining coherent signals from K vapor, and observe two-quantum interactions that indicate an exciton model can describe the atomic gas.

7600-50, Session 12

Exciton dephasing dynamics and disorder in semiconducting single-walled carbon nanotubes

M. W. Graham, Y. Ma, Univ. of California, Berkeley (United States); A. A. Green, M. C. Hersam, Northwestern Univ. (United States); G. R. Fleming, Univ. of California, Berkeley (United States)

Semiconducting single-walled carbon nanotubes (SWNTs) are one of the most intriguing nanomaterials due to their large aspects ratios, size tunable properties, and dominant many body interactions. Their optical properties in particular, are determined by a manifold of stable exciton states resulting from strong electron-hole coulombic interactions owing to one-dimensional confinement. While SWNT population dynamics have been well characterized, optical dephasing processes have only been examined indirectly through steady state measurements like single-molecule spectroscopy which yield highly variable estimates of the homogeneous linewidth. To bring clarity to conflicting estimates, a time domain measurement of exciton dephasing at the ensemble level is necessary. In this contribution, we report the results obtained using femtosecond photon echo spectroscopies on a sample highly enriched in the (6,5) nanotubes species. We find that both exciton-exciton and exciton-phonon scattering have profound affects on the dephasing process.

Three-pulse photon echo peak shift (3PEPS) measurements were conducted over a broad range of temperatures, and theoretical simulations of obtained results revealed that the lowest (E11) exciton lineshape is dominated by inhomogeneous broadening. We were further able to estimate the strength and timescale for exciton-phonon coupling of dominant nuclear modes (e.g. the radial breathing mode). A surprisingly long room temperature dephasing time of 204 fs was extracted for solution phase (6,5) tube species, which is in stark contrast to those found in molecular systems and quantum dots. This long dephasing time suggests occurrence of remarkable exciton delocalization, and makes nanotubes ideal to study many-body coherent effects in spatially confined systems in real time.

7600-51, Session 12

Probing many particle correlation in semiconductor quantum wells using double-quantum coherence signal

L. Yang, S. Mukamel, Univ. of Califorina, Irvine (United States)

Multidimensional analysis of coherent signals is commonly used in nuclear magnetic resonance to study correlation among spins. These techniques were recently extended to the femtosecond regime and applied to chemical, biological and semiconductor systems. In this work, we propose a two-dimensional correlation spectroscopy technique employing double quantum coherence to investigate the many-body effects in a semiconductor quantum well. The signal is detected along the direction K1+K2-K3, where K1, K2 and K3 are the pulse wave vectors. Controlling the time ordering in such a technique is critical for the unambiguous identification of many-body correlation. We show that the signal detected along this direction is particularly sensitive to the many-body correlation beyond time-dependent Hartree-Fock interactions. The correlation energy of biexciton can be probed with a very high resolution arising from a two-dimensional correlation spectrum, where two-exciton couplings spread the cross peaks along both axes of the spectrum and create a characteristic highly resolved pattern. This level of detail is not available from conventional one-dimensional four-wave mixing or other two-dimensional correlation spectroscopy signals such as the photo echo, in which two-exciton couplings show up along a single axis and are highly congested. Moreover, the double quantum coherence signal also has the potential in separating the coherent and incoherent signals in the nonlinear optical response of semiconductor nanostructures.

7600-52, Session 12

Dynamics of shaping ultra-short optical pulses in the actively mode-locked semiconductor laser with an external long-haul single-mode fiber cavity

A. S. Shcherbakov, P. P. Moreno Zarate, National Institute for Astrophysics, Optics, and Electronics (Mexico)

The active mode-locking in semiconductor lasers can be naturally considered as circulating optical pulse in a cavity, because usually the pulse width exceeds the transverse relaxation time, so that a modified two-level approach is applicable for describing pulse dynamics. The transverse relaxation time determines the gain contour, which can be approximated by the Lorentz profile. The frequency of external modulation is conditioned by the recovery time for a gain within spacing the circulating pulses. At no stimulated radiation, the gain recovery depends on the velocity of injection and the longitudinal relaxation time. When the modulation period and the longitudinal relaxation time are close to each other, the gain has no time to recover completely. In connection with this, the presented model for analyzing the dynamics of optical pulses in the actively mode-locked semiconductor laser with an external long-haul single-mode fiber cavity includes three principal contributions. The first one describes the gain, which includes parameters of the modulating signal. Our approach makes possible considering various modulating signals providing specific composite regimes of a multi-pulse active mode-locking. The second contribution reflects various lumped and distributed losses, while the third contribution includes linear and nonlinear phase shifts. The combined actions of dispersion, distributed losses, and nonlinearity are assisting in shaping the average-soliton regime of pulse propagation in a single-mode fiber cavity. We analyze this phenomenon and characterize the trains of picosecond optical pulses generated. The theoretical results are compared with the corresponding data obtained from the experiments with the InGaAsp/InP lasers matched to a long-haul single-mode silicon fiber cavity.

7600-53, Session 12

Confined electron emission with femtosecond timing: nonlinearity, localization, enhancement

C. Ropers, Georg-August-Univ. Göttingen (Germany)

The local extraction of electrons from metal nanotips is the basis for some of the most powerful analytical instruments, including the scanning tunneling microscope and electron microscopes based on field emission cathodes. In order to equip such tools with ultrafast temporal resolution, laser-triggered electron emission from sharp tips is studied by a number of research groups. In this talk, recent experimental and theoretical efforts are reviewed.

Specifically, strategies to confine optical illumination and electron emission to the apex are presented. The experimental approaches include the addition of a static bias voltage to the tip and making use of optical field enhancements from surface plasmon resonance. Further confinement is reached by employing multiphoton electron emission or optical field emission (tunneling). The transition between these two regimes, governed by the Keldysh parameter, is discussed regarding the consequences for spatial and temporal emission characteristics. Because of the high optical nonlinearities involved, electron emission takes place exclusively at those regions on the tip where the field enhancement is strongest.

First applications of a local source of laser-triggered electrons include imaging experiments, where a sample is placed in the near-field or in the far-field of the source. The prospects and limitations of these approaches are discussed.

7600-54, Session 13

Multiple-quantum 2D spectroscopy of many-body correlations in GaAs quantum wells

K. A. Nelson, Massachusetts Institute of Technology (United States)

Multiple-quantum two-dimensional Fourier transform optical (2D FTOPT) spectroscopy was developed and conducted on GaAs quantum wells. Spatiotemporal femtosecond pulse shaping was used to control the optical phases and time delays of ultrashort pulses in multiple non-collinear beams so that fully coherent four-wave and higher-order mixing measurements could be conducted without delay stages, multiple interferometers, or any active phase control. Coherences of biexcitons, unbound but correlated exciton pairs, and higher-order correlations, and rephasing of the coherences, were observed directly. Separate work in which time-resolved terahertz-pump/terahertz-probe spectroscopy was developed and used to examine hot carrier dynamics deep in bulk semiconductors will be discussed briefly.

7600-55, Session 13

Ultrafast coherent control of electric currents at metal surfaces

U. Höfer, J. Güdde, M. Rohleder, Philipps-Univ. Marburg (Germany); T. Meier, Univ. Paderborn (Germany); S. W. Koch, Philipps-Univ. Marburg (Germany)

We report on the development of an experimental technique to measure the dynamics of electric currents on the femtosecond timescale. The technique combines methods of coherent control with time- and angle-resolved photoelectron spectroscopy. Direct snapshots of the momentum distribution of the excited electrons as function of time are then determined by photoelectron spectroscopy. In this way we gain information on the generation and decay of ultrashort current pulses in unprecedented detail. In particular, this technique allows the observation of elastic electron scattering in terms of an incoherent population dynamics in momentum space. We have applied this optical current generation and detection scheme to electrons in so-called image-potential states which represent a prototype of two-dimensional electronic surface states. Electrons in these states are bound perpendicular to the metal surface by the Coulombic image-potential whereas they can move almost freely parallel to the surface. For the (n=1) image-potential state of Cu(100) we find a decay time of 10 fs due to electron scattering with steps and surface defects.

7600-56, Session 13

Two-dimensional mode-locking in planar waveguide arrays

M. O. Williams, J. N. Kutz, Univ. of Washington (United States)

Semiconductor waveguide array lasers have been used to generate pulses mode-locked in a single dimension. A vertical stack of planar waveguiding regions, similar to a vertical cavity surface emitting laser (VCSEL), is theoretically capable of producing pulses mode-locked in two dimensions. In the waveguiding regions, Bragg gratings are used to generate Bragg solitons to confine the optical field in the direction of propagation. The saturable absorption generated by the coupling between waveguides allows for mode-locking in the remaining two dimensions. The planar waveguide array structure is capable of producing stationary, breathing, and multiple pulse solutions. For the lowest allowable values of gain, white noise initial conditions generate radially symmetric two dimensionally mode-locked pulses. The maximum intensity of the pulse is directly related to the gain, but there exists a maximum value of gain for which the single pulse solution is stable. Beyond this threshold value, it is conjectured the stationary solution loses stability to breather solutions through a torus bifurcation. The breather solutions are characterized by an oscillatory radial pulse and a stationary, non-radial noise background. At yet larger gains, the breather solution loses stability and the multiple-pulse stationary solutions become the dominant behavior. The stationary multiple-pulse solutions are individually radially symmetric and, like the single pulse case, the noise background is eliminated. Additionally, the pulses are stable for a range of gains. Therefore, planar waveguide arrays are a viable technology for two-dimensional passive mode-locking as they produce stable mode-locked pulses starting from noise.

7600-57, Session 13

Toward nonlinear magneto optics

R. Morandotti, Y. Linzon, K. Rutkowska, Institut National de la Recherche Scientifique (Canada); B. A. Malomed, Tel Aviv Univ. (Israel)

Nonlinear light propagation in multidimensional self-focusing media is generally influenced by instabilities that, if the input power exceeds a certain threshold value, can lead to catastrophic collapse after a finite propagation distance. In the past decade, the problem of the collapse of (2+1)-dimensional [(2+1)D] optical beams in Kerr-type media has become the subject of intensive studies. In such cases, which typically take place when light propagates through amorphous media and crystals without any specific symmetries, the nonlinear Schrödinger equation (NLSE) can be applied to theoretically investigate the nonlinear behavior associated to light propagation. The possibility of wave collapse control (in particular to prevent its negative effects leading to material damage) has recently drawn much attention. In particular, it can be achieved via the use of optical birefringence, which in turn allows for the control of energy and phase transfer between the beam polarization components. In this paper, we demonstrate that the optical birefringence can act as a powerful tool for (2+1)D beam collapse management. Our numerical studies, as well as the results of a series of experiments we have performed show that the combined effects of linear and circular birefringences can affect the dynamics of beam collapse in bulk self-focusing media. We find that the acceleration, the deceleration, or even the suppression of light collapse can be obtained for certain values of birefringences. We also show experimentally that the linear and circular birefringences required for the collapse management can be easily induced in transparent magnetooptical (MO) Yttrium Iron Garnet (YIG) crystals by applying an external dc magnetic field.

7600-58, Session 14

Manipulation of a single Mn spin using excitation transfer between two coupled CdTe/ZnTe quantum dots

M. Goryca, Univ. of Warsaw (Poland)

A semiconductor quantum dot (QD) containing a single Mn atom is a promising system, close to the ultimate miniaturization limit for information processing and storage on a single spin. An efficient optical read-out of the Mn spin state in a CdTe/ZnTe quantum dot, as well as studies of dynamics of this state, were recently reported by L. Besombes and co-workers.

This work is focused on the advancement in writing and storing of information on the Mn spin state. We demonstrate optical writing of information on the spin state of a single Mn ion embedded in a CdTe QD and we test the storage time in the range of a few tenths of a millisecond. A spin-conserving excitation transfer between two coupled QDs is used as a tool for optical manipulation of the Mn spin. Excitons resonantly created in a dot without magnetic atom by circularly polarized light tunnel to the dot with the Mn ion in a few picoseconds. Then they act on the Mn ion via the sp-d exchange interaction and orient its spin. The orientation is much more efficient in presence of a magnetic field of about 1T, due to suppression of fast spin relaxation channels. Storage time of the information on the Mn spin was measured in a time-resolved experiment, in which the intensity and polarization of excitation were modulated. It was enhanced by the magnetic field and reached about half a millisecond at 1T.

7600-59, Session 14

Measurement of (3) in CdS nano-particles prepared by thermochemical method under a low-power CW He-Ne laser irradiation

Z. Dehghani, E. Saievar Iranizad, Tarbiat Modares Univ. (Iran, Islamic Republic of); M. H. Majles Ara, Tarbiat Moallem Univ. (Iran, Islamic Republic of); M. Molaei, Tarbiat Modares Univ. (Iran, Islamic Republic of)

CdS nano-particles synthesis with thermochemical method. Initial materials in this method are CdSO4, Na2S2O3 and thiogelycerol as capping agent. Recently the nonlinear effects of nano-particles have attracted much interest. The second order refractive index and nonlinear absorption coefficient are measured by use of z-Scan technique. The optical limiting behavior is investigated by transmission measurement through the sample. Linear absorption coefficient ( ) is obtained about 1.19 cm-1.

The positive sign obtained indicated that there is a self-focusing effect in the sample. The nonlinear refractive index n2 was in the order of 10−7 cm2W−1. The nonlinear absorption coefficient, , was calculated by the use of the open-aperture z-scan technique to be + 1.27×10−2 cmW−1.

These nano-particles exhibit the strong saturable absorption; therefore, the third-order nonlinear optical susceptibility (3) was measured for this material.

7600-60, Session 14

Ultrafast coherent spectroscopy with strain pulses in semiconductor nanostructures

D. R. Yakovlev, Technische Univ. Dortmund (Germany)

We apply ultrafast optical and acoustic techniques to study dynamical processes in semiconductor nanostructures. For generating the strain pulse a 100 nm thick metal transducer layer was attached to the substrate. This metal film was hit by 100-fs intense laser pulse and due to

thermoelastic effect a strain pulse with duration of 10 ps and amplitude up to 0.1% was injected into a substrate. This strain pulse travels strongly directed through the crystal towards the quantum well, where it induces the exciton resonance shift on a value up to 10 meV on a ps time scale. Dynamics of the following energy evolution is detected by pump-probe optical techniques. At high excitation power formation of the picosecond acoustic solitons is observed. While passing the quantum well the soliton induces the chirping (coherent frequency modulation) of optical transition. In a semiconductor quantum well microcavity in the strong coupling regime by injecting terahertz strain pulses a novel modulation domain has be obtained in which large variations of the optical frequency are induced on time scales shorter than the polariton decoherence. Under these conditions characteristic sidebands, which are spectral fingerprints of the terahertz modulation process, appear in the spectrum near the polariton resonance. The energy separation between the sideband fringes is determined by the modulation rate. The results are supported by the theoretical analysis. In collaboration with A. V. Akimov, A. V. Scherbakov, T. Berstermann, N. A. Gippius, B. A. Glavin, I. Sagnes, J. Bloch, and M. Bayer.

7600-61, Session 14

Low-dimensional plasmons in metallic atom sheets, atom chains, and nano-sheets

T. Nagao, National Institute for Materials Science (Japan)

When the size of the object shrinks beyond micrometer scale and it reaches down to nanometer or sub-nanometer scale, novel effects that originate from its smallness come into view. The most common and important effect is the size effect, or the confinement effect. Plasmons in metallic tiny objects show pronounced size/shape effects in reduced dimensions, especially in nanometer scale. This fits perfectly to the demand for developing the new functional properties at the nanoscale for the next generation nano-photonics/optics devices. In this context, not only from the scientific point of view but also from the technical point of view, it is of great importance to clarify whether plasmons are confined and can propagate in atom-scale tiny objects such as in atom chains etc. Such investigation will be the first step towards the realization of the ultimately small atom-scale/nano-scale optics. In the present talk, I will introduce our recent works on the shape effects, dimensionality effects, Rashba effects, in atom-scale plasmons. Also we introduce our recent work on the development of the plasmon-enhanced chemo/bio-sensing materials fabricated by both the top-down and the bottom up wet-chemical processes.

7600-62, Session 15

Carrier multiplication is more efficient in bulk PbS and PbSe than in quantum dots

M. Bonn, FOM Institute for Atomic and Molecular Physics (Netherlands)

Semiconductor Quantum Dots (QDs) have been proposed as efficient light absorbing materials for future solar cells. QDs are attractive building blocks for solar cells owing to the tunability of their optical properties by variation of QD size. A second important quality is that QDs have been reported to exhibit efficient Carrier Multiplication (CM), the process in which the absorption of a single, high-energy photon results in the generation of 2 or more electron-hole pairs, i.e. two electron-hole pairs for the price of one photon. The efficiency of CM in QDs has been highly debated. The key question is whether quantum-confinement actually leads to an increase of CM efficiencies in semiconductors. To answer this question, a reliable comparison between CM efficiencies in bulk and nanostructured materials is required. We report the efficiency of CM in bulk PbSe and PbS using (ultrafast) TeraHertz time-domain spectroscopy (THz-TDS). Within picoseconds after photo-excitation, we can determine the plasma frequency through THz absorption, which is proportional to the number of photogenerated carriers. We extract the number of photogenerated carriers per absorbed photon by comparing the magnitude of the THz absorption for various excitation energies (from UV to the IR). Comparing our bulk results with reported CM efficiencies in QDs, we conclude that quantum-confinement in fact leads to a reduction of CM in QDs.

7600-63, Session 15

Extreme THz nonlinearities in bulk and nanostructured semiconductors

A. Sell, A. A. Anappara, Univ. of Konstanz (Germany); T. Kampfrath, K. von Volkmann, M. Wolf, Freie Univ. Berlin (Germany); G. Biasiol, Lab. Nazionale TASC/INFM (Italy); L. Sorba, Lab. Nazionale TASC/INFM (Italy) and Scuola Normale Superiore (Italy); A. Tredicucci, Scuola Normale Superiore di Pisa (Italy); A. Leitenstorfer, R. Huber, Univ. of Konstanz (Germany)

Phase-locked electromagnetic transients in the terahertz (THz) spectral domain have been a unique contact-free probe of the femtosecond dynamics of low-energy excitations in semiconductors [1]. Access to their nonlinear response, however, has been limited by the shortage of sufficiently intense THz sources. We introduce a novel table-top facility generating few-cycle multi-THz transients with unprecedented electric field amplitudes of up to 108 MV/cm [2]. This source opens the door to the regime of non-perturbative THz nonlinearities. At the same time, ultrabroadband electro-optic sampling provides direct access to the THz-induced femtosecond dynamics on a sub-cycle time scale. Several lead-off examples of extreme nonlinearities are discussed:

Multi-terahertz fields of the order of MV/cm are used to coherently promote optically dark 1s para excitons in the semiconductor Cu2O into the 2p state. Electro-optic gating directly monitors the nonlinear field response of the exciton dynamics. Up to two internal Rabi cycles are identified [3], pointing out a promising route towards laser cooling of excitons.

Bulk semiconductors are exposed to peak electric fields as high as 1 V/Å [2]. A near-infrared pulse with a duration of 8 fs directly probes the THz-induced breakdown of the power expansion of the nonlinear polarization.

Finally, we employ a quantum well waveguide structure to switch on ultrastrong light-matter coupling, on a sub-cycle time scale [4]. Multi-THz transients trace how bare photons transform into cavity polaritons during this non-adiabatic process.

[1] see e.g. R. Huber et al., “How many-particle interactions develop after ultrafast excitation of an electron-hole plasma”, Nature 414, 286 (2001); J. Kröll et al., “Phase-resolved measurements of stimulated emission in a laser”, Nature 449, 698 (2007).

[2] A. Sell et al., “Phase-locked generation and field-resolved detection of widely tunable terahertz pulses with amplitudes exceeding 100 MV/cm”, Opt. Lett. 33, 2767 (2008).

[3] S. Leinß et al., “Terahertz coherent control of optically dark paraexcitons in Cu2O”, Phys. Rev. Lett. 101, 246401 (2008).

[4] G. Günter et al., “Sub-cycle switch-on of ultrastrong light-matter interaction,” Nature 458, 178 (2009).

7600-64, Session 15

Nonlinear terahertz spectroscopy

M. Woerner, Max-Born-Institut für Nichtlineare Optik und Kurzzeitspektroskopie (Germany)

In most THz experiments the THz radiation is used as a linear probe.

Using THz radiation for nonlinear excitation requires the ability to generate high enough THz intensities. Our recent development of a simple and reliable method to generate THz pulses with high intensities (equivalent to high electric field amplitudes) has paved the way for nonlinear optics in the THz regime. The novel tool of nonlinear terahertz spectroscopy allows for the investigation of both (i) nonlinear transport phenomena of free carriers in the electric field regime beyond the breakdown voltage and (ii) coherent nonlinear manipulation of systems with discrete energy levels, e.g. shallow impurities in semiconductors or intersubband transitions in quantum wells. Our most recent experiments on bulk n-type GaAs gives new insights into phenomena like Bloch oscillations and Zener tunneling in bulk semiconductors. Another novel development in this field is the two-dimensional terahertz spectroscopy. Here, we present first experiments on intersubband transitions in GaAs/AlGaAs quantum wells.

7600-65, Session 15

Nonlinear transient absorption bleaching of intense THz pulses in semiconductors

F. Su, Univ. of Alberta (Canada); F. Blanchard, G. Sharma, L. Razzari, Institut National de la Recherche Scientifique (Canada); A. K. Ayesheshim, T. L. Cocker, L. V. Titova, Univ. of Alberta (Canada); T. Ozaki, J. Kieffer, R. A. Morandotti, Institut National de la Recherche Scientifique (Canada); M. E. Reid, Univ. of Northern British Columbia (Canada); F. A. Hegmann, Univ. of Alberta (Canada)

Recent progress in the development of intense, few-cycle terahertz pulse sources has led to a surge in research over the past few years studying the ultrafast nonlinear optical response of materials in the terahertz frequency range. In particular, the large electric field amplitude associated with high-power THz pulses is ideally suited as a non-contact probe of nonlinear carrier transport dynamics in semiconductors over picosecond and sub-picosecond time scales. In our studies, a large aperture ZnTe optical rectification source illuminated by 800 nm, 30 fs laser pulses from the Canadian Advanced Laser Light Source (ALLS) is used to generate intense, few-cycle THz pulses with peak electric field amplitudes of up to 200 kV/cm at the focus. We observe nonlinear transient absorption bleaching in the THz pulse transmission at high THz fields in photoexcited GaAs and n-doped InGaAs using optical-pump - THz-probe (OPTP) and Z-scan techniques, respectively. A simple model of the THz-pulse-driven electron dynamics reveals that the observed absorption bleaching behavior arises from THz-electric-field-induced intervalley scattering over sub-picosecond time scales as well as an increase in the intravalley scattering rate from carrier heating, both of which have the effect of reducing carrier mobility and, therefore, increasing THz pulse transmission. Furthermore, due to the nonlinear nature of the THz pulse transmission, time-resolved terahertz spectroscopy of photoexcited GaAs at high THz probe fields produces a significant deviation from the Drude response observed at low THz probe fields, highlighting the need to explore ultrafast nonlinear THz pulse interactions with materials in the time-domain.

7600-66, Session 15

Terahertz radiation emission from silicon and magnesium-doped indium nitride

I. Wilke, Rensselaer Polytechnic Institute (United States)

Indium nitride (InN) thin films and nanorods are novel sources of broadband terahertz (THz) frequency radiation. Emission of THz-radiation occurs upon irradiation of InN with femtosecond near-infrared laser pulses. Since InN is a narrow band gap semiconductor, InN is an exciting material for future time-domain THz-spectroscopy and THz-imaging systems powered by femtosecond fiber lasers operating at communication wavelengths (1550nm) and directly diode-laser pumped femtosecond solid state lasers emitting in the 1000-1600nm wavelengths range. Advantages of InN as THz-emitter compared to other semiconductors are strong intrinsic electric fields, potentially low intrinsic carrier concentrations and a very low probability of intervalley scattering of photocarriers.

In my presentation I will give an overview of current research on THz-radiation emission from InN. Particularly, I will discuss recent results on the impact of n- and p-type dopants on THz-radiation emission from InN thin films. InN thin films are grown by molecular beam epitaxy (MBE) on c-plane sapphire with AlN nucleation layers and GaN buffer layers. Emission of THz-radiation from silicon (Si) -doped and native n-type InN increases with mobility as expected for transient photocurrents as primary mechanism of terahertz radiation emission. Doping of InN with magnesium (Mg) enhances the emission of THz-radiation compared to doping of InN with Si. This is experimental evidence for Mg acting as an electrically active acceptor in InN. THz- radiation emission from InN:Si is weaker than emission of THz-radiation from native n-type InN because of increased electron concentrations due to Si being an electrically active donor in InN.

7600-67, Poster Session

Ultrafast conductivity dynamics in optically excited InGaN/GaN multiple quantum wells, observed by transient THz spectroscopy

D. Turchinovich, H. Porte, D. G. Cooke, P. Uhd Jepsen, Technical Univ. of Denmark (Denmark)

We report on optical pump - THz probe experiments performed on an InGaN/GaN multiple quantum well (MQW) sample with a built-in strain-induced piezoelectric field of 3 MV/cm. The presence of such a strong electric field in the QWs results in a pronounced quantum-confined Stark effect (QCSE), which manifests itself in the decrease in optical transition energy (Stark shift), and quenching of the photoluminescence due to the weaker overlap between the electron and hole wavefunctions. In our experiment, sub-100-fs, 400-nm wavelength pump pulses were used to excite a population of polarized electrons and holes in the QWs, and a 300-fs THz probe pulse with useful spectrum of 0.5-2.5 THz was used to monitor the onset and subsequent decay of photoinduced conductivity. We observe nonexponential photoconductivity decay dynamics in the sample, featuring a drastic slow-down of the decay rate as the time after the photoexcitation increases. Furthermore, frequency-resolved transient spectroscopy reveals that the photoexcited charges display a pronounced non-Drude conductivity, resembling that of a disordered conductor. Strong photoexcitation leads to a partial or even complete removal of the QCSE by screening of the built-in field. It is reasonable to attribute the observed slowing-down of the decay dynamics to the gradual restoration of the built-in piezoelectric field in the QWs as the carriers recombine. This interpretation is supported by independent time-integrated photoluminescence (PL) measurements that show both a strong, blue-shifted PL peak (screened bias field) as well as a weaker and broader Stark-shifted PL peak at longer wavelength (unscreened bias field).

7600-68, Poster Session

Increased-bandwidth in multiphoton intrapulse interference phase scan(MIIPS) using angle-dithered nonlinear-optical crystal

C. Lee, S. Liu, National Sun Yat-Sen Univ. (Taiwan)

Ultra-broad-bandwidth laser have been attracted lots of attentions due to their wide applications in spectroscopy, dynamics and coherent quantum control. To overcome the limitation of electronic speed, plenty of approaches, such as correlation technique, were proposed to characterize the ultrafast pulse. Furthermore, combined with spectrum, full characterization of pulse were also developed well, like frequency-resolved optical grating (FROG), multiphoton intrapulse interference phase scan (MIIPS). MIIPS is iterative a pulse characterization and pulse compensation metheod. The measurement are achieved using a pulse shaper which introduces a reference phase function. The SHG spectra are recorded and generated the MIIPS trace. From the MIIPS trace, it is possible to obtain the spectral phase distortions of the pulse. This information is used to design a phase compensation function that is introduced to cancel the measured distortion. Basically, a proper

nonlinear process is necessary. However, the nonlinear-optical phase-matching bandwidth is inversely proportional to the crystal thickness, so very thin crystals are required for ultrashort light pulses. An extremely thin crystal was too damageable and inconvenient to use. As the SHG efficiency scales as the square of the crystal thickness, use of such an extremely thin crystal yields drastically reduces the sensitivity of MIIPS technique. In this work, combining nonlinear crystal angle-dithering technique and MIIPS, effective and wider phase matching bandwidth(over 250nm) are demonstrated with thick crystal(100um). Meanwhile, higher sensitive can also be performed.

7600-69, Poster Session

Terahertz plasmonic imaging

P. Maraghechi, C. J. Straatsma, Z. Liu, H. Zhao, A. Y. Elezzabi,
Univ. of Alberta (Canada)

In this work dielectric objects embedded in a metallic media were imaged via THz time domain spectroscopy. Coupling the THz electric field to particle plasmons and propagating it through the metallic medium is the mechanism utilized in this technique. The low quality images acquired in this experiment where processed by a super-resolution image algorithm to enhance their quality. It was observed that unlike conventional THz imaging methods where the transmitted pulse power is analyzed, the pulse arrival time and the phase magnitude information provided more details of the embedded object.

Conference 7601: Terahertz Technology and Applications III

Wednesday-Thursday 27-28 January 2010 • Part of Proceedings of SPIE Vol. 7601

Terahertz Technology and Applications III

7601-21, Poster Session

Theoretical optimization of InGaAs-based photomixers for broadband continuous-wave terahertz emission

J. Shin, N. Kim, K. H. Park, Electronics and Telecommunications Research Institute (Korea, Republic of)

Terahertz (THz) sources have received considerable attention for their medical, agriculture, environmental, and security applications. Up to now, the most promising candidate as a portable and widely-tunable THz emitter is the photomixer pumped by an optical beat source. Recently, there have been several reports on low-temperature-grown (LTG) InGaAs and ion-implanted InGaAs photoconductive switches that can act as photomixers aiming at the connection between the THz and the well-developed InP-based communication technologies [1]. However, the InGaAs-based photomixers have a disadvantage of high dark current compared to the LTG-GaAs counterpart.

In this paper, an analytical equation for the THz output power from interdigitated-finger-gap photomixers is proposed for the case of high dark current for the first time. The equation, which can be driven by the same procedure proposed by Brown et al. [2], is further extended to represent the saturated THz output power limited by the dark and photo current related joule heat. From the equation, several points are predicted: 1) THz output power is maximized when the pump area equals to the digitated-finger area, 2) the optimized carrier lifetime depends not only on the THz frequency but also on the dark carrier density as well as on the gap number, 3) the optimized carrier lifetime and gap number for below-3-THz application are 0.3~1.0 ps and 5~6, respectively, when the dark carrier density is 10^15 ~ 10^16 cm^-3.

[1]. A. Takazato et al., Appl. Phys. Lett. 90, 101119 (2007)

[2]. E. R. Brown et al., J. Appl. Phys. 73, 1480 (1993)

7601-01, Session 1

Using terahertz pulsed imaging in quality control: from nondestructive film coating quality analysis to dissolution prediction to on-line measurements

P. F. Taday, TeraView Ltd. (United Kingdom)

Coatings are applied to pharmaceutical tablets (or pills) to for either cosmetic or release control reasons. Cosmetic coatings control the colour or to mask the taste of an active ingredient; the thickness of these coating is not critical to the performance of the product. On the other hand the thickness and uniformity of a controlled release coating has been found affect the release of the active ingredient. In this work we have obtained from a pharmacy single brand of pantoprazole tablet and mapped them using terahertz pulsed imaging (TPI) prior to additional dissolution testing. Three terahertz parameters were derived for univariate analysis for each layer: coating thickness, terahertz electric field peak strength and terahertz interface index.

Because there is an interaction between pantoprazole (the active ingredient) and the acidic moieties often used on the enteric polymers. This tablet requires to be coated with a thick inert layer which is placed between the controlled released coating and the tablet core. The cross-sectional views across a number of products shows that there are significant differences between tablets scanned this maybe due to different process parameters. Univariate analysis of the dissolution time and the thicknesses of the various layers where undertaken. The best correlation (R2=0.9147) is found with the combined thickness of the controlled-release coating and inert layers. These results will be discussed in this paper.

Moreover, due to the speed of the technique there are opportunities of the application of TPI for on-line measurements. These developments will be reviewed in this presentation.

7601-02, Session 1

Improved terahertz imaging with a sparse synthetic aperture array

Z. Zhang, T. Buma, Univ. of Delaware (United States)

There is considerable interest in using electromagnetic terahertz (THz) pulses for imaging purposes. Sparse arrays are highly attractive for practical considerations but come at the cost of degraded image quality. In ultrawideband arrays, path differences exceeding a single-cycle result in complete walk-off between signals from neighboring elements. Although this avoids the undesired constructive interference plaguing narrowband arrays, the non-interfering pulses still degrade image quality. We demonstrate significantly improved performance by further exploiting the coherent ultrawideband nature of THz pulses. We compute two weighting factors to each time-delayed signal before final summation to form the reconstructed image. The first factor employs cross-correlation analysis to measure the degree of walk-off between time-delayed signals of neighboring elements. The second factor measures the spatial coherence of the time-delayed delayed signals. Synthetic aperture imaging experiments are performed with a THz time-domain system employing a single transceiver scanned over a 10 mm aperture in increments of 1 mm. This element spacing is over three times larger than the wavelength at 1 THz. The test object consists of metal wires placed 4, 6, and 8 mm away from the transceiver path. Conventional reconstruction with this 10-element array produces an image with exceedingly strong artifacts from non-interfering signals. The proposed image reconstruction improves image contrast by over 12 dB, a significant improvement considering the relatively few elements in the array. These encouraging results suggest that the proposed image reconstruction technique can be highly beneficial to both synthetic aperture as well as physical THz sparse arrays.

7601-03, Session 1

Dual-frequency continuous-wave terahertz transmission imaging of monmelanoma skin cancers

C. S. Joseph, Univ. of Massachusetts Lowell (United States); A. N. Yaroslavsky, Wellman Ctr. of Photomedicine (United States); R. H. Giles, Univ. of Massachusetts Lowell (United States); W. E. Nixon, U.S. Army National Ground Intelligence Ctr. (United States)

Continuous wave terahertz imaging has the potential for diagnosing and delineating skin cancers. While contrast has been observed between cancerous and normal tissue at terahertz frequencies, the source mechanism behind this contrast is not clearly understood. Transmission measurements of 5µm thick sections of nonmelanoma skin cancer were taken at two frequencies of 1.39 THz and 1.63 THz that lie within and outside the tryptophan absorption band, respectively. The water absorption characteristics at these frequencies are different as well. Two CO2 pumped Far-Infrared molecular gas lasers were used for interrogating the tissue. And the transmitted signals were registered using a liquid Helium cooled Silicon bolometer. The images were acquired with 0.5mm optical resolution. Transmission images of the nonmelanoma skin cancers were collected at both frequencies and their difference image was generated. The resulting images were compared to the sample histology. The results of the imaging experiments will be presented and discussed.

7601-04, Session 1

Coherent imaging at 2.4 THz with a CW quantum cascade laser transmitter

A. A. Danylov, T. M. Goyette, J. Waldman, M. J. Coulombe, R. H. Giles, X. Qian, S. Vangala, N. Chandrayan, W. D. Goodhue, Univ. of Massachusetts Lowell (United States); W. E. Nixon, U.S. Army National Ground Intelligence Ctr. (United States)

A coherent transceiver using a THz quantum cascade laser (TQCL) as the transmitter and an optically pumped molecular laser (OPL) as the local oscillator (LO) has been used, with a pair of Schottky diode mixers in the receiver and reference channels, to acquire high-resolution images of fully illuminated targets, including scale models and a handgun. Phase stability of the received signal, sufficient to allow coherent image processing of the rotating target (in azimuth and elevation), was obtained by frequency-locking the TQCL(1) to the free-running, highly stable OPL. While the range to the target was limited by the available TQCL power (several hundred microwatts) and reasonably strong indoor atmospheric attenuation at 2.408 THz (2.0 dB/m at 40% RH), the coherence length of the QCL transmitter will allow coherent imaging over distances up to several hundred meters. In contrast to non-coherent heterodyne detection, coherent imaging allows signal integration over time intervals considerably longer than the reciprocal of the source, or signal bandwidth, with consequent improvement in the signal-to-noise ratio. Image data obtained with the system will be presented.

7601-05, Session 1

Application of wavelet transforms in terahertz spectroscopy of rough surface targets

M. H. H. Arbab, D. P. Winebrenner, E. I. Thorsos, A. Chen, Univ. of Washington (United States)

Previously, we have shown that scattering of terahertz waves by surface roughness of the target can alter the terahertz absorption spectrum and thus obscure the detection of such chemicals in both transmission and reflection geometries. This phenomenon primarily occurs due to the material grain sizes and their RMS surface height being on the same order of magnitude as the wavelength of terahertz radiation. In this paper, we demonstrate that wavelet methods can be used to retrieve spectroscopic information from a broadband terahertz signal reflected from a rough surface target. Sample pellets were prepared by inscribing surface roughness from a sheet of P80 grit sandpaper on a mixture of lactose and spectroscopic grade polyethylene powder under approximately 6000 psi pressure. Several wavelet transforms were implemented on terahertz reflection spectra obtained from rough lactose pellets in frequency domain. Furthermore, a comparison of Multi Resolution Analysis (MRA) of several wavelet transforms using the Maximum Overlap Discrete Wavelet Transform (MODWT) algorithm is presented. It is concluded that while a simple frequency domain deconvolution method failed to accurately characterize and detect the resonance in the dielectric constant of rough surface lactose pellets, advanced wavelet techniques were able to successfully identify such features.

7601-06, Session 1

THz pulse time-domain holography

A. A. Gorodetsky, V. G. Bespalov, St. Petersburg State Univ. of Information Technologies, Mechanics and Optics (Russian Federation)

We present recent results on THz pulse time-domain holography. The experimental results show themselves to prove the modeling presented the past two years. The low-cost, energy-efficient setup for THz time domain holography is presented. And modeling results showing two possible reconstruction ways as well as noise dependency and resolution of method. It is shown that using 'virtual' reference beam we eliminate most of noise affect on reconstruction and the possibility of realtime reconstruction by IR or visible wavelengths, despite the resolution of this technique is worse than one used for referenceless THz time-domain holograms.

7601-07, Session 2

Measurement and modeling of rough surface effects on terahertz spectroscopy and imaging

S. C. Henry, S. Schecklman, G. P. Kniffin, L. M. Zurk, Portland State Univ. (United States)

Recent advances in ultrafast laser technology have improved the generation and detection of energy within the terahertz (THz) portion of the electromagnetic spectrum. While there are many promising THz sensing applications, there are several outstanding technical challenges that need to be addressed before robust systems can be deployed. A particularly compelling application is the potential use of THz reflection spectroscopy for stand-off detection of drugs and explosives. In addition to signal-to-noise ratio (SNR) limitations, rough surface scattering can lower reflected intensity at the specular angle. However, diffuse scattering may be observed at all angles, suggesting possible use in robust imaging of non-cooperative targets, although the strength of the returns can vary depending on the surface statistics and viewing geometry. Furthermore, the scattering physics can also distort the reflection spectra, complicating material classification.

In this work, rough surface scattering effects were first isolated by measuring full bidirectional reflectance distribution functions (BRDF's) for gold-coated sandpaper of varying roughness. Secondly, we measured scattering returns from a rough sample with a spectral signature, namely -lactose monohydrate mixed with Teflon and pressed with sandpaper to introduce controlled roughness. For both the specular and diffuse reflection measurements, the application of traditional spectroscopy techniques provided the ability to resolve the 0.54 THz absorption peak. These results are compared with results from a smooth surface and predictions from rough surface scattering models. Implications of the results on the ability to detect explosives with THz reflection spectroscopy are also presented and discussed.

7601-08, Session 2

Modeling of an electrically tunable quantum dot photodetector for terahertz detection

W. Wu, D. Dey, O. G. Memis, H. Mohseni, Northwestern Univ. (United States)

The terahertz region (1-10 THz) has potential applications in many areas, such as chemical sensing, medical imaging and free-space optical communications. With the demonstration of terahertz sources, it is quite necessary to develop the detection technology in terahertz. Here we propose an electrically tunable quantum dot infrared photodetector to detect the terahertz region. The proposed detector applies a lateral electrical confinement on the quantum wells and forms a quantum disk in the quantum well area. The two-dimensional quantum confinement of the quantum disk combining the vertical confinement from the quantum barrier forms a quantum dot structure. Using the energy states and intersublevel energy spacing in the dot, the detector can be used to detect the terahertz region. Changing the lateral electrical confinement, the intersublevel energy spacing can also be tuned and in hence different wavelengths can be detected. Our modeling and simulation results show the tunability of peak detection wavelength of the photodetector from

~3.3 to ~6.5 THz with a gate voltage applied on the detector from -2 to -5 volts. The peak absorption coefficients of the detection are shown in the range of 20,000 cm-1. Compared with the quantum dot photodetector produced by self-assembled growth the detector proposed here is easier to be tuned and the effective sizes have a much higher uniformity, because of using electrical confinement.

7601-09, Session 2

Optical requirements and modeling of coupling devices for future far-infrared space missions

N. A. Trappe, National Univ. of Ireland, Maynooth (Ireland)

The next generation of space missions targeting far-infrared bands will require large-format arrays of extremely low-noise detectors. The development of Transition Edge Sensors (TES) array technology seems to be a viable solution for future mm-wave to Far-Infrared (FIR) space applications where low noise and high sensitivity is required. In space applications, where the background loading is low the required NEP (noise equivalent power) will be of the order of 10-19 W Hz-1/2 whereas the current TES detectors developed for ground-based applications have NEPs of around 10-17 WHz-1/2.

Therefore much development work is required on the detector technology itself but in this paper we concentrate on a key element for a high sensitivity TES detector array, that of the optical coupling between the incoming electromagnetic field and the phonon system of the suspended membrane. An intermediate solution between free space coupling and a single moded horn is where over-moded light pipes are used to concentrate energy onto multi-moded absorbers. This approach has advantages at short wavelengths such as the dimensions of the absorber can be much smaller than the separation between pixels. We present a comparison of modeling techniques to analyse the optical efficiency of such light pipes and their interaction with the front end optics and detector cavity.

7601-10, Session 2

Magnetic-field enhancement beyond the skin depth limit

J. Shin, Korea Advanced Institute of Science and Technology (Korea, Republic of); N. Park, Seoul National Univ. (Korea, Republic of); S. Fan, Stanford Univ. (United States); Y. Lee, Korea Advanced Institute of Science and Technology (Korea, Republic of)

It was recently shown, by some of the present authors, that it is possible to achieve a factor of 1,000 enhancement of the electric field amplitude over a deep-subwavelength scale spatial region (~ wavelength/30,000) in the terahertz regime, using a narrow slit on a thin metal film. A similar enhancement of the magnetic field would be very interesting as it has applications of its own in fundamental science and real-world engineering as well as those from the combined effect of Poynting vector enhancement. However, it was reported that one cannot achieve a similar order of enhancement of the magnetic field by using the structures that are complementary to the electric field enhancing ones, as the cardinal conditions of the Babinet's principle are violated in these length scales.

Here, the authors propose and confirm the operation of magnetic field enhancing structures that are based on different principles. While the previous structures, e.g., the metal slit structure and the complementary metal wire structure, directly rely on the high conductivity of metals to achieve the enhancement of electric and magnetic fields, respectively, the proposed structure uses a geometry-based enhancement scheme. Using the new structure, it is shown that one can achieve large magnetic field enhancement even when the conductance of the metallic element is non-ideal due to its nanoscale size, which is smaller than the skin depth in the terahertz regime. Theoretical explanation as well as numerical verification is provided.

7601-11, Session 3

Electro-optic dendrimer-based difference frequency terahertz source

A. Rahman, Applied Research & Photonics, Inc. (United States)

Dendrimer is an attractive nanomaterial for high electro-optic (EO) coefficient non-linear optical applications. Unlike side-chain linear polymers, dendrimer's core-shell structure allows a highly monodispersed structure whose molecular size varies from ~4nm to ~12nm based on its generation. Since the end-groups (shells) are multivalent, it possesses an increased number of available sites for attaching foreign molecules. Thus, dendrimer's property can be tailored by doping with selective chromophores for enhanced electro-optic properties. Also, unlike side-chain polymers, dendrimer requires small doping concentration for property enhancement. For instance, PAMAMOS dendrimer doped with a commercially available chromophore (~3 wt%) exhibits an electro-optic coefficient, r33 of ~130 pm/V at 633nm. This value is very stable with respect to time and pump intensity. Such chi^2-dendrimer is suitable for terahertz generation via difference frequency method. CW diode lasers can be used to pump the chi^2-dendrimer emitter to produce high power terahertz radiation that is suitable for many practical applications such as spectrometry and imaging. Here an EO dendrimer emitter is reported where two diode lasers were used to pump ~100µm thick dendrimer target. The generated radiation was measured with a thermopile type detector that was filtered with a combination of a spectral band-pass filter (that truncates up to 1500nm) and a 3.3 mm thick polyethylene plate that eliminates any IR. Both diode lasers' power was varied at equal intervals from 0 to 2.25 W that generated ~3.4 mW terahertz radiation at a combined pump power of 5.5 W. Spectrometric analysis reveals that the spectrum spans from ~0.1THz to ~20THz.

7601-12, Session 3

Optically synchronized dual-channel THz-signals for high-performance transmitter/receiver system

N. Shimizu, K. Oh, NTT Microsystem Integration Labs. (Japan); S. Kohjiro, K. Kikuchi, National Institute of Advanced Industrial Science and Technology (Japan); A. Wakatsuki, NTT Photonics Labs. (Japan); N. Kukutsu, Y. Kado, NTT Microsystem Integration Labs. (Japan)

We propose a generator for high-sweeping-speed optically synchronized dual-channel terahertz signals, GHOST. Its concepts are as follows: One wavelength-tunable laser source (TLS) and two wavelength-fixed laser sources (FLS1 and FLS2) generate two optical beat signals (OBSs) by mixing the optical signal from the TLS with that from FLS1, and that from FLS2. Then, each OBS is converted into terahertz signal with a photomixer. The advantage is that the frequency difference between two terahertz signals is determined by the wavelengths of FLS1 and FLS2 and independent of the frequency of the terahertz signals themselves. This feature is essential for a heterodyne detection of the terahertz signal with various frequencies. Therefore, a frequency-sweepable terahertz transmitter (Tx)/receiver (Rx) system can be realized by using a GHOST for the Tx and the photonic local oscillator of the heterodyne Rx.

To verify our concepts, we developed a GHOST with a commercially available TLS, DFB-LDs, and uni-traveling-carrier photodiodes. For the Rx, we used a superconductor-insulator-superconductor mixer. The GHOST sweeps the frequency from 200 to 500 GHz within three seconds in frequency steps of 0.5 GHz. The maximum Tx output and minimum Rx sensitivity are -2.7 and -84 dBm at 350 GHz, respectively. The corresponding power margin is larger than 80 dB. The absorption line measurements for nitrous oxide and water vapor showed that the developed Tx/Rx system can detect the gas absorption with the optical depth of 0.04.

These results indicate the high potential of the GHOST with a superconductor-insulator-superconductor mixer for various terahertz spectroscopic applications.

7601-13, Session 3

Handheld terahertz systems based on telecom technologies

H. Roehle, B. Sartorius, D. Stanze, Fraunhofer-Institut für Nachrichtentechnik Heinrich-Hertz-Institut (Germany)

The potential of Terahertz for various applications e.g. in security or material inspection has been demonstrated already. However, for real world use the THz systems have to shrink in size and price. Our way is to exploit technologies developed and matured originally for 1.55 µm fiber-optic telecom applications.

Our key devices are photoconductive antennas (PCAs) for converting 1.55 µm telecom light into THz radiation and for coherent detection. LT-grown InGaAs on InP is well-suited for this wavelength, but exhibits very high dark currents. We solved this problem by combining conventional compensation techniques (Be-doping) with a novel attempt, embedding multiple thin InGaAs photoconductive layers between InAlAs layers. The latter own deep traps capturing the residual electrons out of the photoconductor. As result, we obtain a high-speed and high-resistivity photoconductor operating up to 1.55 µm.

THz antennas were integrated on chips containing the novel InGaAs/InAlAs structure. The PCAs were packaged into fiber coupled modules with Si-lens for efficient THz extraction. These handheld THz-emitter and -receiver heads were driven by a 1.55 µm pulsed fiber laser (Menlo). The laser station comprises an amplifier stage (EDFA, 2x100 mW) and a dispersion compensating fiber. Adjusting the fiber lengths properly one gets pulse lengths < 100 fs on the PCAs. A tunable delay comprises an oscillating mirror for real-time (50 Hz) measurements, and a linear drive for high precision spectroscopy (lock-in detection).

The paper will describe our new compact THz system and demonstrate its performance up to 4 THz.

7601-14, Session 3

Terahertz photonic transmitters with a high-gain open-ended rampart slot array antenna

Y. Huang, H. Chen, National Taiwan Univ. (Taiwan); P. Chiu, J. Chyi, National Central Univ. (Taiwan); B. Wang, S. Chen, National Taiwan Univ. (Taiwan); C. Sun, National Taiwan Univ. (Taiwan) and Research Ctr for Applied Sciences, Academia Sinica (Taiwan)

We propose to integrate a high-gain open-ended rampart slot array antenna in our edge-coupled terahertz (THz) photonic transmitters. By locating the open circuits at the end of each quarter-wavelength slot antenna, the reflected terahertz wave can constructively interference with the input wave and hence produce higher gain. In addition, the folded feeding networks turn more propagating waves into the effective radiating segments rather than the dispersive surface waves. A THz resonant cavity is also designed under our monolithic THz-wave circuits. A 300-nm gold layer is coated below the substrate to serve as a reflecting mirror to reflect back the THz waves to the antenna. The resonant cavity design not only provides a robust base for post device processing but also greatly enhances the gain of antenna. With the design of open-ended rampart slot array antenna and THz resonant cavity, we demonstrate that the gain of antenna can reach 5~6 dBi.

7601-15, Session 3

Extended spectral coverage of BWO combined with frequency multipliers

W. C. Hurlbut, V. G. Kozlov, Microtech Instruments, Inc. (United States)

Millimeter wave Backward Wave Oscillators (BWOs), operating across 100-300 GHz, served well to the global research community for 2-3 decades by now. Generating 10-100 mW of power, these devices were never optimized in terms of output coupling efficiency. Our recent experiments demonstrated that much more power can be extracted out of a BWO tube by improving output impedance matching. Such improvement is achieved by coupling BWO output to a transmission line of non-linear diodes in a solid state frequency multiplier.

Power conversion efficiency of frequency multipliers varies from 10% at frequencies below 500 GHz to 0.01-1% at higher frequencies. Mixing and matching these multipliers with BWO tubes can improve conversion efficiency by a factor of two on average, reaching close to 100% at a few specific frequencies. BWO's combined with multipliers also generate fairly smooth coverage across the tuning range, as conversion efficiency usually peaks at frequencies where BWO power drops. This is another indication that poor impedance matching between BWO and free space results in a spiky power spectra of BWOs.

Starting with 10-100 mW of BWO output power across 0.1-0.3 THz, Microtech demonstrated continuous spectral coverage on 0.1-1.0 THz range with 0.1-1 mW of power and quasi-continuous coverage across 1.0-2.1 THz with 0.001-0.01 mW of power. Combination of these THz sources with recently improved Golay Cell detectors enables powerful spectroscopic and imaging instruments.

7601-16, Session 4

Terahertz dynamics of ionic liquids from a combined dielectric relaxation, terahertz, and optical Kerr effect study: evidence for mesoscopic aggregation

K. Wynne, D. Turton, Univ. of Strathclyde (United Kingdom); J. Hunger, A. Stoppa, Univ. of Regensburg (Germany); G. Hefter, Murdoch Univ. (Australia); A. Thoman, M. Walther, Albert-Ludwigs-Univ. Freiburg (Germany); R. Buchner, Univ. of Regensburg (Germany)

To exploit the great potential of room-temperature ionic liquids (RTILs) as solvents that offer both low environmental impact and product selectivity, an understanding of the liquid structure, the microscopic dynamics, and the way in which the pertinent macroscopic properties, such as viscosity, thermal conductivity, ionic diffusion, and solvation dynamics depend on these properties, is essential. We have measured the intermolecular dynamics of the 1,3-dialkylimidazolium-based RTILs [emim][BF4], [emim][DCA], and [bmim][DCA], at 25 °C from below 1 GHz to 10 THz by ultrafast optical Kerr effect (OKE) spectroscopy and dielectric relaxation spectroscopy (DRS) augmented by time-domain terahertz and far-infrared FTIR spectroscopy. This concerted approach allows a more detailed analysis to be made of the relatively featureless terahertz region, where the higher frequency diffusional modes are strongly overlapped with librations and intermolecular vibrations. In the terahertz region, the signal-to-noise ratio of the OKE spectra is particularly high and the data show that there is a greater number of librational/intermolecular vibrational modes than previously detected. Of greatest interest though, is an intense low frequency (sub-alpha) relaxation that we show is in strong accordance with recent simulations that observe mesoscopic structure arising from aggregates or clusters; structure that explains the anomalous and inconveniently-high viscosities of these liquids.

[1] D.A. Turton et al., “Dynamics of Imidazolium Ionic Liquids from a Combined Dielectric Relaxation and Optical Kerr Effect Study: Evidence for Mesoscopic Aggregation”, J. Am. Chem. Soc. in press (2009)

[2] G. Giraud, C.M. Gordon, I.R. Dunkin, K. Wynne, J. Chem. Phys. 119, 464-477 (2003).

7601-17, Session 4

Electric coupling resonance variation in THz metamaterials by liquid crystal

B. Kang, J. H. Woo, E. Y. Choi, H. Lee, J. H. Kim, E. S. Kim, Ewha Womans Univ. (Korea, Republic of); T. Y. Hong, J. H. Kim, Yonsei Univ. (Korea, Republic of); J. Wu, Ewha Womans Univ. (Korea, Republic of)

Metallic THz metamaterials with double split ring resonator structure possessing resonances in the range of 0.1-1.2 THz have been fabricated on a p-doped silicon wavefer. By forming a nematic liquid crystal cell composed of a fused silica and the metalic metamaterial, variations in the electric coupling resonance have been investigated as the alignment of the mematic director is changed in parallel and perpendicular to the direction of gap-bearing arm of the double split ring resonators. Time domain THz measurement has been adopted to obtain the transmission characteristics of metamaterial liquid crystal cell. Difference in the dielectric constant tensor components, i.e., extra-ordinary and ordinary components, is found to be responsible fot the variation in the electric coupling resonance, while the magneto-electric coupling lying in the lower frequency remains the same regardless of the orientation of nematic director.

7601-18, Session 4

A floating gate double-quantum well far-infrared photoconductor

E. Ledwosinska, T. Szkopek, McGill Univ. (Canada)

The design and characterization of a floating gate GaAs/AlGaAs double

quantum well long-infrared photoconductor is reported, with record operating temperature and modulation bandwidth for a device of this type. The principle of device operation relies on the photoionization of one quantum well, which functions as a floating gate, to modulate the conductance of the other quantum well, which serves as a transistor channel. Photoionization under normal incidence illumination is facilitated by a metal grating. Responsivity of 80 - 160 A/W for 12-20 um long-infrared radiation has been

observed at a 10 K device temperature, and photoresponse is clearly

discernable up to 30 K. The modulation bandwidth was measured to exceed 1kHz. An NEP = 4.7 x 10^-11 W/sqrt(Hz) and D* = 1.7 x 10^8 cm sqrt(Hz)/W were measured, as limited by quantum well conductance fluctuations. Device performance is in fair competition with conventional QWIPs.

7601-19, Session 4

Design and performance of reflective ultra broadband terahertz time domain spectroscopy with air-biased-coherent-detection

I. Ho, X. Guo, X. Zhang, Rensselaer Polytechnic Institute (United States)

We report the design and evaluation of a reflective terahertz time domain spectroscopy (THz-TDS), using air as THz wave emitter and sensor, together with air-biased-coherent-detection (ABCD) method. With pulsed amplified laser, we demonstrate a usable ultra bandwidth from 0.5 THz to 10 THz, with a peak dynamic range (DR) better than 2000:1 and the peak THz electrical field greater than 30 kV/cm. By applying the beam steepening unit, the usable bandwidth is further expanded continuously to over 20 THz with a peak DR better than 1000:1.

We have used this newly invited THz spectrometer for semiconductor characterization. Several far-infrared optical properties such as phonon resonance and plasma resonance in various samples are reported. We also compared both transmission and reflection. Furthermore, the time-resolved optical pump THz probe experiment for GaAs sample is performed. The broaden plasma appears around 8 THz and shifts to lower frequency when the pump power decreases. By integrating the dual chopping frequencies, the differential THz spectroscopy provides better contrast ratio.

Finally, the uniqueness and advantage of this spectrometer are comprehensively compared with traditional THz-TDS and Fourier transform infrared (FTIR) spectroscopy, including radiation source, detector, DR, bandwidth, resolution, peak power, and other features. In terms of signal to noise ratio (SNR), this study provides the SNR variation with frequency in both broadband reflection THz-TDS and FTIR spectroscopy.

7601-20, Session 4

Design of hybrid GaAs waveguide emitters for generation of terahertz radiation based on phase-matched optical rectification process pumped by 1550-nm fiber lasers

T. Yang, J. Wang, R. Li, M. Sang, Tianjin Univ. (China)

A hybrid corrugated asymmetric dielectric planar waveguide made up of nongrating sections and grating sections is proposed and designed as a new potential terahertz radiation emitter. In each nongrating section, a core layer of GaAs is sandwiched between air and the substrate of AlxGa1-xAs, and in each grating section a second-order rectangular grating is etched on the interface of GaAs. Electromagnetic waves in terahertz band could be generated in the nongrating sections pumped longitudinally by a pulsed fiber laser at the center wavelength of 1550nm based on optical rectification process. The calculation shows that coherent length of this nonlinear optical process can be more than 950 mm for the component of 2THz when the thickness of core layer of GaAs is about 145μm and the value of x in substrate of AlxGa1-xAs is set to be 0.1. The conclusion is inferred that the phase matching can be reached by exploring the waveguide mode dispersion because the coherent length is only 0.78mm at 2THz in bulk of GaAs for the same nonlinear process. In following grating section, a rectangular second-order grating structure is introduced to diffract transversely THz electromagnetic waves propagating longitudinally into free space of air in order to reduce the dielectric absorption and to form THz radiation. Calculations show that the coupling efficiency could be more than 60% when the length of grating section is about 1 mm covered with 25 grating pitches and the depth of the 50% duty factor rectangular grating is 36μm. Finally, the power of terahertz radiation is expected to scale up by adding more units of alternating nongrating section and grating section along with the longitudinal direction of this waveguide device.

Conference 7602: Gallium Nitride Materials and Devices V

Monday-Thursday 25-28 January 2010 • Part of Proceedings of SPIE Vol. 7602

Gallium Nitride Materials and Devices V

7602-01, Session 1

Growth of self-standing GaN substrates

H. Lee, Tohoku Univ. (Japan); S. Lee, Wavesquare Inc. (Korea, Republic of); J. Ha, Univ. of California, Santa Barbara (United States); C. Kim, Kyunghee Univ. (Korea, Republic of); J. Chang, Korea Maritime Univ. (Korea, Republic of); K. Fujiii, T. Yao, Tohoku Univ. (Japan)

We are going to give a comprehensive review on various removal techniques for sapphire substrates to obtain free-standing GaN substrates by HVPE. The sapphire substrate removal techniques to be discussed will include (1) the formation of evaporable buffer, (2) chemical lift-off by using ZnO buffer, (3) chemical lift-off by using CrN buffer. Strain situation during substrate removal and in free-standing GaN substrates will be also addressed.

7602-02, Session 1

Selective growth and impurity incorporation in semipolar GaN grown on Si substrate

N. Sawaki, Aichi Institute of Technology (Japan); Y. Honda, Nagoya Univ. (Japan)

Growth of semipolar (1-101)GaN was attempted on a 7degree off oriented (001)Si substrate by selective MOVPE. Narrow grooves having (111) side facets were made along <1-10> axis by anisotropy etching in a KOH solution. On the (111) facets, GaN was grown selectively via AlN buffer layer. Since the c axis of the GaN was tilted 62 degree on the substrate surface, top face of the crystal was of semipolar (1-101) surface. Uniform (1-101)GaN platelet was achieved via epitaxial lateral overgrowth. Because the growth was self-organized on the facet, the (1-101) face was atomically flat, which in turn could offer a uniform GaInN/GaN heterostructure.

SIMS analyses showed that Si and C were unintentionally doped more than that found in (0001) GaN. Intentional doping of Mg, Si and C was investigated. Mg incorporation was more efficient on (1-101) plane than on (0001) plane. Moreover, the surface segregation of the Mg elements was less than that found in (0001)GaN. Hall analyses showed that the self-compensation effect at high doping levels is suppressed substantially in (1-101)GaN. The results are attributed to the fact that the top most surface is terminated by N atoms, in contrast to the fact that the (0001) surface is terminated by Ga. The doping of Si and C were attempted using MMSi and CCl4 or C2H2, respectively. It was found that Si acts as shallow donor while C acts as shallow acceptor to offer low resistive p-type conduction.

7602-03, Session 1

Preparation of the high-quality large-size GaN substrates

X. Xiu, R. Zhang, Nanjing Univ. (China)

Gallium nitride (GaN) is an important direct band gap semiconductor for ultraviolet light-emitting diodes, laser diodes and optoelectronic devices. In recent years, high quality, large size, low cost GaN bulk substrates have obtained more attention. Free-standing thick GaN wafers grown by hydride vapor phase epitaxy and laser-induced lifted off from the substrate is currently the most feasible way for the substitution of a real bulk material because of the difficulties in the growth of bulk GaN. HVPE grown system is currently considered as the key equipment for obtaining free-standing GaN bulk-like substrates instead of the native bulk nitride substrate. In this paper, we discuss the key methods for the HVPE free-standing GaN: thick GaN films growth, HVPE growth system, laser induced lift-off and self-peel off technology etc. We have designed and fabricated several horizontal HVPE system and vertical HVPE growth system. We have carried out the simulation of HVPE system and the simulation results are consistent with our experimental results, which indicate that our HVPE is a good system. We have grown the GaN thick film by means of many new methods. We have obtained 2in free-standing GaN substrates with the thickness of 1.5mm by our HVPE and self-peel off technology.

7602-04, Session 1

Applications of monolayer of microspheres on LEDs and solar cells

C. Chen, C. Chan, C. Hou, G. Chen, J. Chyi, National Central Univ. (Taiwan)

We demonstrate a cost-effective method to deposit an anti-reflection coating on surface of optoelectronic devices.

We used spheres and their inversed structures as the etching mask to pattern a substrate to enhance the GaN LEDs efficiency. The sphere-patterned substrates are used to manufacture GaN LEDs and growth crack-free GaN films on AlGaN patterned substrate. The monolayers can be used as an etching mask to enhance the output power of GaN LEDs upto 35%.

We also used this single layer spheres array technique applied on solar cell to enhance the efficiency. The conversion power efficiency of GaAs solar cell could also be increased by about 25%.

The monolayers of microspheres deposited on the window layer of OLED can be applied to enhance the transmission of the air-glass interface from 90% to 94%.

7602-05, Session 1

Stress management and improvement of luminescence efficiency in thick crack free GaN layers MOVPE grown on Si(111) directly imaged by cathodoluminescence microscopy

A. Dempewolf, F. Bertram, T. Hempel, J. Christen, Otto-von-Guericke-Univ. Magdeburg (Germany); A. Dadgar, A. J. Krost, Otto-von-Guericke-Univ. Magdeburg (Germany) and Azzurro Semiconductors AG (Germany)

Heteroepitaxy of GaN on Silicon substrates offers a capable and inexpensive alternative to the growth on other substrates like sapphire or SiC. It allows large area growth (here e.g. on 150 mm diameter Si wafers), the possibility of vertical contacting due to high electrical conductivity of Si, and the opportunity to integrate GaN based LEDs with Si electronics. To accomplish several µm thick, crack free GaN layers of high crystalline and optical quality for efficient LEDs, exact control of the thermal stress between GaN and Si, e.g. by using AlN interlayers, is essential. Additionally, the high dislocation density in heteroepitaxial GaN is decreased by SiN nano masks. Highly spatially and spectrally resolved low temperature cathodoluminescence (CL) microscopy was performed to investigate the luminescence properties of thick, crack free GaN-layers MOVPE grown on Si(111) substrates. Starting with our optimized template, consisting of an AlN seed layer, a 300 nm thick AlGaN layer, and a nominally undoped GaN layer of 700 nm thickness, several micrometers of Si-doped GaN separated by AlN interlayers were subsequently grown on top. Cross sectional CL microscopy reveals the impact of the various interlayers on quantum efficiency. The changing spectral position of the GaN (D0,X) emission in highly spectrally resolved line scans directly visualizes the stress management as well as the evolution of the free carrier concentration from the substrate to the surface. Microscopic Al fluctuations within the AlGaN layers are directly imaged both, in cross section (vertical) as well as in plan view (lateral) CL microscopy.

7602-06, Session 2

The influence of thermal annealing on optical and electrical properties indium nitride films grown by MOVPE

B. Gil, S. Ruffenach, M. Moret, O. Briot, Univ. Montpellier 2 (France)

Within the last decade, a lot of research efforts have been devoted to Indium Nitride (InN), the least known of the semiconducting group-III nitrides. Most of the samples available today have been grown using the Molecular Beam Epitaxy (MBE) technique, and fewer using the Metal Organic Vapor Phase Epitaxy (MOVPE) method. Whatever the method used, growth of InN with high quality is extremely challenging, in particular due to the fact that no lattice matched substrate is currently available. The growth of low temperature InN buffer layers on both sapphire and GaN layers will be discussed here, along with the use of surfactants (indium halides) in the growth ambient to improve morphology. Furthermore, we will show that an ad-hoc post-growth thermal treatment of InN films dramatically improves both the optical and electrical properties of InN. Thermal annealing of InN layers, here grown by MOVPE is investigated in a nitrogen ambient, for temperatures ranging from 400°C to 550°C and heat treatment times up to 12 hours. This treatment results in hydrogen out diffusion, lowering significantly the residual n-type background doping. By assuming the presence of two hydrogen stable sites in InN, outdiffusion activation energies are estimated at 2.68eV and 2.45eV. Thermal annealing of InN samples under ammonia atmosphere leads to a hydrogenation of the layer. Thermal annealing under ammonia atmosphere of samples annealed under nitrogen ambient leads to a similar optical and electrical properties than the as-grown sample. Hydrogen outdiffusion is thus a reversible process. These results establish a process that allows to obtain InN samples from the MOVPE growth technique which exhibit similar electrical properties than MBE grown samples. This issue is of major importance in view of future industrial production of InN based devices.

7602-07, Session 2

Impacts of point defects on the luminescence properties of (Al,Ga)N

S. F. Chichibu, Tohoku Univ. (Japan); A. Uedono, Univ. of Tsukuba (Japan)

(Invited) Threading dislocations (TDs) in (Al,In,Ga)N are said to affect the luminescence efficiency of the near-band-edge (NBE) emission. However, principal roles of point defects such as vacancies on the luminescent properties have not been fully understood. In this presentation, impacts of point defects on the luminescence quantum efficiency of NBE emissions and on the intensity of characteristic deep emission bands in (Al,Ga)N will be shown, based on the results of steady-state and time-resolved photoluminescence (TRPL) and positron annihilation measurements.

Room temperature nonradiative lifetime of the NBE excitonic photoluminescence (PL) peak in GaN films and crystals having a variety of orientations, polar directions, and polytypes that were grown by various growth techniques was shown to increase with the decrease in concentration or size of Ga vacancies (VGa) and with the decrease in gross concentration of point defects including complexes. The results indicate that nonradiative recombination process is governed not by single point defects, but by certain defects introduced with the incorporation of VGa, such as VGa-defect complexes.

In addition to nonradiative process, cation vacancy concentration was found to correlate with the intensity ratio of characteristic deep emission band to the NBE emission (Ideep/INBE) in AlN and AlxGa1-xN alloys. Since the relative intensities of 3.1 eV and 3.8 eV bands in AlN films grown by NH3-MBE increased remarkably with lowering the supply ratio of NH3 to Al (V/III ratio) and growth temperature (Tg), they were assigned to originate from VAl-O as well as VAl-shallow donor complexes.

7602-08, Session 2

Threading dislocation evolution in patterned GaN nanocolumn growth and coalescence overgrowth

T. Tang, Y. Chen, W. Shiao, W. Chang, C. Liao, C. Lin, K. Shen, C. Yang, National Taiwan Univ. (Taiwan); M. Hsu, Epistar Corp. (Taiwan); J. Yeh, Epistar Corp (Taiwan); T. Hsu, Epistar Corp. (Taiwan)

Threading dislocation (TD) evolution during patterned GaN nanocolumn (NC) growth and coalescence overgrowth with metaloragnic chemical vapor deposition is studied based on the comparisons of NC and coalescence overgrowth samples of different NC cross-section diameters and spacing sizes. From the measurement results of depth-dependent X-ray diffraction and cross-section transmission electron microscopy, it is found that the TD density in an NC depends on the patterned hole size for NC growth. Also, the TD formation at the beginning of coalescence overgrowth is related to the NC spacing size. Although the TD density at the bottom of the overgrown layer is weakly dependent on NC and spacing sizes, at its top surface, the TD density strongly relies on NC size. Among the overgrowth samples of different NC diameters and spacing sizes with a fixed NC diameter/spacing ratio, the one with the smallest size and spacing leads to the lowest TD density, the largest lateral domain size, and the highest photoluminescence efficiency. Also, the optical and crystal qualities at the surfaces of all the overgrowth samples are superior to those of a GaN template.

7602-09, Session 2

Molecular beam epitaxial growth, fabrication, and characterization of InN/Si nanowire heterojunction solar cells

Y. Chang, Z. Mi, McGill Univ. (Canada)

InGaN materials hold great promise for realizing future low cost and high efficiency multi-junction solar cells, due to their ability to encompass the entire solar spectrum. However, current progress has been severely limited by the lack of suitable substrates as well as the difficulty in achieving efficient p-doping. In this context, we have investigated the molecular beam epitaxial growth, fabrication, and characterization of InN/Si nanowire heterojunction solar cells. In this experiment, vertically aligned n-type InN nanowires were spontaneously formed on p-type Si(111) substrates under nitrogen rich conditions. To realize a reasonably good p-n diode, we have first optimized the growth conditions of InN nanowires on Si and achieved, for the first time, non-tapered epitaxial InN nanowires by employing an in situ deposited thin In seeding layer prior to growth initiation. InN/Si heterojunction junction solar cells were fabricated using standard photolithography and contact metallization techniques. The diodes display a rectifying ratio of larger than 1,000 under dark. We measured a short-circuit photocurrent density of ~ 10 mA/cm2 and an energy conversion efficiency of ~ 1% under AM1.5 illumination. Further improvement in the power efficiency is being investigated by optimizing the growth and fabrication process. In addition, the design, growth, fabrication, and characterization of InGaN nanowire multi-junction solar cells on Si will be presented.

7602-10, Session 2

The comprehensive characteristics of quaternary AlInGaN with various TMI molar rate

S. Yu, R. Lin, Chang Gung Univ. (Taiwan)

The crystal structure characteristics and surface morphology of very thick AlInGaN (~ 400 nm) quaternary alloys on GaN epilayer, which was grown by atmospheric pressure MOCVD were investigated. We successfully got a fully lattice-match crystal structure as indium (Trimethylidium, TMI = 18.76 mol/min) incorporated into Al0.13Ga0.87N alloy. And the growth rates of AlInGaN epilayers were decreased instantly as the flow rates of TMI molar were increased. We also demonstrated the variation of In, Al composition, mobility and concentration of difference AlInGaN films. On the other hand, the V-defect pits density and pits size were dramatically decreased when increasing TMI precursor flow rate. It shows that the Indium incorporated into AlGaN ternary epilayer may effectively make up the V-defects pits. Meanwhile, the PL spectrum shows the interesting phenomenon that a lower energy band gap state exhibited besides the main AlInGaN peak and this wavelength and intensity would depend on TMI molar flow rate. Finally, HRXRD (302) omega scan measurement would point out the crystal quality have critical concerned as indium incorporated into AlGaN alloys.

7602-11, Session 3

Ammonothermal growth of GaN substrates

R. Dwilinski, R. Doradzinski, J. Garczynski, L. Sierzputowski, M. Zajac, Ammono Sp. z o.o. (Poland)

Ammonothermal method focuses great interest of both scientific and industrial community due to its merits like growth in equilibrium conditions, growth in a closed system and scalability. Recently, a large progress has been made in the development of the growth of truly bulk GaN crystals by ammonothermal method. High quality 2-inch c-plane GaN substrates have been presented by AMMONO last year. Currently 1 and 1.5-inch substrates are available on the market. In considered crystals a low dislocation density (5 x 10E3 cm-2) is attainable. At the same time the crystal lattice is extremely flat and the (0002) rocking curve is very narrow (FWHM=16 arcsec).

Because of no piezoelectric field along the [1-100] or [11-20] direction in GaN crystals, there is also increasing interest in non-polar m-plane substrates. Such wafers can be cut out from thick GaN crystals grown by ammonothermal method. A low dislocation density, of the order of 10E4 cm-2, was achieved. Perfect crystallinity manifests also in very narrow X-ray (0002) rocking curves, with FWHM values of about 16 arcsec. GaN epilayers deposited on these substrates exhibit intrinsic narrow exciton lines, which are very sensitive to the optical selection rules typical for hexagonal symmetry - the free exciton A line completely disappears in E || c configuration, proving truly nonpolar character of AMMONO-GaN substrates.

Other challenges like homogenous insulating properties or high p-type conductivity have been also accomplished by means of ammonothermal method. Semiinsulating crystals of resistivity up to 10E11 Ω x cm and p-type conductivity within hole concentration up to 10E18 cm-3 are already available in diameters up to 1.5-inch. The conductivity was confirmed by both capacitance-voltage and optical spectroscopy measurements results (change of the surface band bending from n-type samples to p-type samples).

7602-12, Session 3

Nonpolar m-plane GaN film and polarized InGaN/GaN LED grown on LiAlO2 (001) substrates

R. Zhang, Z. Xie, B. Liu, X. Xiu, D. Fu, Z. Zhang, P. Han, Y. Zheng, Nanjing Univ. (China); S. Zhou, Shanghai Institute of Optics and Fine Mechanics (China)

Polarization and strain are key factors to influence energy bands of III-nitrides and their quantum wells, due to very large spontaneous and piezoelectric polarization in these materials. Based on these effects, people could tailor the band structures and design novel devices with new features. In this talk we will present theoretical calculations of band modification based on controlling polarization and strain in the III-nitride films and quantum structures. Polar and non-polar III-nitride materials are investigated via theoretical and experimental studies.

The m-plane GaN films and GaN/InGaN QWs were grown by metal-organic chemical vapor deposition (MOCVD). The band structures of the GaInN/GaN QWs are studied by simulation and photoluminescence (PL) measurements. It is found that the degenerated valence bands of the InGaN/GaN QWs split into some subbands with different polarization directions. This polarization effect is related to the broken of symmetry of original wurtzite structure due to the anisotropic strain distribution in the growth plane. The theoretical model of splitted bands and new selection rules will be described and discussed. The non-polar m-plane InGaN/GaN quantum wells (QWs) and blue/green light-emitting diodes (LEDs) on LiAlO2 (100) substrates are reported. The almost stationary electroluminescence (EL) peaks at 515~516nm are observed with injection currents in excess of 20mA, which proves the absence of polarization fields in the active region.

7602-13, Session 3

Magnetic cages of GaN nanoclusters doped with Gd and Nd

V. Kumar, Dr. Vijay Kumar Foundation (India); J. M. Zavada, U.S. Army Research Office (United States)

We have studied (GaN)n nanoclusters with n in the range of 12-48 using ab initio pseudopotential calculations with generalized gradient approximation (GGA) for the exchange-correlation energy. We find cage structures of GaN clusters to be lower in energy as compared to bulk fragments which have been fully optimized. Selected cages have been doped with Gd and Nd atoms by substituting Gd or Nd on Ga sites. The atomic structures of such doped nanoclusters have been optimized using spin-polarized GGA and by including all f electrons on the rare earth atoms. We find the doped nanoclusters to be magnetic with 7 μB (3 μB) magnetic moments when 1 Gd (Nd) atom is doped. However, when 2 Gd (Nd) atoms are substituted, then often there is ferromagnetic coupling between the rare earth atoms, but we also find zero net magnetic moment in the nanocluster depending upon the separation between the doped atoms suggesting that both ferromagnetic and antiferromagnetic couplings may occur between the rare earth dopants. The results of the electronic structure of the doped clusters will be discussed and compared with experiments where available.

Work supported by the US Army Research Office and the US Army International Technology Center-Pacific (ITC-PAC). Discussions with Dr. J.P. Singh (ITC-PAC) are gratefully acknowledged.

7602-14, Session 3

Growth of rare-earth-doped GaN crystals by the ammonothermal technique

B. Wang, D. F. Bliss, M. J. Suscavage, S. Swider, C. Lynch, W. Eikenberry, Air Force Research Lab. (United States)

Rare-earth-doped GaN crystals have interesting luminescence properties, and therefore have potential applications as infrared laser host materials. In addition, rare-earth additives in the growth media can function as oxygen getters to reduce contamination. Growth of bulk GaN crystals for electronic and optoelectronic applications is under development at the US Air Force Research Laboratory at Hanscom AFB. We have grown undoped and doped GaN crystals using the ammonothermal technique, which employs high-pressure ammonia solution to produce free-standing GaN crystals in a cost-effective manner. Here we will report the ammonothermal growth of rare-earth (lanthanum, erbium and ytterbium) doped GaN bulk crystals, and discuss the incorporation of these elements into GaN crystals. The concentration of dopants, as well as the effect of the doping on crystal morphology, structural quality and optical properties characterized by SIMS, microscope, X-ray and PL will be also presented.

7602-15, Session 3

Extended defects in semipolar (11-22) nitride semiconductors

Y. Arroyo Rojas Dasilva, P. Ruterana, Ecole Nationale Supérieure d'Ingenieurs de Caen et Ctr. de Recherche (France); L. Lahourcade, E. Monroy, Commissariat à l'Énergie Atomique (France); G. Nataf, Ctr. de Recherche sur l'Hétéro-Epitaxie et ses Appliations (France)

Gallium nitride (GaN) is the subject of extensive investigations due to its numerous applications for optoelectronics and electronics. C-plane is the most common orientation for the growth of GaN films. During the last years, a tremendous reduction of the defects densities has taken place through the use of techniques such as lateral epitaxial overgrowth allowing huge improvement of the device performances. However, c-layers suffer from intrinsic limitations due to polarization effects, which produce strong electric fields in heterostructures, reducing the radiative recombination efficiency of nitride devices. One approach to avoid this problem is to grow the layers along directions perpendicular (non-polar) or inclined (semi-polar) to the [0001] axis. In semi-polar layers, the [0001] axis lies at an angle of the heterostructure interfaces, and therefore the polarization effects are attenuated.

This work shows Transmission Electron Microscopy analysis investigating (11-22) semi-polar GaN layers grown by metal-organic vapour phase epitaxy (MOVPE) and molecular beam epitaxy (MBE) techniques. Our preliminary results show that the majority of the formed extended defects may not be perfect dislocations as when the growth is carried out along the c-axis. Instead, most of the defects are formed inside the basal planes. Stacking faults are found terminating by a network of partial dislocations. These partial dislocations have Burgers vectors b=1/3<1-100> and b=1/6<20-23> limiting basal stacking faults of I1 and I2 types. These results will be discussed within the framework of the particular growth geometry.

Acknowledgement: The authors acknowledge the support of the National Research Agency under contract N° ANR-08-BLAN-0298-01

7602-16, Session 4

Plasmon-assisted dissipation of LO-mode heat in nitride 2DEG channels

A. Matulionis, Puslaidininkiu Fizikos Institutas (Lithuania)

Heat dissipation is the central problem for nitride heterostructure field-effect transistors designed for high-power applications. The heat, accumulated inside the two-dimensional electron gas (2DEG) channel, causes additional scattering of electrons, reduces transistor frequency and efficiency. Poor efficiency, in its turn, enhances heat accumulation. The traditional approach simplifies the problem to heat capacitance and thermal resistance. This approach is inadequate for nitrides-it totally ignores the heat accumulated by longitudinal optical (LO) phonons (LO-mode heat). Due to strong electron-LO-phonon coupling, the LO-mode heat is mainly responsible for the enhanced electron scattering.

Dissipation of the LO-mode heat will be discussed in terms of plasmon-assisted decay of non-equilibrium LO phonons. The measured non-monotonous dependences of the LO-phonon lifetime on the 2DEG density and the supplied power are explained by the LO-phonon-plasmon resonance: the fastest decay of LO phonons takes place near the resonance. The resonance 2DEG density depends on the supplied electric power. A higher hot-electron drift velocity is demonstrated when the lifetime is made shorter.

The conventional wisdom of the increased electron density leading to better devices does not hold at electron densities exceeding the resonance 2DEG density. Longer LO-phonon lifetimes lead to stronger accumulation of LO-mode heat, and the resultant reduced electron velocity and power conversion efficiency. Because of steep increase of the LO-phonon lifetime with the 2DEG density, no improvement of HEMT performance is expected beyond the resonance density. Knowledge of the optimal conditions for dissipation of LO-mode heat is important for advanced HFET engineering.

7602-18, Session 4

The role of buffer/substrate strain and comparison with charge control analysis of gallium nitride HFET failure mechanisms

A. Christou, Univ. of Maryland, College Park (United States)

Conventional high electron mobility transistors (HFETs) based on AlGaN/GaN heterostructures have been accurately modeled and the results are described in this paper. The Schroedinger's equation and the Poisson's equation have been solved self-consistently in order to obtain a relationship between the polarization sheet carrier density and the applied gate voltage. The relationship is treated using a non-linear exponential fit that enables a more accurate analysis of the saturation region compared to other models used hitherto. The I-V characteristics have then been predicted by a charge control analysis that utilizes the exponential charge-potential relationship which helps exactly identify the saturation point without having to resort to parameter extraction from other experiments. This leads to separating the linear and saturation regions by a well defined boundary as a result of which the I-V characteristics are more accurately modeled. The intrinsic non-linearity in polarization charge determines the lack of well defined pinch off voltage as well as the current collapse when trap centers are present. Specifically the two donor type traps and one acceptor trap were included in the current voltage calculation.

CHARGE CONTROL

There are two important issues that govern the AlGaN/GaN high electron mobility transistors (HEMTs) which are significantly different from HEMTs made from structures such as AlGaAs/GaAs or InAlAs/InGaAs. The first has to do with the very strong piezoelectric effect present due to the lattice mismatch between AlGaN and GaN. It is known that group III nitrides have large piezoelectric constants along the (0001) direction. When (0001)-oriented thin AlGaN layers are grown pseudomorphically on a thick GaN, the biaxial strain induces a piezoelectric field in the material. As a result, there is a strong interface charge at the HEMT interface. The second effect has to do with interface roughness. Although this effect is present in other HEMT structures as well, the larger band discontinuity combined with larger effective mass in the channel makes interface roughness much more important in controlling the channel mobility. Additionally, the combination of interface roughness and piezoelectric effect can cause the charges at the interface to be distributed nonuniformly.

In fact, a unique feature of AlGaN/GaN material system is the high sheet carrier concentration (in the order of 1 x 1013 cm), which can be achieved in the channel not only due to the large bandgap discontinuity at the interface, but also due to the pizoelectric and spontaneous polarization effects without intentionally doping the barrier layer. Theoretical and experimental studies carried out by many researchers showed the effect of both spontaneous and piezoelectric polarizations on the carrier distribution at the heterointerface, and the importance of

proper inclusion of these effects in the analysis of III nitride structures.

In the area of device modeling, several theoretical models have been reported in the literature. One group of these models solves Poisson's equation coupled with Schrodinger's wave equation self-consistently using trial wave functions [1]. However, the treatment of the 2DEG was carried out in a similar way like that in AlGaAs/GaAs HEMTs, and the obtained results reflected only the difference in material systems of the two devices. Another group of models gives simple analytical formula for the sheet carrier density ns versus the Al mole fraction x, for normally undoped HEMT structures including piezoelectric polarization effect. This formula was further modified to include the effect of both spontaneous and piezoelectric polarizations and doping of the barrier layer [2,3]. In another attempt, an analytical expression for the Fermi-level versus ns and interpolation formulae for calculation of the polarization sheet charge density are given. Non-linear formulae for the polarization effects were incorporated into a quasi-2D model presented in, instead of the linear interpolations.

THE PHYSICS OF FAILURE

High electron mobility transistors fabricated from nitride semiconductors utilizing the AlGaN/GaN heterojunction demonstrate excellent performance in RF range. However, the nitride devices demonstrate reliability problems where the dc current and RF output power continually decrease as a function of time. One of the reliability problems is related to the conduction characteristics of the gate electrode and an electron tunneling mechanism where electrons leak from the gate to the surface of the semiconductor. Although the degree of performance degradation varies with the design, processing steps, and device manufacturer, all high voltage AlGaN/GaN transistors are affected and the problem is more severe as operating frequency is increased. However, the more detailed study should consider trap generations, trapping behaviors (regarding long-term and temporary recovery), and correlation between damage and trap density. The degradation mechanism should include issues such as piezoelectric effects, tensile strain, and electron trapping, defect formation, aimed to predict electrical behavior of the device (Current Collapse, Power soak, DC and RFdegradation. In the present work, the Poisson's and the Schroedinger's equations are solved self-consistently to obtain the wave functions, the eigenenergies and the carrier distribution at the hetero-interface. Calculations are performed for different gate biases to obtain a relationship between the carrier density and the applied gate voltage. We neglect higher order terms, since from [4], electron-electron interactions within inversion layers on polar materials is negligible.

We have applied the Rayleigh-Ritz method to solve the two dimensional Schroedinger equation equation. The procedure for solving eigenvalue problems using the variational method is obtained from [4]. This method determines the finite set of eigenvalues and eigenfunctions. The basis functions that characterize the wave function are chosen so as to satisfy the boundary conditions: (0) = 0, and (a) = 0, where a is the width of the channel which is set to 10 nm as this would be suitable for a typical AlGaN/GaN conventional structure.

SUMMARY AND CONCLUSION

The I-V characteristics of an AlGaN HEMT have been accurately simulated by a charge control model that takes into account the size quantization effects present in the interface. This has been done by self-consistently solving the Poisson's and the Schroedinger's equations. We have used an exponential charge - potential relationship which more accurately describes the I-V characteristics of a HEMT by actually dealing with the real non-linear nature of these devices near the saturation, a region of most interest in device applications. The exponential relationship, when used in the charge control model, determines the saturation point without having to resort to parameter extractions from other data. The exponential relationship also explains the non-linear pinch-off characteristics found in these devices

1. Frank S., S Nour, and H. Morkoc, "Theoretical investigation of electrical characteristics of AlGaN/GaN modulation doped field-effect transistors," J.Appl. Phys., Sept. 1 (1996).

2. E. T. Yu, , P. Asbeck, C. D. Wang, D. Qiao, and S. S. Lau , " Measurement of piezoelectrically induced charge in GaNY'AlGaN heterostructure field- effect transistors," Appl. Phys. Lett., Nov. 10 (1997).

3. E. T. Yu, P. Asbeck, X. Z. Dang, S. S. Lau, G. J. Sullivan, "Spontaneous and piezoelectric polarization effects in IIIV nitride heterostructures," J. Vac. Sci Technol. B17 (4), Jul/Aug. (1999)].

4. Mathew N. O. Sadiku. Numerical Techniques in Electromagnetics, p. 255-302. CRS Press, 1992.

7602-19, Session 4

Transmission electron microscopy and XRD investigations of InAlN/GaN thin heterostructures for HEMT applications

A. Vilalta Clemente, M. Morales, M. Chauvat, Y. Arroyo-Rojas Dasilva, Ecole Nationale Supérieure d'Ingenieurs de Caen et Ctr. de Recherche (France); M. A. Poisson, Alcatel-Thales III-V Lab. (France); M. Heuken, C. Giesen, AIXTRON AG (Germany); P. Ruterana, Ecole Nationale Supérieure d'Ingenieurs de Caen et Ctr. de Recherche (France)

The InxAl1−xN material system is highly attractive for possible applications in high electron mobility transistor. Heterostructures InAlN/GaN, grown by metal organic chemical vapour deposition (MOCVD), have been investigated by transmission electron microscopy (TEM), atomic force microscopy (AFM) and X-ray diffraction for determination of the residual strain. The TEM samples were prepared by optimized conditions of mechanical polishing and Ar ion beam thinning at low voltage and LN2 temperature in order to keep as close as possible the local structure and chemistry of the layers. In these materials where the lattice parameters are so different, the control of the growth conditions is probably a challenge and tight iterative characterisation of the processes is often necessary for optimisation. Observations show that in this instance, in a same growth sequence, the composition of the layers may oscillate between 13-21% In composition. So, the control of the growth parameters may not be so straightforward.

In this work, we have carried out extensive investigation, by total reflection XRD and TEM, of ultrathin AlInN and QWs layers grown by MOVPE. The observations point out the important role of the few AlN monolayers (MLs) which are often deposited at the onset of the ternary. We will report on the evolution of the local strain with these AlN MLs at and around the lattice matched In fraction.

The support of the EU under Grant agreement N°: PITN-GA-2008-213238 (RAINBOW project: Initial Training Network of the 7th RTD Framework) is gratefully acknowledged.

7602-79, Session 4

GaInN light-emitting diodes with highly transparent ZnO:Ga oxide cap layer

H. Liu, X. Li, X. Ni, V. Avrutin, N. Izyumskaya, Ü. Özgür, H. Morkoç, Virginia Commonwealth Univ. (United States)

High-efficiency nitride-based light emitting diodes (LEDs) are considered as one of the most attractive solutions for energy-efficient lighting. One of the factors limiting the efficiency of LEDs is the high resistivity of p-type GaN giving rise to severe current crowding under the p-type electrode as well as the partial opacity of the semitransparent contact metal.
To alleviate this problem, thin Ni based contacts annealed in oxygen-containing ambient and indium tin oxide (ITO) electrodes have been extensively investigated as transparent oxide contact layers. However, the transparency of the Ni/Au based contacts is below 70% in the visible spectral region [1] while that of ITO is in the vicinity of 80-90% with the aggravating factor of potential scarcity of In for this purpose. ZnO-based TCO films appear to be one the most attractive material systems, since ZnO and GaN are the structural twins that offer the possibility of epitaxial growth of transparent electrodes with improved carrier mobility and optical transparency. In addition, they exhibit several advantages over ITO, such as superior thermal conductivity, transparency, and thermal stability [2].

We have demonstrated that the transparency of epitaxial ZnO heavily

doped with Ga (GZO) on sapphire can reach ~95% while maintaining an electrical resistivity as low as ~2 x 10-4 Ω cm [3]. In this work, we report on improved current spreading and light emission uniformity for InGaN/GaN LED structures employing top GZO transparent electrodes.

The InGaN/InGaN LEDs with varying active-region structures emitting at 400-410 nm were grown on (0001) sapphire substrates in a vertical low-pressure metalorganic chemical vapor deposition system.GZO transparent electrodes were grown epitaxially on the top p-type GaN of the LED structures at 300oC by plasma-assited molecular-beam epitaxy under metal-rich conditions. Resistivity, electron density, and mobility in the GZO were 2-to-3 x 10-4 Ω cm, 7-to-9 x 1020 cm-3,and ~35 cm2/(Vs) respectively. Relative external quantum efficiencies of the LEDs with the GZO and control devices with thin Ni/Au top electrodes were assessed from electroluminescence measurements. LEDs with the GZO transparent electrode showed slightly lower forward voltage for a given current as compared to that with the Ni/Au contacts but much more uniform light output and superior brightnesses exceeding those of controls by a factor of ~1.5. Furthermore, the Ni/Au contact ones suffer from filamentation which is absent in GZO varieties.

REFERENCES

[1] H. Kim, D. J. Kim, S. J. Park, and H. Hwang, J. Appl. Phys. 89, 506-1508 (2001).

[2] J.-K. Sheu, Y. S. Lu, M.-L. Lee, W. C. Lai, C. H. Kuo, and C.-J. Tun, Appl. Phys. Lett. 90, 263511 (2007).

7602-20, Session 5

Quantum 1/f noise theory and experiment in QWIPs

A. M. Truong, P. H. Handel, Univ. of Missouri-St. Louis (United States)

The dark current of Quantum Well Inter-subband Photodetectors is known to be affected by quantum 1/f noise. This limits the detectivity. This paper compares various experimental 1/f noise measurements in QWIPs with the prediction of the conventional quantum 1/f noise expression for GaN/AlGaN QWIPs. Both the collisionless and collision-dominated cases are considered. The elementary process causing the dark current is the transfer of an electron from one well to the neighboring well. This happens under the influence of the applied electric field, and has in general both thermally activated and tunneling components. The larger the applied electric field, the larger is the squared velocity change of the carriers, and the larger is the obtained conventional quantum 1/f effect. The detectivity of the devices is calculated on this basis. The results are compared with measurements of 1/f noise in QWIPs by J. Jiang [1], C. Jelen [2] and M. C. Hsu, and the agreement is good.

[1] J. Jiang, “Infrared focal plane array based on GaInAs/InP QWIPs”, Northwestern U. PhD Thesis, Evanston, IL, 2003.

[2] Christopher Jelen, Steven Slivken, Vivian Guzman, Manijeh Razeghi, and Gail J. Brown: InGaAlAs-InP Quantum-Well Infrared Photodetectors for 8-20µm Wavelengths, IEEE J. of Quantum Electronics, 34, 1873-1876 (1998)

7602-21, Session 5

HFET and MISHFET stability, 1/f noise, and reliability

P. H. Handel, Univ. of Missouri-St. Louis (United States); H. Morkoç, Virginia Commonwealth Univ. (United States)

Our recently found stability criterion [1] for HFETs is applied to AlGaN/GaN and other types [2] of HFETs and structures with spontaneous polarization of the gate insulation, to determine in which conditions the criterion is satisfied. In essence, the criterion requires a faster decrease of the spontaneous gate polarization than of the resistivity when temperature increases locally. The instability will be stronger in certain temperature intervals, and will result in 1/f noise increase. The implications for engineering design for increased device reliability at large positive gate bias and high power dissipation are analyzed.

We further investigate the beneficial effects noticed in our previous paper, arising from insulating layers deposited on top of the AlGaN layer in GaN HFETs. These devices are also known as MISHFETs. We also include the effect of the insulating layer, e.g., SiO2, on the channel 1/f noise and on the device noise figure. This investigation is done on the basis of the quantum 1/f theory [3] and of our stability criterion mentioned above. Both QED and piezoelectric quantum 1/f effects are considered.

[1] Qian Fan e.a. “Comparison of various gate dielectrics in the performance of AlGaN/GaN HFETS” in Gallium Nitride Materials and Devices III. Edited by Morkoç, Hadis e.a., Proceedings of the SPIE, Vol. 6894, 689426 (2008). pp.1-7.

[2] J. Pavelka e.a. “Low-Frequency Noise Characteristics of InGaAs/InAlAs Heterostructures”, AIP Conf. Proceedings #1129, “Noise and Fluctuations” ISBN 978-0735406650, pp.183-186.

[3] P.H. Handel e.a. Nanoscale Engineering for Reducing Phase Noise, Proc. IEEE 93, 1784-1814 (2005).

7602-22, Session 5

Analytical calculation of the quantum 1/f coherence parameter for HFETs

P. H. Handel, Univ. of Missouri-St. Louis (United States)

The ratio s of the coherent magnetic energy term and the incoherent mechanical kinetic energy terms of the drift motion in the hamiltonian of a current carrying system is calculated for the special cases of a HFET or FET. This ratio defines the resulting quantum 1/f noise from the coherent and conventional quantum 1/f effects.

In this case of FETs and HFETs of much larger width w>>LDS>t, the kinetic energy Ek of average motion with drift velocity vd per unit length in the direction of the drain-source distance LDS in the channel of thickness t, is still given by Nmvd2/2, but the magnetic energy Em per unit length in the direction of LDS is roughly proportional with the first power of w only, instead of w2, and can be approximated by Em = π[ln(w/2LDS)]LDS[nevS/c]2/w. This indicates decoherence along the device width w. This yields a coherence ratio of s Em/Ek ≈ πnrotLDSln(w/2LDS), which shows that only an effective width w=weff about equal to LDS should be used in the calculation of the coherence parameter s in this special case; larger widths are subject to de-coherence. This favors lower, mainly conventional, quantum 1/f noise in these devices, in spite of the large values of w. It also explains for the first time why the huge widths are possible with impunity, i.e., without causing the much larger coherent quantum 1/f noise to appear. For non-uniform current distribution across t, and for piezoelectric coupling, improved forms are derived for s.

7602-23, Session 5

Measurements of gate lag in high quality nearly lattice matched InAlN/AlN/GaN HFET structures

J. H. Leach, M. Wu, X. Ni, X. Li, Ü. Özgür, H. Morkoç, Virginia Commonwealth Univ. (United States)

InAlN-based HFET devices are promising due to the relatively large band discontinuity at the interface and lack of misfit strain when grown lattice matched to GaN. However, there still exists some question as to what the true lattice matching condition of InAlN to GaN is due to discrepancies in the literature values of lattice parameters of the InN binary, and of the InAlN bowing parameters. We used the gate lag measurement as a supplementary technique to verify lattice matching to the underlying GaN, as strain-free layers would be free of one source of lag, associated with piezoelectric charge at the surface. We observe very low lag for a nearly lattice matched barrier, and a marked increase as the composition deviates from the lattice matched condition. Additionally, FETs fabricated on a nearly lattice matched layer boast a maximum drain current of over 1.5A/mm and ~2.0A/mm and transconductances of ~275mS/mm and ~300mS/mm at DC and in pulsed modes, respectively, and a cutoff frequency of 15.9GHz (an fT*LG product of 10.3) for a gate length of 0.65mm.

7602-24, Session 6

Spatio-time-resolved cathodoluminescence spectroscopy imaging: microscopic correlation of real structure and recombination kinetics in InGaN quantum wells

J. Christen, S. Metzner, F. Bertram, Otto-von-Guericke-Univ. Magdeburg (Germany); T. Wunderer, F. Lipski, S. Schwaiger, F. Scholz, Univ. Ulm (Germany)

MOVPE selective area overgrowth of SiO_2 mask patterned into hexagons results in the formation of 3D inverse pyramids formed by {10-11} and {11-22} facets. An InGaN single quantum well was grown on top of this patterned surfaces. The differences in crystal structure, strain, polarization fields, In-incorporation and/or SQW-thickness result in an extremely complex interaction of relaxation, recombination in energy, space, and time, as well as transport of the excited carriers. For a clear cut understanding of this complex nanoscopic kinetics highly spatio-time-resolved techniques are essential. We present results from ps-time- and nm-spatially resolved cathodoluminescence (CL) microscopy. Microscopic local transients taken at the center of the inverted pyramids exhibit a very short lifetime down to 200 ps. Upon going up to the ridge of the pyramid, the life time dramatically increases reaching > 10 ns at the ridges. Time delayed CL maps TDCLI directly reveal the strong difference of the local lifetime. In particular at the center of the pyramids the CL intensity vanishes very fast in less than a few ns after switching off the excitation, whereas at the ridges the CL persists even after 55 ns. This gigantic microscopic modulation of the initial lifetime is imaged in lifetime mappings, which directly correlate with the nano-morphology as well as the microscopic local emission wavelength of the InGaN QW, i.e. the local In-content and/or SQW-thicknesses. Normalizing the total lifetime to the local quantum efficiencies yields a microscopic image of the radiative lifetime directly mapping the local SQW oscillator strengths.

7602-25, Session 6

Nano-ultrasonic based on GaN nano-layers

C. Sun, Y. Wen, National Taiwan Univ. (Taiwan)

Through the accurate control of material growth and advanced femtosecond technology, the successful generation and detection of high frequency nano-acoustic waves has lead to the new field of nanoultrasonics and nanophononics, which make nanoinvasive 3D nanoimaging and SASER generation possible. In this presentation, we review our current development on nano-ultrasonic by using piezoelectric nano-layers based on the GaN material system. Our study indicated that piezoelectric semiconductor nanostructures can serve as optical piezoelectric transducers to generate and detect nanoacoustic waves through the piezoelectric effect. The nanoacoustic waves, with a wavelength on the order of or shorter than 10 nm, can be used for high accuracy THz electron control, noninvasive sub-nanometer interface probing, and nano-ultrasonic imaging. Detailed experimental observations and the design principles will be given in the talk.

7602-26, Session 6

Effect of Fe doping on the conductivity of HVPE grown GaN studied by time-domain terahertz spectroscopy

F. Kadlec, C. Kadlec, Institute of Physics of the ASCR, v.v.i. (Czech Republic); T. Paskova, K. R. Evans, Kyma Technologies, Inc. (United States)

A set of GaN bulk single crystals with different degree of Fe doping were investigated using time-domain terahertz spectroscopy at temperatures from 300 to 900 K. The samples were produced by Kyma Technologies using hydride vapor phase epitaxy (HVPE). The undoped sample contains free charge carriers the presence of which is linked to atoms of impurities. Its room temperature spectra of optical constants exhibit a Drude-like shape which makes it possible to deduce the plasma frequency and other parameters of the free carriers. Upon heating and with increasing Fe contents, the Drude-like character of the spectra gradually disappears.

In the spectra of optical constants of all samples, three contributions can be discerned: (i) that of free carriers which determines the shape of the spectra for the undoped and weakly doped samples; (ii) a flat background due to polar excitations beyond the accessible frequency range, which displays a slow and doping independent increase upon heating and (iii) a small broad peak, observable at frequencies above 2 THz and especially at higher temperatures.

The effect of doping is the most pronounced in the room temperature conductivity of the samples. In the undoped sample, the THz range conductivity can be extrapolated to the DC conductivity value of 1 $(Ohm.cm)^{-1}$. For other samples, the curves cannot be reliably extrapolated but the conductivity values at a fixed frequency can be compared. At 0.5 THz, the conductivity difference between the most conductive (undoped) sample and the least conductive one reaches almost three orders of magnitude.

7602-27, Session 6

Temperature dependent micro-photoluminescence of the inversion domain boundary in GaN

R. Kirste, Technische Univ. Berlin (Germany); R. Collazo, North Carolina State Univ. (United States); G. Callsen, M. R. Wagner, Technische Univ. Berlin (Germany); A. Rice, North Carolina State Univ. (United States); S. Mita, J. Xie, HexaTech, Inc. (United States); Z. Sitar, North Carolina State Univ. (United States); A. Hoffmann, Technische Univ. Berlin (Germany)

We report on lateral resolved, temperature dependant micro-photoluminescence (micro-PL) measurements of inversion domain boundaries (IDB) in GaN-based lateral polar junctions (LPJs) grown by MOCVD. By etching a low temperature (LT-) AlN nucleation layer deposited on a sapphire substrate a LPJ was grown, thus the inversion domain from the Ga- to the N-polar region could be characterized with SEM, on-plane Raman spectroscopy and micro-PL. SEM reveals a smooth surface morphology for the Ga-polar regions and a rougher surface morphology in the case of the N-polar regions. Lateral resolved Raman spectroscopy shows a small compressive strain but high crystal quality for the Ga-polar regions and a nearly relaxed layer with decreased quality for the N-polar regions. At low temperatures micro-PL measurements reveal a strong emission line around 3.46 eV in the IDB, which is in good agreement with previous results [Schuck et al., APL 79, No.7 (2001)]. Comparing the intensities at this energy an increase by more than two orders of magnitude compared to the Ga- or N-polar region can be observed. At 8K the emission area is a stripe along the IDB with a thickness of 250 nm, which is the resolution limit of the setup. With increasing temperature the stripe broadens up to a thickness of 10 µm at 100 K. A reason for that broadening could be carrier diffusion or

thermalization from potential barriers [Fiorentini, APL 82, No.8 (2003)], which is clarified by the investigation of samples with different carrier mobility.

7602-28, Session 6

Aging of deep-UV AlGaN quantum well LED studied by scanning near-field optical spectroscopy

S. Marcinkevicius, Kista Photonics Research Ctr (Sweden); A. Pinos, Kista Photonics Research Ctr. (Sweden)

Emission from a 285 nm light emitting diode (LED) based on AlGaN quantum wells has been studied by scanning near-field optical spectroscopy. During the measurements, electroluminescence (EL) and morphology scans over a typical area of 10×10 µm with a 100 nm step size have been performed. At each point of the scan, an EL spectrum has been recorded. Analysis of the spectra allowed plotting maps of the EL intensity and central emission wavelength. The near-field scans showed that in the prevailing part of the device spectral variations of the emission are very small with the peak wavelength varying within 1 nm. At certain locations, however, µm-size domain-like areas, emitting with a higher intensity and at a longer wavelength, have been found. The longer emission wavelength has been attributed to local variation of Al molar fraction, previously observed in AlGaN epitaxial layers. Subsequent scans have revealed that, with time, EL intensity from the "hot" spots increases and emission wavelength shifts to the red, indicating a change of the quantum well alloy composition. This has allowed distinguishing a novel LED aging mechanism based on a positive feedback that involves locally increased current, temperature and atom migration.

7602-29, Session 6

Thermal Conductivity Measurement of Pulsed-MOVPE InN Alloy Grown on GaN / Sapphire by 3 Method

H. Tong, J. A. Herbsommer, V. A. Handara, H. Zhao, G. Liu, N. Tansu, Lehigh Univ. (United States)

Recently, the thermoelectric and device cooling applications of InGaN alloy draw a lot of attention, which leads to the importance of accurate thermal conductivity measurements of high-quality InN and InGaN alloys. The thermal conductivities of GaN and AlN have been reported in literatures. However, the thermal conductivity of high-quality InN is still absent, due to the challenge in growing high-quality InN material.

In this work, we present the thermal conductivity measurement and growth of InN alloy grown on GaN on sapphire substrate by employing pulsed-MOVPE method. The use of pulsed-MOVPE resulted in high-quality narrow-bandgap (0.77eV) InN alloy, with strong room temperature photoluminescence. The thermal conductivity of the InN layer was measured by employing 3 method, and thermal conductivities of sapphire substrate and GaN layer were measured to confirm the measurement technique. We found that the conventional 3 differential technique used in data reduction of thermal conductivity for thin films is not applicable, as the thermal conductivities of GaN and InN are larger than that of sapphire substrate. To accurately extract the thermal conductivities of GaN and InN grown on sapphire substrate, 2D multilayer thermal diffusion model and 3 slope technique are developed. The thermal conductivity of sapphire substrate is measured as 41W/mK. The thermal conductivity of u-GaN layer is measured as 108W/mK, in agreement with reported values. High-quality pulsed-MOVPE InN exhibited thermal conductivity of 126W/mK, which is higher in comparison to the previously-reported value of porous InN ceramics (45W/mK), yet lower than the theoretical value (176W/mK) based on phonon scattering.

7602-30, Session 7

Radiative and non-radiative decay in group III nitrides

A. Hoffmann, M. R. Wagner, R. Kirste, Technische Univ. Berlin (Germany)

For all nitride based opto-electronic devices the understanding of the radiative and non-radiative processes of the ternary alloys InGaN and AlGaN is of essential importance. Optical experiments reveal that the non-linear contribution of the alloy composition on the energy gap dependence is small in AlGaN. Thus, AlGaN behaves different compared to InGaN where the bowing is large. A key issue is to understand why the free carrier concentration in AlGaN and InGaN drops significantly whereas at the same time the thermal activation energy of the conductivity increases considerably. In this contribution, we report on optical properties of group III nitrides by calorimetric absorption spectroscopy. The experiment delivers the values of the quantum efficiency at low temperatures. These are calibrated fix points for time- and temperature dependent measurements. Hence, an efficient tool to determine the radiative and non-radiative part of the decay in group III nitrides is available. This study offers the possibility to investigate the origin of the non-radiative processes. The influence of phonon assisted processes and auger mechanisms in the non-radiative decay will be discussed. Furthermore, calculations of the electron and hole envelope functions lead to values of the exciton binding energies and oscillator strengths. The thresholds for lasing in nitride-based MQWs are probably lowered by the distribution of piezoelectric field in the barrier layers. Such a distribution counterbalances the quantum confined Stark effect in single quantum wells. The understanding of the defect incorporation will assist in the control of piezoelectric fields and the non-radiative decay.

7602-31, Session 7

Cathodoluminescence microscopy of self-organized InGaN nanostructures on GaN pyramids

S. Metzner, F. Bertram, J. Christen, Otto-von-Guericke-Univ. Magdeburg (Germany); M. Jetter, C. Waechter, P. Michler, Univ. Stuttgart (Germany)

The luminescence of InGaN nano-structures grown by selective MOVPE is analyzed by highly nm-spatially, spectrally, and ps-time resolved cathodoluminescence microscopy. Self organized grown hexagonal GaN pyramids on c-plane sapphire were overgrown by an InGaN single quantum well and capped with a GaN top layer. The geometry strongly impacts the InGaN SQW forming quantum dot like potential minima at the pyramid's tips. Intense GaN luminescence can be obtained from both, the pyramids as well as the buffer layer in between. In contrast, the InGaN luminescence is exclusively emitted from the pyramids. The most intense InGaN SQW luminescence originates from the base and the upper part of the pyramids. A striation-like contrast is observed at the lower part of the pyramids, both, in intensity and peak wavelength: higher intensities one-by-one locally correlate with longer peak wavelengths. The average wavelength results in 550 nm. In the upper part of the pyramids two distinctly different wavelengths are emitted: while the center of the facets is dominated by 530 nm emission a CL peak wavelength of 590 nm dominates at the edges and at the very top. This directly visualizes higher indium incorporation and/or a thicker quantum well at the edges and tops of the pyramids, i.e. the self organized formation of quantum wires at the edges and quantum dots at the tips. We will directly correlate this real structure with the recombination kinetics of the quantum structures using local transients, sets of time delayed CL intensity mappings, transient line scans, and lifetime mappings.

7602-32, Session 7

Nature of surface states and dislocations on non-polar GaN(1-100) surfaces investigated by scanning tunneling microscopy

H. Eisele, L. Ivanova, Technische Univ. Berlin (Germany); S. Borisova, Forschungszentrum Jülich GmbH (Germany); M. Dähne, Technische Univ. Berlin (Germany); P. Ebert, Forschungszentrum Jülich GmbH (Germany)

For non-polar GaN surfaces only little is known about the exact energetic positions of surface states, and thus their possible influence on the Fermi level. Furthermore, GaN still suffers from high dislocation densities, far above that of zincblende type III-V semiconductor crystals. Dislocations are detrimental for optoelectronic applications of GaN, because dislocations act as non-radiative recombination centers.

We investigated the GaN(1-100) surface by scanning tunneling microscopy (STM) and spectroscopy (STS). We were able to identify the energetic positions of the intrinsic surface states and the Fermi level. We found that both, the filled N-derived and empty Ga-derived dangling bond states are outside the fundamental band gap, the latter one being 0.1 - 0.2 eV above the conduction band minimum. The observed band gap is 3.4 ± 0.2 eV, in agreement with the nominal value from the bulk. The observed Fermi level pinning of about 1.0 eV below the conduction band edge is attributed to a high defect density at the surface, but not to intrinsic surface states.

Furthermore, at large scan range STM images we were able identify dislocations, forming localized bunches of entangled non-parallel dislocation lines. Within these bunches the dislocation density reached values of 1.2 × 108 cm-2. Two different dislocation types were found, uncharged perfect dislocations with a/3{11-20} Burgers vectors and negatively charged Shockley partials with an a/3{1-100} Burgers vector and a related intrinsic type-2 stacking fault. This stacking fault could be identified as ...ABABCACA... stacking sequence, thus inserting one monolayer of cubic GaN within the wurtzite crystal.

7602-33, Session 7

Effect of UV exposure on the surface photovoltage behavior for GaN

A. A. Baski, M. A. Foussekis, J. D. Ferguson, X. Ni, M. A. Reshchikov, H. Morkoc, Virginia Commonwealth Univ. (United States)

Band bending for a variety of n-type GaN samples has been investigated via the surface photovoltage (SPV) effect using a Kelvin probe setup. Negative surface charge causes an initial upward band bending of up to 1 eV for n-type GaN, which is then reduced during UV illumination due to the photogeneration of holes, i.e., surface photovoltage. Interestingly, the SPV signal in air can slowly decrease during illumination (after its initial fast rise), because of the photo-induced chemisorption of negatively charged oxygen species. The SPV for a new sample is typically 0.6 eV and can decrease by up to 0.3 eV over 1 hour. We have found, however, that samples with several hours of UV exposure in air ambient have a smaller SPV change during illumination, indicating the growth of a surface oxide layer which prevents electrons from reaching the surface. The original SPV behavior can be restored by chemical etching of the sample to remove its surface oxide. In addition to this UV exposure effect, we have also investigated the effect of UV intensity during measurements. It appears that the SPV decreases at a significantly faster rate during high-intensity illumination (>10 mW/cm2) as compared to lower intensities. These experiments demonstrate the important role of photo-induced processes both during SPV measurements and in the eventual growth of a surface oxide that impacts subsequent sample behavior.

7602-34, Session 7

Optical and electrical properties of p-InxGa1-xN alloys with high In contents

B. N. Pantha, L. Jing, J. Lin, H. Jiang, Texas Tech Univ. (United States)

P-type InGaN alloy is of great interest because of its higher hole concentration, and much lower growth temperature compared to those of p-GaN. In particular, lower growth temperature of p-layer is beneficial in devices such as green laser diodes (LDs), long wavelength emitters, and solar cells where their active region has to be grown at temperature lower than that of top p-GaN layer. Other potential applications include high efficiency photoelectronchemical (PEC) cells and thermoelectric (TE) power generation. Here, we present optical and electrical properties of Mg-doped InxGa1-xN (0 ≤ x ≤ 0.4) alloys synthesized by metal organic chemical vapor deposition (MOCVD). A record low resistivity at room temperature ~0.4 -cm with hole concentration ~ 5 x 1018 cm-3 and hole mobility ~3 cm2/Vs has been achieved in In0.22Ga0.78N:Mg. Activation energy as function of x in InxGa1-xN:Mg alloys up to x= 0.4 will be presented using temperature dependent Hall-effect measurements. Optical study shows that photoluminescence (PL) intensity decreases severely as In content increases. Process involving impurity transitions including Mg and compensating centers will be discussed in detail.

7602-35, Session 8

Theory for optical spectra of nitride quantum dot systems

F. Jahnke, M. Lorke, J. Seebeck, K. Schuh, Univ. Bremen (Germany); S. Schulz, Tyndall National Institute (Ireland); P. Gartner, G. Czycholl, Univ. Bremen (Germany)

The influence of structural properties and interaction-induced effects on optical spectra of Nitride-based self-assembled quantum-dot systems is analyzed within a microscopic theory. The single-particle properties of the quantum-dot and wetting-layer states are determined on an atomistic level from tight-binding calculations. The resulting wave functions are used to evaluate interaction matrix elements. Multi-exciton states and the corresponding absorption as well as luminescence spectra are determined from full-configuration interaction calculations involving the localized quantum-dot states. Furthermore, solutions of the semiconductor Bloch equations including Coulomb interaction effects and carrier-phonon interaction are used to incorporate additionally the influence of the WL states on the optical properties and to study excitation-induced effects for elevated carrier densities at room temperature. We find rather strong excitation-induced line shifts of the QD transitions (dominated by the Coulomb-Hartree interaction of the excited carriers) in addition to the excitation-induced line-broadening. While these results are often masked in conventional lasers due to strong inhomogeneous broadening, they are directly relevant for the application of QDs in microcavity lasers.

7602-36, Session 8

GaN/AlN quantum dots in nanowires: optical properties

B. Gayral, J. Renard, Commissariat à l'Énergie Atomique (France); R. Songmuang, Institut Néel (France); G. Tourbot, O. Landré, Commissariat à l'Énergie Atomique (France); C. Bougerol, Institut Néel (France); B. Daudin, Commissariat à l'Énergie Atomique (France)

GaN nanowires with diameters of a few tens of nanometers can be spontaneously grown by plasma-assisted MBE. These objects hold the promise to obtain defect-free III-N heterostructures, notably due

to surface strain relaxation. In this work, we present an optical study of GaN/AlN quantum dots embedded in nanowires. We show that such polar heterostructures are prone to the quantum confined Stark effect, although with a smaller magnitude than for two-dimensional structures of same thickness. This result is attributed to the reduction in piezoelectric polarization in nanowire heterostructures. Nanowires can be removed from their growth substrate and dispersed so as to study a single nanowire. This allowed us to study single QDs in nanowires with an emission around 4 eV, which show sharp photoluminescence lines (in the 1 to 10 meV range). Such a single line shows a clear antibunching behavior, thus demonstrating that this is indeed a single emitter. The observation of the biexcitonic transition allowed us to measure the biexciton binding energy of these QDs, which is quite large (in the 15 to 40 meV range) and is much larger than for Stranski-Krastanow QDs emitting in the same energy range.

7602-37, Session 8

Quantum wells, quantum dots and crystallographic defect in nitride semiconductors

P. Ruterana, ENSICAEN (France); M. Chauvat, Ecole Nationale Supérieure d'Ingenieurs de Caen et Ctr. de Recherche (France); E. Monroy, L. Lahourcade, Commissariat à l'Énergie Atomique (France)

Nitride semiconductors offer the possibility for optoelectronic devices from infrared to the UV range (InN:0.7 eV) to (AlN: 6.2 eV). The most challenging system is InGaN where the lattice mismatch between GaN and InN is 11%. For AlN/GaN, the misfit is 2.5% and the growth of quantum wells (QWs) has been shown to follow the 2D growth mode and high quality quantum dots (QDs) have been obtained. Many crystallographic defects are present during the growth of the ternary QWs and QDs; they take part in the strain relaxation as well as in the diffusion processes. In order to get around the spontaneous polarisation effects, growth along non polar and semipolar directions is under investigation. The aim is to improve the emission of the devices and achieve optimized LDs and LEDs past the green range. However, the growth within these geometries is still a challenge and new crystallographic defects are introduced.

The structure of the extended defects will be reviewed, and their interaction with QWs and Qdots discussed. The role of threading dislocations on the nucleation of GaN/AlN QDs will be addressed. Using HRTEM, strain analysis and finite elements modelling, it was shown that in the best layers with low densities of defects, the indium composition may not be uniform. Depending on the growth conditions, clusters of 2 nm high and 3nm wide can reach 45% In composition. Moreover, the presence of threading dislocation may constitute a driving force for clustering. Case studies will be presented in polar and semipolar layers.

7602-38, Session 8

Excitonic complexes in single group-III nitride quantum dots

A. Hoffmann, S. Werner, G. Hönig, M. Winkelnkemper, D. Bimberg, Technische Univ. Berlin (Germany); C. Kindel, S. Kako, Y. Arakawa, The Univ. of Tokyo (Japan)

Single quantum dots (QDs) are promising candidates for the realization of electrically triggered sources of single photons or entangled photon pairs for application in quantum cryptography. Devices based on III-N QDs are operable at much higher temperatures than their arsenide counterparts, and, furthermore, provide the possibility to tune the emission wavelength over a wide range, even down to the infra-red region using InN/GaN QDs in the future.

In this presentation, we study the fundamental processes of photon emission by excitonic complexes confined in single III-N QDs using InGaN/GaN and GaN/AlN QDs as examples. Experimental results from time-integrated and time-resolved single-QD spectroscopy are evaluated as well as theoretical results obtained by Hartree-Fock calculations based on realistic eight-band k.p wave functions.

We show that the emission properties of excitonic states in III-N QDs are dominated by an interplay of valence-band mixing effects and electron-hole exchange effects within the excitonic states. Excitonic fine-structure splitting and polarization of the emission lines can be controlled by external uniaxial stress.

7602-39, Session 8

Micro-photoluminescence study of InGaN quantum wells grown on c-plane, semipolar, and nonpolar orientation

U. T. Schwarz, J. Danhof, L. Schade, Univ. Regensburg (Germany) and Freiburg Univ. (Germany); T. Wernicke, M. Weyers, Ferdinand-Braun-Institut für Höchstfrequenztechnik (Germany); M. Kneissl, Ferdinand-Braun-Institut für Höchstfrequenztechnik (Germany) and Technical University Berlin (Germany)

Growth of InGaN-based laser diodes on semipolar or nonpolar crystal orientations has recently obtained great interest, in particular for emitters in the green spectral region. One benefit is the zero or at least significantly reduced piezoelectric field for InGaN quantum wells grown along these orientations. In addition, different growth mechanisms and therefore indium incorporation can be expected for semipolar and nonpolar growth. In this paper we have investigated the homogeneity of the InGaN quantum well (QW) photoluminescence on a sub-micrometer length scale.

The QWs were grown homoepitaxially on low threading dislocation density semipolar and nonpolar bulk substrates. The threading dislocations of the original HVPE growth of the substrate are oriented along c-direction. These dislocations run parallel to the surface of the nonpolar grown samples and under a small angle in the semipolar samples. With a spatial resolution of about 250 nm we have searched for signatures of these threading dislocations in the spatial fluctuation of the photoluminescence, both in intensity and wavelength shift. We also investigated the fluctuations in regions free of threading dislocations.

We found a pronounced difference in the growth modes between c-plane, semipolar, and nonpolar samples. The c-plane samples show the typical dark spots of reduced photoluminescence around threading dislocations. Semipolar and nonpolar samples exhibit a significantly improved PL homogeneity. While the semipolar samples show an asymmetric polygonal structure around single threading dislocations, nonpolar samples are very homogeneous on a sub-micrometer to several micrometer length scale. Irregular features of the substrate cause structures on a larger length scale.

7602-40, Session 9

GaN-based two-dimensional photonic drystal surface-emitting lasers with AlN/GaN DBR

T. Lu, S. Chen, T. Kao, T. Liu, C. Chen, Y. Hou, C. Chen, P. Weng, H. Kuo, S. Wang, National Chiao Tung Univ. (Taiwan)

We have fabricated and demonstrated the GaN-based two dimensional photonic crystal surface emitting lasers with AlN/GaN distributed Bragg reflector.

In the experiment results, the lasing action could be clearly observed by different lasing wavelength from 395 nm to 425 nm in different devices with increasing pumping energy density which can be classified in three band-edge frequencies (, K, M).

For example, we took the data from the PC laser device with the PC lattice constant of about 234 nm. The threshold current density of PC laser is about 2.7 mJ/cm2 which has a dominated wavelength at 401.8

nm with a linewidth of about 0.16 nm.

The degree of polarizations of the band-edge PC lasers including , K, and M were around 50%. The result shows the main polarization directions and the main diffracted laser beams which can be corresponding to our hexagonal PC lattice in a K-space.

In addition, the coupling factor and the characteristic temperature of our devices are around 5x10-3 and 148K, respectively. Furthermore, we measured the dispersion diagram of PC 1 mode by angular-resolved μ-PL system which can indicate the exact guided mode in PCSEL structures.

7602-41, Session 9

Investigation of AlInGaN-based laser diodes by the effect of quantum well release layer in blue and green wavelength

T. Jang, K. S. Jeon, S. M. Cho, Y. S. Eum, Y. Choi, M. Noh, LG Electronics Inc. (Korea, Republic of)

Mobile or portable projection systems that require blue and green optical sources are the next potential market for GaN laser diodes (LDs). In order to develop LDs for display systems, In-rich InGaN quantum well (QW) which has large lattice mismatch and In localization should be grown with proper LD structures. Therefore blue-green LD showed poor characteristics of LD compared to blue LD. We believe that the poor performances of blue-green LD could be improved by introducing the quantum well release layer. The quantum well release layer which is next to quantum well would improve the crystal quality and electrical/optical properties of quantum well. In addition, asymmetric structure of LD which is beneficial to increase the COD level could be achieved via optimizing the thickness and composition of release layer.

In this study, the characteristics of AlInGaN based blue and blue-green laser diodes were investigated by the thickness and composition of the quantum well release layer. Comprehensive PL (photoluminescence), EL (electroluminescence), electrical measurements and simulation results were correlated with the characteristics of blue and blue-green LDs.

7602-42, Session 9

GaN-based VCSELs: analysis of internal device physics and performance limitations

J. Piprek, NUSOD Institute LLC (United States); Z. S. Li, Crosslight Software Inc. (Canada)

GaN-based vertical-cavity surface-emitting lasers (VCSELs) are expected to exhibit several advantages over their edge-emitting counterparts, including lower manufacturing costs, circular output beams, and longer lifetime. In contrast to the great success of GaN-based edge-emitting lasers in recent years, GaN-VCSELs still face significant challenges. Electrically pumped devices have been demonstrated only recently and they exhibit severe performance restrictions. We here analyze these recently manufactured GaN-VCSELs using advanced laser simulation software. The simulation self-consistently combines carrier transport, photon emission, and multi-mode optical wave guiding. For the quantum wells, Schrödinger and Poisson equations are solved iteratively at every bias point to account for the Quantum-Confined Stark Effect.

Our analysis shows that thick quantum wells allow for the almost complete elimination of the built-in quantum well polarization field. The simulations also reveal several performance limiting effects, e.g., gain-peak offset, current crowding, and electron leakage. Several design optimization options are proposed and discussed. For instance, electron overflow can be reduced by inserting a suitable electron stopper layer above the multi-quantum-well (MQW) active region. Such electron stopper layer is shown to also reduce the current crowding as it enforces a more uniform hole injection into the MQW.

7602-43, Session 9

High-power high-efficiency continuous-wave InGaN laser diodes in the violet, blue, and green wavelength regime

J. W. Raring, E. M. Hall, M. C. Schmidt, C. Poblenz, B. Li, N. Pfister, D. F. Feezell, R. Craig, J. S. Speck, S. P. DenBaars, S. Nakamura, Kaai, Inc. (United States)

We present new advances in green, blue, and violet laser diodes based on InGaN. We report on high power, high efficiency, continuous-wave operation from single transverse mode electrically pumped laser diodes at wavelengths from 405 nm to greater than 500 nm. These devices offer dramatic improvement in size, weight, and cost over conventional gas or solid state lasers, and they may enable a variety of new applications in defense, biomedical, industrial, and consumer projection displays.

7602-44, Session 9

Growth and properties of blue InGaN-based laser diodes with InGaN waveguides

R. D. Dupuis, J. Liu, Y. Zhang, J. Ryou, S. Kim, S. Shen, D. Yoder, Georgia Institute of Technology (United States); K. Sun, Q. Wei, Y. Huang, T. Li, A. Fischer, F. Ponce, Arizona State Univ. (United States)

For blue and longer-wavelength InGaN based LDs, the refractive index difference between the GaN and AlGaN layers becomes smaller compared to violet LDs. To compensate for this effect, one option is to use InGaN waveguides because of the larger refractive index of InGaN compared to GaN. Another advantage of InGaN waveguides is that they can improve the material quality of the active region. Time-resolved cathodoluminescence data for blue LDs without and with In0.03Ga0.97N waveguides show improved carrier lifetimes for the LDs with InGaN waveguides. A comparison of the spontaneous EL intensity and FWHMs of LD structures with and without In0.03Ga0.97N waveguides as a function of injection current also shows improved performance for LDs with InGaN waveguides. The EL intensity at 50 mA current of LD structure with In0.03Ga0.97N waveguides is 80% higher than that of LD structure without In0.03Ga0.97N waveguides. Both LD structures have been fabricated to laser diodes with ridge geometry. LDs without In0.03Ga0.97N waveguides can not lase, while LDs with In0.03Ga0.97N waveguides lase at =455 nm with FWHM~0.5nm at room-temperature. Figure 3 shows the light-current curve of LDs with In0.03Ga0.97N waveguides under pulse mode operation, demonstrating Jth = 3.3 kA/cm2. The devices with non-optimized heat sinking also lase CW at 300K at Jth ~11 kA/cm2. In this paper, we will report further characteristics of blue LDs with InGaN waveguides and improved active region designs

7602-45, Session 10

Nitride infrared intersubband devices

M. Tchernycheva, H. Macchadani, S. Sakr, L. Nevou, J. Mangeney, L. Vivien, F. H. Julien, Univ. Paris-Sud 11 (France); P. K. Kandaswamy, A. Wirthmüller, E. Monroy, Commissariat à l'Énergie Atomique (France); A. Vardi, S. E. Schacham, G. Bahir, Technion-Israel Institute of Technology (Israel); G. Pozzovivo, S. Golka, G. Strasser, Technische Univ. Wien (Austria)

III-nitride nanostructures in the form of quantum dots (QD) or quantum wells (QW) offer great prospects for ultrafast intersubband devices operating in a wide spectral range from the near-infrared to THz domain. In this talk, we will report on recent achievements in terms of GaN/AlGaN-based intersubband physics, devices and technology.

We will first concentrate on the intersubband devices operating in the

telecommunication range. As a first example we will show how electron tunneling between coupled quantum wells can be applied to the fabrication of fast electro-optical modulators at 1.3-1.55 µm wavelengths. Then, we will present recent experiments on ultrafast detectors based on the quantum cascade concept. We will finally discuss the intraband physics of GaN/AlN QDs. We will describe the intraband light emission at a record short wavelength of 1.5 µm and the pump-probe femtosecond measurements which show the extremely short intraband lifetime (165 fs) while the intraband saturation intensity (0.27 pJ/µm^2) remains low. These results open prospects for ultrafast saturable absorbers and all-optical switches based on GaN QDs for telecommunication applications.

The large energy of GaN LO-phonons (92 meV) is a major advantage for nitride ISB lasers and detectors. Not only it allows operation at wavelengths inaccessible to other III-V semiconductors (Reststrahlen absorption) but it is also a key feature for increasing the operating temperature of THz lasers. We will present different approaches to extend the operation wavelength of nitride ISB devices to mid-infrared spectral range as well as to the THz frequency range.

7602-46, Session 10

First-principles simulation of GaN material and devices: an application to GaN APDs

E. Bellotti, M. Moresco, F. Bertazzi, Boston Univ. (United States)

This work provides a contribution toward the development of a fitting-parameter-free model to describe the high field electron and hole transport in wurtzite GaN. We have developed a novel model for the carrier-phonon interaction in wurtzite GaN based on the rigid pseudoion approach, using the nonlocal empirical pseudopotential method to calculate the electronic structure and the linear response technique within density functional theory to determine the phonon dispersion. This approach makes it possible to eliminate the use of adjustable parameters and to compute the deformation potential interaction parameters both for electron- and hole-phonon scattering rates directly from first-principle. On the same footing the electrons and holes impact ionization rates and the polar carrier-phonon interaction have been computed using the GaN full band structure. Because of the complex GaN band structure, it is necessary to properly account for the multi-band transport phenomena that significantly change the carrier dynamics at high energies. Neglecting this effect, would result in a significantly lower impact ionization coefficients and, as a consequence, smaller multiplication gains and higher breakdown voltages in APDs. To evaluate the ability of the new model to predict the performance of realistic devices, we have computed the electrons and holes multiplication gains, noise factors, breakdown voltages and bandwidth of different APD structures fabricated on different crystallographic planes and performed a detailed comparison with the available experimental data. We find that the model correctly predicts, within the experimental errors, the multiplication gains and breakdown voltages of several fabricated and characterized devices structures.

7602-47, Session 10

Low-frequency and high-efficiency energy harvesting with micromachined AlN suspended structures

A. Passaseo, A. Massaro, S. De Guido, M. De Vittorio, National Nanotechnology Lab. (Italy)

In the last years, there has been an increasing interest for energy harvesting from renewable energy sources. Among them, energy harvesting from mechanical vibrations, represent a very promising energy source and can be transformed into useful electrical power by different transduction mechanisms, such as piezoelectric transduction that directly convert applied strain energy into electric energy. However, there is a lack of results exploiting piezoelectric materials with resonances at low frequencies where most ambient vibration exists.

In this work we present the realization of micro power generators based on micromachined AlN suspended structures which can efficiently harvest energy from low-frequency external vibrations. The proposed structures consist of a piezoelectric AlN thin film embedded between two molybdenum (Mo) electrodes that are deposited by DC magnetron sputtering on a Si substrate coated with a SiO2 sacrificial layer. By exploring the self-rolling phenomena due to the residual stress of the structures, AlN ring-shaped suspended structure are obtained. Thank to the high flexibility of their geometrical configuration, AlN rings show high vibration amplitude directly in the range of 100 Hz, without using any additional mass. The control of the deposition parameters of Mo and AlN layers and their thickness allows a large range of ring radius (60 µm< r <250 µm), allowing the control of the ring frequency resonances. The experimental results provide piezoelectric resonances from 70 Hz up to340 Hz for different ring diameters. A maximum power density of 1.87 µW/mm3 has been measured for an input vibration having a frequency of 80 Hz.

7602-48, Session 10

GaN-based optoelectronics on silicon

A. J. Krost, R. Clos, and A. Dadgar, Otto-von-Guericke-Univ. Magdeburg (Germany)

Due to the lack of homosubstrates GaN growth is usually performed on hetero¬substrates as sapphire and SiC. Both substrates have a large lattice and thermal mismatch to GaN and are insulating or very expensive. Meanwhile, silicon is considered to be a serious alternative to these substrates, especially because of its low price, large diameter wafers, and thermally well conducting properties. It may also enable new device structures by an integration of GaN-based optoelectronics with Si electronics. In the last years fundamental problems such as the huge thermal mismatch leading to cracks for layers exceeding 1 µm in thickness and thus preventing high quality device growth have been overcome by several groups using different approaches such as (Al,Ga)N buffer layers, low-temperature AlN interlayers, or growth on patterned substrates. Most of the recent work and published device results have been for GaN growth on (111) silicon substrates, with the first commercial chips, mainly HEMTs, now available. Meanwhile, we have achieved crack-free layers on Si(111) with 7 µm thickness of up to 150 mm in diameter with twist (10-10) and tilt (0002) values around 600" and 300", respectively. This is achieved by a proper strain management during growth with the help of an in situ curvature monitor enabling balancing of tensile and compressive strain sources. By this 4.5 µm thick templates can be overgrown with 2 µm full LED structures. With theoretical models we describe the evolution of stress during growth.

We have also obtained the first MOVPE-grown, crack-free, GaN-based LED on (100) silicon paving the way towards integrated optoelectronics with GaN-on-Silicon technology. Latest results will be also presented on the growth of GaN on Si(110).

7602-50, Session 10

Promising composite die-bonding materials for high-power GaN-based LED applications

R. Horng, J. Hong, Y. Tsai, D. Wuu, National Chung Hsing Univ. (Taiwan)

The increasing demand for high-power LED applications makes the conventional die-bonding solder material of silver paste no longer qualified due to its poor thermal conductivity (2~25 W/mK). Diamond is a highly thermal conductive material, and diamond-added solder pastes are expected to have good thermal conductive capability. Therefore, in this paper we propose a composite solder for nitride-based LED package, and the composite solder was prepared by mixing the commercial Sn-3wt.%Ag-0.5wt.%Cu (SAC305) solder paste with the diamond paste [0.25(W)475-MA, Engis, USA] in a weight ratio of 10:1. This paper compares the thermal performances of GaN-based LEDs bonded on metal core printed circuit board by various solders, including

silver paste, AgSnCu solder paste, and diamond-added AgSnCu composite solder paste. Thermal resistance analysis shows that the total thermal resistance of the LED packaged using the composite solder is only 6.4 K/W, which is much lower than 9.2 K/W of the LED using AgSnCu solder and 10.4 K/W of the LED using silver paste. As a result, the LED with the composite solder exhibits higher light output power and lower junction temperature than the other two samples do. The improved device performance is mainly due to enhanced heat dissipation of the die-bonding materials used. These results suggest that the diamond-added AgSnCu composite solders are promising in high-power LED applications.

7602-68, Session 11

Ab initio study of structural properties for zincblende AlInN: comparison of LDA and GGA

B. Liou, Hsiuping Institute of Technology (Taiwan); B. Wu, De Lin Institute of Technology (Taiwan)

The III-nitride semiconductors have received much attention in the past few years since they have potential applications in light emitting diodes (LEDs) for displays, laser diodes (LD) for high-density optical storage, and photoelectronic detectors. This is due to their relatively wide band gap corresponding to the spectral region from the infrared, visible to the near ultraviolet and high emission efficiency. Compared to the AlGaN and InGaN alloys, the AlInN alloys are less applied. Nevertheless, the alloys have the largest miscibility in band gap and are a good choice for lattice matched confinement layers in optical devices. Hexagonal wurtzite structure and cubic zincblende structure are the two basic crystal structures of III-nitride semiconductors. The wurtzite structure is extensively utilized because most III-nitride semiconductors have been grown on sapphire substrates, which exhibit hexagonal structure. The zincblende structure still possesses distinct advantages over wurtzite structure. For example, the zincblende structure is provided with larger optical gain and lower threshold current density because of its smaller effective mass, and has mirror facets compatible with substrates such as GaAs. Furthermore, it is suggested that the electronic and thermal properties of zincblende nitrides are superior to those of the wurtzite materials due to reduced phonon scattering in the high symmetry crystals. The objective of this study is to investigate the structural properties of ternary zincblende AlInN alloys using ab initio calculations based on density functional theory (DFT). The structural properties of ternary zincblende AlInN, such as the equilibrium lattice constant, total energy, bulk modulus, and the pressure derivative of bulk modulus, are computed with LDA and GGA and compared with those available in the literature in order to develop a better understanding of the influence of the approximate exchange-correlation functional on these properties.

7602-68, Session 11

Ab initio study of structural properties for zincblende AlInN: comparison of LDA and GGA

B. Liou, Hsiuping Institute of Technology (Taiwan); B. Wu, De Lin Institute of Technology (Taiwan)

The III-nitride semiconductors have received much attention in the past few years since they have potential applications in light emitting diodes (LEDs) for displays, laser diodes (LD) for high-density optical storage, and photoelectronic detectors. This is due to their relatively wide band gap corresponding to the spectral region from the infrared, visible to the near ultraviolet and high emission efficiency. Compared to the AlGaN and InGaN alloys, the AlInN alloys are less applied. Nevertheless, the alloys have the largest miscibility in band gap and are a good choice for lattice matched confinement layers in optical devices. Hexagonal wurtzite structure and cubic zincblende structure are the two basic crystal structures of III-nitride semiconductors. The wurtzite structure is extensively utilized because most III-nitride semiconductors have been grown on sapphire substrates, which exhibit hexagonal structure. The zincblende structure still possesses distinct advantages over wurtzite structure. For example, the zincblende structure is provided with larger optical gain and lower threshold current density because of its smaller effective mass, and has mirror facets compatible with substrates such as GaAs. Furthermore, it is suggested that the electronic and thermal properties of zincblende nitrides are superior to those of the wurtzite materials due to reduced phonon scattering in the high symmetry crystals. The objective of this study is to investigate the structural properties of ternary zincblende AlInN alloys using ab initio calculations based on density functional theory (DFT). The structural properties of ternary zincblende AlInN, such as the equilibrium lattice constant, total energy, bulk modulus, and the pressure derivative of bulk modulus, are computed with LDA and GGA and compared with those available in the literature in order to develop a better understanding of the influence of the approximate exchange-correlation functional on these properties.

7602-69, Session 11

Output power enhancement of light-emitting diodes with defect passivation layer

M. Lo, Y. Cheng, National Chiao Tung Univ. (Taiwan)

A high efficiency LED with defect selective passivation to block the propagation of threading dislocations is demonstrated. The defect selective passivation is achieved by using defect selective chemical etching to locate defect sites, silicon oxide filling of the etched pits, and epitaxial over growth. The threading dislocation density in the regrown epilayer is significantly improved to 4x107 cm-2. The defect passivated epi-wafer is used to grow LED structure and the output power of the fabricated chip is enhanced by 45% at 20 mA compared to a reference one without using defect passivation

7602-69, Session 11

Output power enhancement of light-emitting diodes with defect passivation layer

M. Lo, Y. Cheng, National Chiao Tung Univ. (Taiwan)

A high efficiency LED with defect selective passivation to block the propagation of threading dislocations is demonstrated. The defect selective passivation is achieved by using defect selective chemical etching to locate defect sites, silicon oxide filling of the etched pits, and epitaxial over growth. The threading dislocation density in the regrown epilayer is significantly improved to 4x107 cm-2. The defect passivated epi-wafer is used to grow LED structure and the output power of the fabricated chip is enhanced by 45% at 20 mA compared to a reference one without using defect passivation

7602-70, Session 11

Comparison of the light extraction efficiency of InGaN/GaN light-emitting diodes with two-dimensional hole and pillar photonic crystal structures

Y. C. Shin, D. H. Kim, B. G. Lee, W. H. Lee, D. J. Chae, J. W. Yang, S. J. Kim, H. D. Kim, Y. J. Seo, K. C. Kim, Korea Univ. (Korea, Republic of); J. Park, K. P. Constant, K. Ho, Iowa State Univ. (United States); H. Ryu, Inha Univ. (Korea, Republic of); J. H. Baek, T. Jung, Korea Photonics Technology Institute (Korea, Republic of); T. G. Kim, Korea Univ. (Korea, Republic of)

High-efficient GaN light-emitting diodes (LEDs) have been used in backlight units for LCD, traffic signals, and indoor illuminators. However, the external quantum efficiency of LEDs is fundamentally limited (~4%) by total internal reflection (TIR) due to Fresnel reflection between GaN medium (n=2.46) and air (n=1). In order to avoid TIR, several researchers have investigated photonic crystal (PC) structures to enhance the light extraction in the vertical direction of LEDs. However, detailed investigations on the effect of PC structures at a nanometer scale on the efficiency of LEDs have not been made yet.

In this work, we investigate the enhancement of light extraction in 2D photonic crystal GaN LEDs, in which either ITO or p-GaN layers have been patterned on a nano-size scale using two-beam laser interference and reactive ion etching. The effect of the lattice constant (460 to 920 nm) on the extraction efficiency has been explored in LEDs with hole- and pillar-patterned photonic crystals of various etch depths. As a result, photonic crystal LEDs with a lattice constant of 750 nm and a hole depth of 260 nm on ITO layers exhibited 1.3 times higher light extraction than LEDs without the photonic crystal, with no degradation in the electrical properties. The LEDs having pillar patterns of 60 nm height on the p-GaN layer have especially shown much higher extraction efficiencies (26%) than the samples with 120 nm-height pillar ITO patterns. More details on the experimental result as well as simulations of the photonic crystal LEDs will be presented.

7602-70, Session 11

Comparison of the light extraction efficiency of InGaN/GaN light-emitting diodes with two-dimensional hole and pillar photonic crystal structures

Y. C. Shin, D. H. Kim, B. G. Lee, W. H. Lee, D. J. Chae, J. W. Yang, S. J. Kim, H. D. Kim, Y. J. Seo, K. C. Kim, Korea Univ. (Korea, Republic of); J. Park, K. P. Constant, K. Ho, Iowa State Univ. (United States); H. Ryu, Inha Univ. (Korea, Republic of); J. H. Baek, T. Jung, Korea Photonics Technology Institute (Korea, Republic of); T. G. Kim, Korea Univ. (Korea, Republic of)

High-efficient GaN light-emitting diodes (LEDs) have been used in backlight units for LCD, traffic signals, and indoor illuminators. However, the external quantum efficiency of LEDs is fundamentally limited (~4%) by total internal reflection (TIR) due to Fresnel reflection between GaN medium (n=2.46) and air (n=1). In order to avoid TIR, several researchers have investigated photonic crystal (PC) structures to enhance the light extraction in the vertical direction of LEDs. However, detailed investigations on the effect of PC structures at a nanometer scale on the efficiency of LEDs have not been made yet.

In this work, we investigate the enhancement of light extraction in 2D photonic crystal GaN LEDs, in which either ITO or p-GaN layers have been patterned on a nano-size scale using two-beam laser interference and reactive ion etching. The effect of the lattice constant (460 to 920 nm) on the extraction efficiency has been explored in LEDs with hole- and pillar-patterned photonic crystals of various etch depths. As a result, photonic crystal LEDs with a lattice constant of 750 nm and a hole depth of 260 nm on ITO layers exhibited 1.3 times higher light extraction than LEDs without the photonic crystal, with no degradation in the electrical properties. The LEDs having pillar patterns of 60 nm height on the p-GaN layer have especially shown much higher extraction efficiencies (26%) than the samples with 120 nm-height pillar ITO patterns. More details on the experimental result as well as simulations of the photonic crystal LEDs will be presented.

7602-71, Session 11

Characterization of InGaN/GaN solar cells with various electrode designs on the surface

P. S. Yeh, H. Huang, K. Zhang, National Taiwan Univ. of Science and Technology (Taiwan)

We report characterization results of InGaN/GaN solar cells with various electrode designs on the surface that include finger electrode, using Ni/Au thin metal as semi-transparent electrode, and using ITO (Indium Tin oxide) as transparent electrode. These devices were characterized and compared in terms of solar cell's I-V curve as well as LED's I-V and L-I curves. The ratio of their solar cell's short-circuit currents was 2: 1: 3.5 (finger: thin metal: ITO), while their series resistances exhibited small differences.

7602-71, Session 11

Characterization of InGaN/GaN solar cells with various electrode designs on the surface

P. S. Yeh, H. Huang, K. Zhang, National Taiwan Univ. of Science and Technology (Taiwan)

We report characterization results of InGaN/GaN solar cells with various electrode designs on the surface that include finger electrode, using Ni/Au thin metal as semi-transparent electrode, and using ITO (Indium Tin oxide) as transparent electrode. These devices were characterized and compared in terms of solar cell's I-V curve as well as LED's I-V and L-I curves. The ratio of their solar cell's short-circuit currents was 2: 1: 3.5 (finger: thin metal: ITO), while their series resistances exhibited small differences.

7602-72, Session 11

Crystal quality improvement of a-plane GaN using epitaxial lateral overgrowth on nanorods

S. Ling, T. Lu, H. Kuo, National Chiao Tung Univ. (Taiwan)

The threading dislocation (TD) density of 3×1010 cm-2 was commonly observed in a-plane GaN grown on r-plane sapphire structure because of the large anisotropic lattice mismatch between these two materials. In this work, we propose an approach of lateral overgrowth on nano-rod a-plane GaN template to realize the defect-reduction and quality improvement in the subsequently grown a-plane GaN layer.

The processing flowchart of nano-rod epitaxial lateral overgrowth (NRELOG) is as follows: First, a 1.5-μm-thick a-plane GaN layer was grown on r-plane sapphire substrates by MOCVD. Then, a SiO_2 film with a 200 nm thickness and a Ni film with a 10 nm thickness were deposited in sequence to act as the etching mask. Subsequently, the thermal annealing treatment was utilized to achieve nano-scale Ni masks. The GaN nanorods were etched through the nano mask openings by reactive ion etching. Finally, the GaN regrowth was performed on the nano-rod template by MOCVD.

The cross-sectional SEM image shows the fully coalesced thickness of NRELOG sample is less than 2 μm. In addition, compared with the as-grown samples, the XRD FWHM on-axis reflection of the NRELOG samples was reduced from 1308 to 542 arcsec. The PL measurement shows that the PL intensity of the NRELOG sample had a 18-fold increase compared with that of the as-grown sample. From the above-mentioned experiment results, we demonstrated that the feasibility of using NRELOG technique to achieve crystal quality improvement and the enhancement of luminescence performance in a-plane GaN.

7602-72, Session 11

Crystal quality improvement of a-plane GaN using epitaxial lateral overgrowth on nanorods

S. Ling, T. Lu, H. Kuo, National Chiao Tung Univ. (Taiwan)

The threading dislocation (TD) density of 3×1010 cm-2 was commonly

observed in a-plane GaN grown on r-plane sapphire structure because of the large anisotropic lattice mismatch between these two materials. In this work, we propose an approach of lateral overgrowth on nano-rod a-plane GaN template to realize the defect-reduction and quality improvement in the subsequently grown a-plane GaN layer.

The processing flowchart of nano-rod epitaxial lateral overgrowth (NRELOG) is as follows: First, a 1.5-μm-thick a-plane GaN layer was grown on r-plane sapphire substrates by MOCVD. Then, a SiO_2 film with a 200 nm thickness and a Ni film with a 10 nm thickness were deposited in sequence to act as the etching mask. Subsequently, the thermal annealing treatment was utilized to achieve nano-scale Ni masks. The GaN nanorods were etched through the nano mask openings by reactive ion etching. Finally, the GaN regrowth was performed on the nano-rod template by MOCVD.

The cross-sectional SEM image shows the fully coalesced thickness of NRELOG sample is less than 2 μm. In addition, compared with the as-grown samples, the XRD FWHM on-axis reflection of the NRELOG samples was reduced from 1308 to 542 arcsec. The PL measurement shows that the PL intensity of the NRELOG sample had a 18-fold increase compared with that of the as-grown sample. From the above-mentioned experiment results, we demonstrated that the feasibility of using NRELOG technique to achieve crystal quality improvement and the enhancement of luminescence performance in a-plane GaN.

7602-73, Session 11

Non-polar m-plane GaN on patterned Si(112) substrates by metalorganic chemical vapor deposition

X. Ni, M. Wu, J. Lee, X. Li, A. Baski, Ü. Özgür, H. Morkoç, Virginia Commonwealth Univ. (United States)

The concept of non-polar m-plane GaN on Si substrates has been demonstrated by initiating growth on the vertical (-1-11) sidewalls of patterned Si(112) substrates using metalorganic chemical vapor deposition. The Si(112) substrates were wet-etched to expose {111} planes using stripe-patterned SiNx masks oriented along the [-110] direction. Only the vertical (-1-11) Si sidewalls were allowed to participate in GaN growth by masking other Si{111} planes using SiO_2, which led to m-plane GaN films. Growth initiating on the Si(-1-11) planes normal to the surface was allowed to advance laterally and also vertically towards full coalescence. The full width at half maximum values for the GaN m-plane x-ray diffraction rocking curves were 9 and 27 arcmin when rocked toward the GaN a-axis (parallel to stripes) and the GaN c-axis (perpendicular to stripes), respectively. Room-temperature photoluminescence showed strong band-edge emission with an intensity comparable to that of laterally overgrown c-plane GaN. InGaN double heterostructure active layers grown on these m-GaN templates on Si exhibited two times higher internal quantum efficiencies as compared to their c-plane counterparts at comparable carrier densities. These results demonstrate a promising method to obtain high-quality non-polar m-GaN films on large area, inexpensive Si substrates.

7602-73, Session 11

Non-polar m-plane GaN on patterned Si(112) substrates by metalorganic chemical vapor deposition

X. Ni, M. Wu, J. Lee, X. Li, A. Baski, Ü. Özgür, H. Morkoç, Virginia Commonwealth Univ. (United States)

The concept of non-polar m-plane GaN on Si substrates has been demonstrated by initiating growth on the vertical (-1-11) sidewalls of patterned Si(112) substrates using metalorganic chemical vapor deposition. The Si(112) substrates were wet-etched to expose {111} planes using stripe-patterned SiNx masks oriented along the [-110] direction. Only the vertical (-1-11) Si sidewalls were allowed to participate in GaN growth by masking other Si{111} planes using SiO_2, which led to m-plane GaN films. Growth initiating on the Si(-1-11) planes normal to the surface was allowed to advance laterally and also vertically towards full coalescence. The full width at half maximum values for the GaN m-plane x-ray diffraction rocking curves were 9 and 27 arcmin when rocked toward the GaN a-axis (parallel to stripes) and the GaN c-axis (perpendicular to stripes), respectively. Room-temperature photoluminescence showed strong band-edge emission with an intensity comparable to that of laterally overgrown c-plane GaN. InGaN double heterostructure active layers grown on these m-GaN templates on Si exhibited two times higher internal quantum efficiencies as compared to their c-plane counterparts at comparable carrier densities. These results demonstrate a promising method to obtain high-quality non-polar m-GaN films on large area, inexpensive Si substrates.

7602-74, Session 11

Comparison of different template structures for high quality and self-separation thick GaN growth

Y. Fang, C. Chao, T. Chi, K. Chen, P. Liu, J. Tsay, Industrial Technology Research Institute (Taiwan)

Two different template structures of dot air-bridges and nano-rods were used for 300μm GaN growth by hydride vapor phase epitaxy (HVPE). The selective growth of arrays of dot air-bridges and nano-rods whose sidewalls coated with SiO_2 are identified and exploited to form a compliant layer to decouple the impact due to the different thermal expansion and lattice mismatch between 300μm overgrown GaN layer and the host sapphire substrate. As the process temperature cooling down from 1050 oC to room temperature in HVPE system, the 300μm freestanding GaN substrates were obtained by the self-separation. The GaN (0002) plane -scans were carried out, and the full-width half-maximum (FWHM) values are lower than 350 and 150 arcsec for the template structure of dot air-bridges and nano-rods structure, respectively. Moreover, the dislocation density was estimated by both the etching pit density method and cathodoluminescence (CL). The dislocation density of the freestanding bulk GaN were lower than 5×106 and 5×107 cm-2 for the template structure of dot air-bridges and nano-rods structure, respectively.

7602-74, Session 11

Comparison of different template structures for high quality and self-separation thick GaN growth

Y. Fang, C. Chao, T. Chi, K. Chen, P. Liu, J. Tsay, Industrial Technology Research Institute (Taiwan)

Two different template structures of dot air-bridges and nano-rods were used for 300μm GaN growth by hydride vapor phase epitaxy (HVPE). The selective growth of arrays of dot air-bridges and nano-rods whose sidewalls coated with SiO_2 are identified and exploited to form a compliant layer to decouple the impact due to the different thermal expansion and lattice mismatch between 300μm overgrown GaN layer and the host sapphire substrate. As the process temperature cooling down from 1050 oC to room temperature in HVPE system, the 300μm freestanding GaN substrates were obtained by the self-separation. The GaN (0002) plane -scans were carried out, and the full-width half-maximum (FWHM) values are lower than 350 and 150 arcsec for the template structure of dot air-bridges and nano-rods structure, respectively. Moreover, the dislocation density was estimated by both the etching pit density method and cathodoluminescence (CL). The dislocation density of the freestanding bulk GaN were lower than 5×106 and 5×107 cm-2 for the template structure of dot air-bridges and nano-rods structure, respectively.

7602-75, Session 11

Analytical methods to study burn-in effects in blue InGaN laser diodes

J. Müller, G. Brüderl, S. Tautz, M. O. Schillgalies, A. Breidenassel, S. Lutgen, OSRAM Opto Semiconductors GmbH (Germany)

An analysis of the short and long-term output stability of encapsulated blue InGaN lasers diodes (LDs) is presented. Laser of a standard design showed stable output power in short and long term experiments yielding in lifetimes of 10,000 h under constant current conditions.

In contrast, R&D test lasers with a different layer design and ridge etch depth suffered a strong burn-in. It was related with changes in quantum efficiency and carrier lifetimes which were longer after stressing. A simple recombination model was fitted to the measurements suggesting no increase in non-radiative recombination centers. Instead the longer carrier lifetimes after burn-in could be well explained with a decrease in carrier density due to an additional current spreading. These results were confirmed by changes in the sub-threshold wavelength shift before and after aging. It was therefore found to be crucial to control current spreading in ridge lasers by carefully adjusting the layer design, doping profile and ridge etch depth.

7602-75, Session 11

Analytical methods to study burn-in effects in blue InGaN laser diodes

J. Müller, G. Brüderl, S. Tautz, M. O. Schillgalies, A. Breidenassel, S. Lutgen, OSRAM Opto Semiconductors GmbH (Germany)

An analysis of the short and long-term output stability of encapsulated blue InGaN lasers diodes (LDs) is presented. Laser of a standard design showed stable output power in short and long term experiments yielding in lifetimes of 10,000 h under constant current conditions.

In contrast, R&D test lasers with a different layer design and ridge etch depth suffered a strong burn-in. It was related with changes in quantum efficiency and carrier lifetimes which were longer after stressing. A simple recombination model was fitted to the measurements suggesting no increase in non-radiative recombination centers. Instead the longer carrier lifetimes after burn-in could be well explained with a decrease in carrier density due to an additional current spreading. These results were confirmed by changes in the sub-threshold wavelength shift before and after aging. It was therefore found to be crucial to control current spreading in ridge lasers by carefully adjusting the layer design, doping profile and ridge etch depth.

7602-76, Session 11

Reduction in operating voltage of UV laser diode

T. Ichikawa, K. Takeda, Y. Ogiso, K. Nagata, M. Iwaya, S. Kamiyama, H. Amano, I. Akasaki, Meijo Univ. (Japan); H. Yoshida, M. Kuwabara, Y. Yamashita, H. Kan, Hamamatsu Photonics K.K. (Japan)

UV laser diodes (LDs) and light emitting diodes (LEDs) are promising for various applications such as super-high-density optical storage, medical, chemical, excitation sources for phosphors, and fine lithography. Although we succeeded in fabrication of GaN/AlGaN multi-quantum wells based UV LDs and high-power UV-LEDs on high-crystalline-quality AlGaN thick templates, the operating voltages of these devices were high. In this study, we conducted several processes of device fabrication for reduction in operating voltage. In particular, we adopted a high annealing temperature of 850 °C, which cannot be adopted for GaInN based visible light emitters, to induced contact.

The UV LDs were fabricated using two-processes. For sample 1, we deposited p-electrodes and then annealed n-electrodes at 525 °C. For sample 2, we deposited the n-electrodes annealed at 850 °C. As a result, the operating voltage of sample 2 (16 V at 100 mA) was about 25% lower than that of sample 1 (20 V at 100 mA).

7602-76, Session 11

Reduction in operating voltage of UV laser diode

T. Ichikawa, K. Takeda, Y. Ogiso, K. Nagata, M. Iwaya, S. Kamiyama, H. Amano, I. Akasaki, Meijo Univ. (Japan); H. Yoshida, M. Kuwabara, Y. Yamashita, H. Kan, Hamamatsu Photonics K.K. (Japan)

UV laser diodes (LDs) and light emitting diodes (LEDs) are promising for various applications such as super-high-density optical storage, medical, chemical, excitation sources for phosphors, and fine lithography. Although we succeeded in fabrication of GaN/AlGaN multi-quantum wells based UV LDs and high-power UV-LEDs on high-crystalline-quality AlGaN thick templates, the operating voltages of these devices were high. In this study, we conducted several processes of device fabrication for reduction in operating voltage. In particular, we adopted a high annealing temperature of 850 °C, which cannot be adopted for GaInN based visible light emitters, to induced contact.

The UV LDs were fabricated using two-processes. For sample 1, we deposited p-electrodes and then annealed n-electrodes at 525 °C. For sample 2, we deposited the n-electrodes annealed at 850 °C. As a result, the operating voltage of sample 2 (16 V at 100 mA) was about 25% lower than that of sample 1 (20 V at 100 mA).

7602-77, Session 11

On the effect of InGaN-based LED structure on internal quantum efficiency

J. Lee, X. Ni, M. Wu, X. Li, R. Shimada, Ü. Özgur, A. Baski, H. Morkoç, Virginia Commonwealth Univ. (United States); T. Paskova, G. Mulholland, K. Evans, Kyma Technologies, Inc. (United States)

All too important internal quantum efficiency in InGaN based LEDs has taken to new heights as the demand for high quantum efficiency and more importantly its retention at high injection levels is increasing owing to candidacy for general lighting applications. Internal quantum efficiency is determined not only by completion between the radiative and non radiative components of the recombination process but also transport in (injection) and transport out (carrier spill over) of electrons and holes, whichever is applicable, to and from the active region. The overall efficiency and in particular the lack of its retention at high injection levels have also become a controversial issue as to the genesis of the latter in that the degree of the role of carrier spill over and Auger recombination the latter of which, if present, becomes increasingly notable at high injection levels. We have used various MQW structured InGaN LEDs on c-plane GaN, with inherent polarization induced field, and also on m-plane GaN, with no such field, to determine the internal quantum efficiency by all optical methods, one relying on the temperature dependence of the emission intensity assuming 100% efficiency at low temperatures and the other on excitation power dependence of emission at room temperature. The results of these investigations which also aimed at the origin of loss of, if any, efficiency degradation at high injection levels will be discussed.

7602-77, Session 11

On the effect of InGaN-based LED structure on internal quantum efficiency

J. Lee, X. Ni, M. Wu, X. Li, R. Shimada, Ü. Özgur, A. Baski, H. Morkoç, Virginia Commonwealth Univ. (United States); T. Paskova, G. Mulholland, K. Evans, Kyma Technologies, Inc. (United States)

All too important internal quantum efficiency in InGaN based LEDs has taken to new heights as the demand for high quantum efficiency and more importantly its retention at high injection levels is increasing owing to candidacy for general lighting applications. Internal quantum efficiency is determined not only by completion between the radiative and non radiative components of the recombination process but also transport in (injection) and transport out (carrier spill over) of electrons and holes, whichever is applicable, to and from the active region. The overall efficiency and in particular the lack of its retention at high injection levels have also become a controversial issue as to the genesis of the latter in that the degree of the role of carrier spill over and Auger recombination the latter of which, if present, becomes increasingly notable at high injection levels. We have used various MQW structured InGaN LEDs on c-plane GaN, with inherent polarization induced field, and also on m-plane GaN, with no such field, to determine the internal quantum efficiency by all optical methods, one relying on the temperature dependence of the emission intensity assuming 100% efficiency at low temperatures and the other on excitation power dependence of emission at room temperature. The results of these investigations which also aimed at the origin of loss of, if any, efficiency degradation at high injection levels will be discussed.

7602-78, Session 11

Analysis and comparison of UV photodetectors based on wide bandgap semiconductors

Q. Wang, S. Savage, B. Noharet, I. Petermann, S. Persson, M. Bakowski, J. Y. Andersson, Acreo AB (Sweden) and IMAGIC Ctr. (Sweden)

For imaging applications, photodetectors with high sensitivity, low noise and outstanding long term stability are generally highly desirable. However, individual applications have individual requirements regarding detector performance, which can be met by selecting a suitable type of detection mechanism and a base material with a structure best suited to achieve the desired performance. In this report we compare various UV photodetectors, developed, produced and evaluated within IMAGIC (IMAGing Integrated Components), an institute centre of excellence coordinated by Acreo. These include the metal-semiconductor-metal (MSM) photodetector, p-i-n diode, and the avalanche photodiode (APD), based on GaN or SiC bulk or quantum well (QW) material. In particular, we present the design, fabrication and characterization of GaN- and SiC-based photodetectors, optimised for sensitivity and stability. The fabricated GaN-based QW p-i-n photodetectors are shown to exhibit a quantum efficiency around 50 % at 365 nm with a peak to visible rejection ratio of more than 3 orders of magnitudes. A novel APD design based on SiC is shown to produce a sharp and stable avalanche breakdown characteristic around 120 V for fabricated devices up to 2 mm in diameter. An increase in the responsivity by almost an order of magnitude when the avalanche voltage is applied is also demonstrated. The performance, advantages and drawbacks of the above photodetectors are analysed and compared, providing valuable information on their suitability for different applications. The analysis also provides information for further enhancement of device performance and for the design of next generation novel UV photodetectors.

7602-78, Session 11

Analysis and comparison of UV photodetectors based on wide bandgap semiconductors

Q. Wang, S. Savage, B. Noharet, I. Petermann, S. Persson, M. Bakowski, J. Y. Andersson, Acreo AB (Sweden) and IMAGIC Ctr. (Sweden)

For imaging applications, photodetectors with high sensitivity, low noise and outstanding long term stability are generally highly desirable. However, individual applications have individual requirements regarding detector performance, which can be met by selecting a suitable type of detection mechanism and a base material with a structure best suited to achieve the desired performance. In this report we compare various UV photodetectors, developed, produced and evaluated within IMAGIC (IMAGing Integrated Components), an institute centre of excellence coordinated by Acreo. These include the metal-semiconductor-metal (MSM) photodetector, p-i-n diode, and the avalanche photodiode (APD), based on GaN or SiC bulk or quantum well (QW) material. In particular, we present the design, fabrication and characterization of GaN- and SiC-based photodetectors, optimised for sensitivity and stability. The fabricated GaN-based QW p-i-n photodetectors are shown to exhibit a quantum efficiency around 50 % at 365 nm with a peak to visible rejection ratio of more than 3 orders of magnitudes. A novel APD design based on SiC is shown to produce a sharp and stable avalanche breakdown characteristic around 120 V for fabricated devices up to 2 mm in diameter. An increase in the responsivity by almost an order of magnitude when the avalanche voltage is applied is also demonstrated. The performance, advantages and drawbacks of the above photodetectors are analysed and compared, providing valuable information on their suitability for different applications. The analysis also provides information for further enhancement of device performance and for the design of next generation novel UV photodetectors.

7602-68, Poster Session

Ab initio study of structural properties for zincblende AlInN: comparison of LDA and GGA

B. Liou, Hsiuping Institute of Technology (Taiwan); B. Wu, De Lin Institute of Technology (Taiwan)

The III-nitride semiconductors have received much attention in the past few years since they have potential applications in light emitting diodes (LEDs) for displays, laser diodes (LD) for high-density optical storage, and photoelectronic detectors. This is due to their relatively wide band gap corresponding to the spectral region from the infrared, visible to the near ultraviolet and high emission efficiency. Compared to the AlGaN and InGaN alloys, the AlInN alloys are less applied. Nevertheless, the alloys have the largest miscibility in band gap and are a good choice for lattice matched confinement layers in optical devices. Hexagonal wurtzite structure and cubic zincblende structure are the two basic crystal structures of III-nitride semiconductors. The wurtzite structure is extensively utilized because most III-nitride semiconductors have been grown on sapphire substrates, which exhibit hexagonal structure. The zincblende structure still possesses distinct advantages over wurtzite structure. For example, the zincblende structure is provided with larger optical gain and lower threshold current density because of its smaller effective mass, and has mirror facets compatible with substrates such as GaAs. Furthermore, it is suggested that the electronic and thermal properties of zincblende nitrides are superior to those of the wurtzite materials due to reduced phonon scattering in the high symmetry crystals. The objective of this study is to investigate the structural properties of ternary zincblende AlInN alloys using ab initio calculations based on density functional theory (DFT). The structural properties of ternary zincblende AlInN, such as the equilibrium lattice constant, total energy, bulk modulus, and the pressure derivative of bulk modulus, are computed with LDA and GGA and compared with those available in the literature in order to develop a better understanding of the influence of the approximate exchange-correlation functional on these properties.

7602-68, Poster Session

Ab initio study of structural properties for zincblende AlInN: comparison of LDA and GGA

B. Liou, Hsiuping Institute of Technology (Taiwan); B. Wu, De Lin Institute of Technology (Taiwan)

The III-nitride semiconductors have received much attention in the past few years since they have potential applications in light emitting diodes (LEDs) for displays, laser diodes (LD) for high-density optical storage, and photoelectronic detectors. This is due to their relatively wide band gap corresponding to the spectral region from the infrared, visible to the near ultraviolet and high emission efficiency. Compared to the AlGaN and InGaN alloys, the AlInN alloys are less applied. Nevertheless, the alloys have the largest miscibility in band gap and are a good choice for lattice matched confinement layers in optical devices. Hexagonal wurtzite structure and cubic zincblende structure are the two basic crystal structures of III-nitride semiconductors. The wurtzite structure is extensively utilized because most III-nitride semiconductors have been grown on sapphire substrates, which exhibit hexagonal structure. The zincblende structure still possesses distinct advantages over wurtzite structure. For example, the zincblende structure is provided with larger optical gain and lower threshold current density because of its smaller effective mass, and has mirror facets compatible with substrates such as GaAs. Furthermore, it is suggested that the electronic and thermal properties of zincblende nitrides are superior to those of the wurtzite materials due to reduced phonon scattering in the high symmetry crystals. The objective of this study is to investigate the structural properties of ternary zincblende AlInN alloys using ab initio calculations based on density functional theory (DFT). The structural properties of ternary zincblende AlInN, such as the equilibrium lattice constant, total energy, bulk modulus, and the pressure derivative of bulk modulus, are computed with LDA and GGA and compared with those available in the literature in order to develop a better understanding of the influence of the approximate exchange-correlation functional on these properties.

7602-69, Poster Session

Output power enhancement of light-emitting diodes with defect passivation layer

M. Lo, Y. Cheng, National Chiao Tung Univ. (Taiwan)

A high efficiency LED with defect selective passivation to block the propagation of threading dislocations is demonstrated. The defect selective passivation is achieved by using defect selective chemical etching to locate defect sites, silicon oxide filling of the etched pits, and epitaxial over growth. The threading dislocation density in the regrown epilayer is significantly improved to 4x107 cm-2. The defect passivated epi-wafer is used to grow LED structure and the output power of the fabricated chip is enhanced by 45% at 20 mA compared to a reference one without using defect passivation

7602-69, Poster Session

Output power enhancement of light-emitting diodes with defect passivation layer

M. Lo, Y. Cheng, National Chiao Tung Univ. (Taiwan)

A high efficiency LED with defect selective passivation to block the propagation of threading dislocations is demonstrated. The defect selective passivation is achieved by using defect selective chemical etching to locate defect sites, silicon oxide filling of the etched pits, and epitaxial over growth. The threading dislocation density in the regrown epilayer is significantly improved to 4x107 cm-2. The defect passivated epi-wafer is used to grow LED structure and the output power of the fabricated chip is enhanced by 45% at 20 mA compared to a reference one without using defect passivation

7602-70, Poster Session

Comparison of the light extraction efficiency of InGaN/GaN light-emitting diodes with two-dimensional hole and pillar photonic crystal structures

Y. C. Shin, D. H. Kim, B. G. Lee, W. H. Lee, D. J. Chae, J. W. Yang, S. J. Kim, H. D. Kim, Y. J. Seo, K. C. Kim, Korea Univ. (Korea, Republic of); J. Park, K. P. Constant, K. Ho, Iowa State Univ. (United States); H. Ryu, Inha Univ. (Korea, Republic of); J. H. Baek, T. Jung, Korea Photonics Technology Institute (Korea, Republic of); T. G. Kim, Korea Univ. (Korea, Republic of)

High-efficient GaN light-emitting diodes (LEDs) have been used in backlight units for LCD, traffic signals, and indoor illuminators. However, the external quantum efficiency of LEDs is fundamentally limited (~4%) by total internal reflection (TIR) due to Fresnel reflection between GaN medium (n=2.46) and air (n=1). In order to avoid TIR, several researchers have investigated photonic crystal (PC) structures to enhance the light extraction in the vertical direction of LEDs. However, detailed investigations on the effect of PC structures at a nanometer scale on the efficiency of LEDs have not been made yet.

In this work, we investigate the enhancement of light extraction in 2D photonic crystal GaN LEDs, in which either ITO or p-GaN layers have been patterned on a nano-size scale using two-beam laser interference and reactive ion etching. The effect of the lattice constant (460 to 920 nm) on the extraction efficiency has been explored in LEDs with hole- and pillar-patterned photonic crystals of various etch depths. As a result, photonic crystal LEDs with a lattice constant of 750 nm and a hole depth of 260 nm on ITO layers exhibited 1.3 times higher light extraction than LEDs without the photonic crystal, with no degradation in the electrical properties. The LEDs having pillar patterns of 60 nm height on the p-GaN layer have especially shown much higher extraction efficiencies (26%) than the samples with 120 nm-height pillar ITO patterns. More details on the experimental result as well as simulations of the photonic crystal LEDs will be presented.

7602-70, Poster Session

Comparison of the light extraction efficiency of InGaN/GaN light-emitting diodes with two-dimensional hole and pillar photonic crystal structures

Y. C. Shin, D. H. Kim, B. G. Lee, W. H. Lee, D. J. Chae, J. W. Yang, S. J. Kim, H. D. Kim, Y. J. Seo, K. C. Kim, Korea Univ. (Korea, Republic of); J. Park, K. P. Constant, K. Ho, Iowa State Univ. (United States); H. Ryu, Inha Univ. (Korea, Republic of); J. H. Baek, T. Jung, Korea Photonics Technology Institute (Korea, Republic of); T. G. Kim, Korea Univ. (Korea, Republic of)

High-efficient GaN light-emitting diodes (LEDs) have been used in backlight units for LCD, traffic signals, and indoor illuminators. However, the external quantum efficiency of LEDs is fundamentally limited (~4%) by total internal reflection (TIR) due to Fresnel reflection between GaN medium (n=2.46) and air (n=1). In order to avoid TIR, several researchers have investigated photonic crystal (PC) structures to enhance the light extraction in the vertical direction of LEDs. However, detailed investigations on the effect of PC structures at a nanometer scale on the efficiency of LEDs have not been made yet.

In this work, we investigate the enhancement of light extraction in 2D photonic crystal GaN LEDs, in which either ITO or p-GaN layers have been patterned on a nano-size scale using two-beam laser interference and reactive ion etching. The effect of the lattice constant (460 to 920 nm) on the extraction efficiency has been explored in LEDs with hole- and pillar-patterned photonic crystals of various etch depths. As a result, photonic crystal LEDs with a lattice constant of 750 nm and a hole depth of 260 nm on ITO layers exhibited 1.3 times higher light extraction than LEDs without the photonic crystal, with no degradation in the electrical properties. The LEDs having pillar patterns of 60 nm height on the p-GaN layer have especially shown much higher extraction efficiencies (26%) than the samples with 120 nm-height pillar ITO patterns. More details on the experimental result as well as simulations of the photonic crystal LEDs will be presented.

7602-71, Poster Session

Characterization of InGaN/GaN solar cells with various electrode designs on the surface

P. S. Yeh, H. Huang, K. Zhang, National Taiwan Univ. of Science and Technology (Taiwan)

We report characterization results of InGaN/GaN solar cells with various electrode designs on the surface that include finger electrode, using Ni/Au thin metal as semi-transparent electrode, and using ITO (Indium Tin oxide) as transparent electrode. These devices were characterized and compared in terms of solar cell's I-V curve as well as LED's I-V and L-I curves. The ratio of their solar cell's short-circuit currents was 2: 1: 3.5 (finger: thin metal: ITO), while their series resistances exhibited small differences.

7602-71, Poster Session

Characterization of InGaN/GaN solar cells with various electrode designs on the surface

P. S. Yeh, H. Huang, K. Zhang, National Taiwan Univ. of Science and Technology (Taiwan)

We report characterization results of InGaN/GaN solar cells with various electrode designs on the surface that include finger electrode, using Ni/Au thin metal as semi-transparent electrode, and using ITO (Indium Tin oxide) as transparent electrode. These devices were characterized and compared in terms of solar cell's I-V curve as well as LED's I-V and L-I curves. The ratio of their solar cell's short-circuit currents was 2: 1: 3.5 (finger: thin metal: ITO), while their series resistances exhibited small differences.

7602-72, Poster Session

Crystal quality improvement of a-plane GaN using epitaxial lateral overgrowth on nanorods

S. Ling, T. Lu, H. Kuo, National Chiao Tung Univ. (Taiwan)

The threading dislocation (TD) density of 3×1010 cm-2 was commonly observed in a-plane GaN grown on r-plane sapphire structure because of the large anisotropic lattice mismatch between these two materials. In this work, we propose an approach of lateral overgrowth on nano-rod a-plane GaN template to realize the defect-reduction and quality improvement in the subsequently grown a-plane GaN layer.

The processing flowchart of nano-rod epitaxial lateral overgrowth (NRELOG) is as follows: First, a 1.5-μm-thick a-plane GaN layer was grown on r-plane sapphire substrates by MOCVD. Then, a SiO2 film with a 200 nm thickness and a Ni film with a 10 nm thickness were deposited in sequence to act as the etching mask. Subsequently, the thermal annealing treatment was utilized to achieve nano-scale Ni masks. The GaN nanorods were etched through the nano mask openings by reactive ion etching. Finally, the GaN regrowth was performed on the nano-rod template by MOCVD.

The cross-sectional SEM image shows the fully coalesced thickness of NRELOG sample is less than 2 μm. In addition, compared with the as-grown samples, the XRD FWHM on-axis reflection of the NRELOG samples was reduced from 1308 to 542 arcsec. The PL measurement shows that the PL intensity of the NRELOG sample had a 18-fold increase compared with that of the as-grown sample. From the above-mentioned experiment results, we demonstrated that the feasibility of using NRELOG technique to achieve crystal quality improvement and the enhancement of luminescence performance in a-plane GaN.

7602-72, Poster Session

Crystal quality improvement of a-plane GaN using epitaxial lateral overgrowth on nanorods

S. Ling, T. Lu, H. Kuo, National Chiao Tung Univ. (Taiwan)

The threading dislocation (TD) density of 3×1010 cm-2 was commonly observed in a-plane GaN grown on r-plane sapphire structure because of the large anisotropic lattice mismatch between these two materials. In this work, we propose an approach of lateral overgrowth on nano-rod a-plane GaN template to realize the defect-reduction and quality improvement in the subsequently grown a-plane GaN layer.

The processing flowchart of nano-rod epitaxial lateral overgrowth (NRELOG) is as follows: First, a 1.5-μm-thick a-plane GaN layer was grown on r-plane sapphire substrates by MOCVD. Then, a SiO2 film with a 200 nm thickness and a Ni film with a 10 nm thickness were deposited in sequence to act as the etching mask. Subsequently, the thermal annealing treatment was utilized to achieve nano-scale Ni masks. The GaN nanorods were etched through the nano mask openings by reactive ion etching. Finally, the GaN regrowth was performed on the nano-rod template by MOCVD.

The cross-sectional SEM image shows the fully coalesced thickness of NRELOG sample is less than 2 μm. In addition, compared with the as-grown samples, the XRD FWHM on-axis reflection of the NRELOG samples was reduced from 1308 to 542 arcsec. The PL measurement shows that the PL intensity of the NRELOG sample had a 18-fold increase compared with that of the as-grown sample. From the above-mentioned experiment results, we demonstrated that the feasibility of using NRELOG technique to achieve crystal quality improvement and the enhancement of luminescence performance in a-plane GaN.

7602-73, Poster Session

Non-polar m-plane GaN on patterned Si(112) substrates by metalorganic chemical vapor deposition

X. Ni, M. Wu, J. Lee, X. Li, A. Baski, Ü. Özgür, H. Morkoç, Virginia Commonwealth Univ. (United States)

The concept of non-polar m-plane GaN on Si substrates has been demonstrated by initiating growth on the vertical (-1-11) sidewalls of patterned Si(112) substrates using metalorganic chemical vapor deposition. The Si(112) substrates were wet-etched to expose {111} planes using stripe-patterned SiNx masks oriented along the [-110] direction. Only the vertical (-1-11) Si sidewalls were allowed to participate in GaN growth by masking other Si{111} planes using SiO2, which led to m-plane GaN films. Growth initiating on the Si(-1-11) planes normal to the surface was allowed to advance laterally and also vertically towards full coalescence. The full width at half maximum values for the GaN m-plane x-ray diffraction rocking curves were 9 and 27 arcmin when rocked toward the GaN a-axis (parallel to stripes) and the GaN c-axis (perpendicular to stripes), respectively. Room-temperature photoluminescence showed strong band-edge emission with an intensity comparable to that of laterally overgrown c-plane GaN. InGaN double heterostructure active layers grown on these m-GaN templates on Si exhibited two times higher internal quantum efficiencies as compared to their c-plane counterparts at comparable carrier densities. These results demonstrate a promising method to obtain high-quality non-polar m-GaN films on large area, inexpensive Si substrates.

7602-73, Poster Session

Non-polar m-plane GaN on patterned Si(112) substrates by metalorganic chemical vapor deposition

X. Ni, M. Wu, J. Lee, X. Li, A. Baski, Ü. Özgür, H. Morkoç, Virginia Commonwealth Univ. (United States)

The concept of non-polar m-plane GaN on Si substrates has been demonstrated by initiating growth on the vertical (-1-11) sidewalls of patterned Si(112) substrates using metalorganic chemical vapor deposition. The Si(112) substrates were wet-etched to expose {111} planes using stripe-patterned SiNx masks oriented along the [-110] direction. Only the vertical (-1-11) Si sidewalls were allowed to participate in GaN growth by masking other Si{111} planes using SiO2, which led to m-plane GaN films. Growth initiating on the Si(-1-11) planes normal to the surface was allowed to advance laterally and also vertically towards full coalescence. The full width at half maximum values for the GaN m-plane x-ray diffraction rocking curves were 9 and 27 arcmin when rocked toward the GaN a-axis (parallel to stripes) and the GaN c-axis (perpendicular to stripes), respectively. Room-temperature photoluminescence showed strong band-edge emission with an intensity comparable to that of laterally overgrown c-plane GaN. InGaN double heterostructure active layers grown on these m-GaN templates on Si exhibited two times higher internal quantum efficiencies as compared to their c-plane counterparts at comparable carrier densities. These results demonstrate a promising method to obtain high-quality non-polar m-GaN films on large area, inexpensive Si substrates.

7602-74, Poster Session

Comparison of different template structures for high quality and self-separation thick GaN growth

Y. Fang, C. Chao, T. Chi, K. Chen, P. Liu, J. Tsay, Industrial Technology Research Institute (Taiwan)

Two different template structures of dot air-bridges and nano-rods were used for 300µm GaN growth by hydride vapor phase epitaxy (HVPE). The selective growth of arrays of dot air-bridges and nano-rods whose sidewalls coated with SiO2 are identified and exploited to form a compliant layer to decouple the impact due to the different thermal expansion and lattice mismatch between 300µm overgrown GaN layer and the host sapphire substrate. As the process temperature cooling down from 1050 oC to room temperature in HVPE system, the 300µm freestanding GaN substrates were obtained by the self-separation. The GaN (0002) plane -scans were carried out, and the full-width half-maximum (FWHM) values are lower than 350 and 150 arcsec for the template structure of dot air-bridges and nano-rods structure, respectively. Moreover, the dislocation density was estimated by both the etching pit density method and cathodoluminescence (CL). The dislocation density of the freestanding bulk GaN were lower than 5×106 and 5×107 cm-2 for the template structure of dot air-bridges and nano-rods structure, respectively.

7602-74, Poster Session

Comparison of different template structures for high quality and self-separation thick GaN growth

Y. Fang, C. Chao, T. Chi, K. Chen, P. Liu, J. Tsay, Industrial Technology Research Institute (Taiwan)

Two different template structures of dot air-bridges and nano-rods were used for 300µm GaN growth by hydride vapor phase epitaxy (HVPE). The selective growth of arrays of dot air-bridges and nano-rods whose sidewalls coated with SiO2 are identified and exploited to form a compliant layer to decouple the impact due to the different thermal expansion and lattice mismatch between 300µm overgrown GaN layer and the host sapphire substrate. As the process temperature cooling down from 1050 oC to room temperature in HVPE system, the 300µm freestanding GaN substrates were obtained by the self-separation. The GaN (0002) plane -scans were carried out, and the full-width half-maximum (FWHM) values are lower than 350 and 150 arcsec for the template structure of dot air-bridges and nano-rods structure, respectively. Moreover, the dislocation density was estimated by both the etching pit density method and cathodoluminescence (CL). The dislocation density of the freestanding bulk GaN were lower than 5×106 and 5×107 cm-2 for the template structure of dot air-bridges and nano-rods structure, respectively.

7602-75, Poster Session

Analytical methods to study burn-in effects in blue InGaN laser diodes

J. Müller, G. Brüderl, S. Tautz, M. O. Schillgalies, A. Breidenassel, S. Lutgen, OSRAM Opto Semiconductors GmbH (Germany)

An analysis of the short and long-term output stability of encapsulated blue InGaN lasers diodes (LDs) is presented. Laser of a standard design showed stable output power in short and long term experiments yielding in lifetimes of 10,000 h under constant current conditions.

In contrast, R&D test lasers with a different layer design and ridge etch depth suffered a strong burn-in. It was related with changes in quantum efficiency and carrier lifetimes which were longer after stressing. A simple recombination model was fitted to the measurements suggesting no increase in non-radiative recombination centers. Instead the longer carrier lifetimes after burn-in could be well explained with a decrease in carrier density due to an additional current spreading. These results were confirmed by changes in the sub-threshold wavelength shift before and after aging. It was therefore found to be crucial to control current spreading in ridge lasers by carefully adjusting the layer design, doping profile and ridge etch depth.

7602-75, Poster Session

Analytical methods to study burn-in effects in blue InGaN laser diodes

J. Müller, G. Brüderl, S. Tautz, M. O. Schillgalies, A. Breidenassel, S. Lutgen, OSRAM Opto Semiconductors GmbH (Germany)

An analysis of the short and long-term output stability of encapsulated blue InGaN lasers diodes (LDs) is presented. Laser of a standard design showed stable output power in short and long term experiments yielding in lifetimes of 10,000 h under constant current conditions.

In contrast, R&D test lasers with a different layer design and ridge etch depth suffered a strong burn-in. It was related with changes in quantum efficiency and carrier lifetimes which were longer after stressing. A simple recombination model was fitted to the measurements suggesting no increase in non-radiative recombination centers. Instead the longer carrier lifetimes after burn-in could be well explained with a decrease

in carrier density due to an additional current spreading. These results were confirmed by changes in the sub-threshold wavelength shift before and after aging. It was therefore found to be crucial to control current spreading in ridge lasers by carefully adjusting the layer design, doping profile and ridge etch depth.

7602-76, Poster Session

Reduction in operating voltage of UV laser diode

T. Ichikawa, K. Takeda, Y. Ogiso, K. Nagata, M. Iwaya, S. Kamiyama, H. Amano, I. Akasaki, Meijo Univ. (Japan); H. Yoshida, M. Kuwabara, Y. Yamashita, H. Kan, Hamamatsu Photonics K.K. (Japan)

UV laser diodes (LDs) and light emitting diodes (LEDs) are promising for various applications such as super-high-density optical storage, medical, chemical, excitation sources for phosphors, and fine lithography. Although we succeeded in fabrication of GaN/AlGaN multi-quantum wells based UV LDs and high-power UV-LEDs on high-crystalline-quality AlGaN thick templates, the operating voltages of these devices were high. In this study, we conducted several processes of device fabrication for reduction in operating voltage. In particular, we adopted a high annealing temperature of 850 °C, which cannot be adopted for GaInN based visible light emitters, to induced contact.

The UV LDs were fabricated using two-processes. For sample 1, we deposited p-electrodes and then annealed n-electrodes at 525 °C. For sample 2, we deposited the n-electrodes annealed at 850 °C. As a result, the operating voltage of sample 2 (16 V at 100 mA) was about 25% lower than that of sample 1 (20 V at 100 mA).

7602-76, Poster Session

Reduction in operating voltage of UV laser diode

T. Ichikawa, K. Takeda, Y. Ogiso, K. Nagata, M. Iwaya, S. Kamiyama, H. Amano, I. Akasaki, Meijo Univ. (Japan); H. Yoshida, M. Kuwabara, Y. Yamashita, H. Kan, Hamamatsu Photonics K.K. (Japan)

UV laser diodes (LDs) and light emitting diodes (LEDs) are promising for various applications such as super-high-density optical storage, medical, chemical, excitation sources for phosphors, and fine lithography. Although we succeeded in fabrication of GaN/AlGaN multi-quantum wells based UV LDs and high-power UV-LEDs on high-crystalline-quality AlGaN thick templates, the operating voltages of these devices were high. In this study, we conducted several processes of device fabrication for reduction in operating voltage. In particular, we adopted a high annealing temperature of 850 °C, which cannot be adopted for GaInN based visible light emitters, to induced contact.

The UV LDs were fabricated using two-processes. For sample 1, we deposited p-electrodes and then annealed n-electrodes at 525 °C. For sample 2, we deposited the n-electrodes annealed at 850 °C. As a result, the operating voltage of sample 2 (16 V at 100 mA) was about 25% lower than that of sample 1 (20 V at 100 mA).

7602-77, Poster Session

On the effect of InGaN-based LED structure on internal quantum efficiency

J. Lee, X. Ni, M. Wu, X. Li, R. Shimada, Ü. Özgur, A. Baski, H. Morkoç, Virginia Commonwealth Univ. (United States); T. Paskova, G. Mulholland, K. Evans, Kyma Technologies, Inc. (United States)

All too important internal quantum efficiency in InGaN based LEDs has taken to new heights as the demand for high quantum efficiency and more importantly its retention at high injection levels is increasing owing to candidacy for general lighting applications. Internal quantum efficiency is determined not only by completion between the radiative and non radiative components of the recombination process but also transport in (injection) and transport out (carrier spill over) of electrons and holes, whichever is applicable, to and from the active region. The overall efficiency and in particular the lack of its retention at high injection levels have also become a controversial issue as to the genesis of the latter in that the degree of the role of carrier spill over and Auger recombination the latter of which, if present, becomes increasingly notable at high injection levels. We have used various MQW structured InGaN LEDs on c-plane GaN, with inherent polarization induced field, and also on m-plane GaN, with no such field, to determine the internal quantum efficiency by all optical methods, one relying on the temperature dependence of the emission intensity assuming 100% efficiency at low temperatures and the other on excitation power dependence of emission at room temperature. The results of these investigations which also aimed at the origin of loss of, if any, efficiency degradation at high injection levels will be discussed.

7602-77, Poster Session

On the effect of InGaN-based LED structure on internal quantum efficiency

J. Lee, X. Ni, M. Wu, X. Li, R. Shimada, Ü. Özgur, A. Baski, H. Morkoç, Virginia Commonwealth Univ. (United States); T. Paskova, G. Mulholland, K. Evans, Kyma Technologies, Inc. (United States)

All too important internal quantum efficiency in InGaN based LEDs has taken to new heights as the demand for high quantum efficiency and more importantly its retention at high injection levels is increasing owing to candidacy for general lighting applications. Internal quantum efficiency is determined not only by completion between the radiative and non radiative components of the recombination process but also transport in (injection) and transport out (carrier spill over) of electrons and holes, whichever is applicable, to and from the active region. The overall efficiency and in particular the lack of its retention at high injection levels have also become a controversial issue as to the genesis of the latter in that the degree of the role of carrier spill over and Auger recombination the latter of which, if present, becomes increasingly notable at high injection levels. We have used various MQW structured InGaN LEDs on c-plane GaN, with inherent polarization induced field, and also on m-plane GaN, with no such field, to determine the internal quantum efficiency by all optical methods, one relying on the temperature dependence of the emission intensity assuming 100% efficiency at low temperatures and the other on excitation power dependence of emission at room temperature. The results of these investigations which also aimed at the origin of loss of, if any, efficiency degradation at high injection levels will be discussed.

7602-78, Poster Session

Analysis and comparison of UV photodetectors based on wide bandgap semiconductors

Q. Wang, S. Savage, B. Noharet, I. Petermann, S. Persson, M. Bakowski, J. Y. Andersson, Acreo AB (Sweden) and IMAGIC Ctr. (Sweden)

For imaging applications, photodetectors with high sensitivity, low noise and outstanding long term stability are generally highly desirable. However, individual applications have individual requirements regarding detector performance, which can be met by selecting a suitable type of detection mechanism and a base material with a structure best suited to achieve the desired performance. In this report we compare various

UV photodetectors, developed, produced and evaluated within IMAGIC (IMAGing Integrated Components), an institute centre of excellence coordinated by Acreo. These include the metal-semiconductor-metal (MSM) photodetector, p-i-n diode, and the avalanche photodiode (APD), based on GaN or SiC bulk or quantum well (QW) material. In particular, we present the design, fabrication and characterization of GaN- and SiC-based photodetectors, optimised for sensitivity and stability. The fabricated GaN-based QW p-i-n photodetectors are shown to exhibit a quantum efficiency around 50 % at 365 nm with a peak to visible rejection ratio of more than 3 orders of magnitudes. A novel APD design based on SiC is shown to produce a sharp and stable avalanche breakdown characteristic around 120 V for fabricated devices up to 2 mm in diameter. An increase in the responsivity by almost an order of magnitude when the avalanche voltage is applied is also demonstrated. The performance, advantages and drawbacks of the above photodetectors are analysed and compared, providing valuable information on their suitability for different applications. The analysis also provides information for further enhancement of device performance and for the design of next generation novel UV photodetectors.

7602-78, Poster Session

Analysis and comparison of UV photodetectors based on wide bandgap semiconductors

Q. Wang, S. Savage, B. Noharet, I. Petermann, S. Persson, M. Bakowski, J. Y. Andersson, Acreo AB (Sweden) and IMAGIC Ctr. (Sweden)

For imaging applications, photodetectors with high sensitivity, low noise and outstanding long term stability are generally highly desirable. However, individual applications have individual requirements regarding detector performance, which can be met by selecting a suitable type of detection mechanism and a base material with a structure best suited to achieve the desired performance. In this report we compare various UV photodetectors, developed, produced and evaluated within IMAGIC (IMAGing Integrated Components), an institute centre of excellence coordinated by Acreo. These include the metal-semiconductor-metal (MSM) photodetector, p-i-n diode, and the avalanche photodiode (APD), based on GaN or SiC bulk or quantum well (QW) material. In particular, we present the design, fabrication and characterization of GaN- and SiC-based photodetectors, optimised for sensitivity and stability. The fabricated GaN-based QW p-i-n photodetectors are shown to exhibit a quantum efficiency around 50 % at 365 nm with a peak to visible rejection ratio of more than 3 orders of magnitudes. A novel APD design based on SiC is shown to produce a sharp and stable avalanche breakdown characteristic around 120 V for fabricated devices up to 2 mm in diameter. An increase in the responsivity by almost an order of magnitude when the avalanche voltage is applied is also demonstrated. The performance, advantages and drawbacks of the above photodetectors are analysed and compared, providing valuable information on their suitability for different applications. The analysis also provides information for further enhancement of device performance and for the design of next generation novel UV photodetectors.

7602-51, Session 12

Realization of high-efficiency AlGaN-based ultraviolet light emitters

S. Jeon, Korea Photonics Technology Institute (Korea, Republic of)

The majority of research related to GaN-based ultraviolet (UV) emitters has been focused on maximizing efficiency for applications such as solid state white lightning, sterilization, and detection of biological/chemical agents. However, the performance of UV emitters is still quite low compared to blue light emitting diodes (LEDs) due to poor material quality; the emission efficiency of UV emitters using AlGaN/GaN-based quantum wells (QWs) as an active medium is governed by numerous parameters, such as compositional fluctuation in InN, threading dislocations, and interface states between well and barrier. It has been widely recognized that the highly efficient emission of InGaN/GaN multiple quantum well (MQW) LEDs is due to Indium segregation, resulting in an increase in the carrier recombination rate. However, AlGaN/(In)GaN-based UV LEDs, with a very low composition of indium, are more affected by dislocation in terms of emission efficiency. Therefore, for high performance UV LEDs having a long lifetime and high quantum efficiency, an important issue to overcome is to reduce the dislocation density.

In this work, I would like to focus on growth of high quality AlGaInN-based QWs and thick layer for improving internal quantum efficiency and present performance of UV LED devices such as 380nm and 365nm emission wavelength.

7602-52, Session 12

Novel device concept for high-efficiency InGaN quantum wells light-emitting diodes

N. Tansu, H. Zhao, Y. Ee, G. Liu, X. Li, G. Huang, Lehigh Univ. (United States)

High-efficiency InGaN based quantum wells (QWs) light emitting diodes (LEDs) play an important role in solid-state lighting application. In this paper, we present the challenges and approaches for high-efficiency InGaN QW LEDs for solid state lighting. Several major limiting issues on the performance of nitride LEDs are as follow: 1) low-efficiency devices in green spectral regime, 2) efficiency-droop in LEDs, 3) low-cost technique for improving light extraction efficiency, 4) reduced dislocation density in GaN materials, and 5) approaches for high-efficiency white LEDs.

One of the major challenges in achieving high radiative efficiency in green-emitting InGaN QW LEDs is the existence of polarization fields in the QW, which in turn leads to charge separation effect. The use of novel quantum wells with improved electron-hole wavefunction overlap leads to an enhancement of radiative recombination rate. Both staggered InGaN QW and type-II InGaN-GaNAs QW leads to enhanced overlap, which in turns leads to enhancement in radiative efficiency of the green-emitting nitride LEDs. Efficiency droop is an important limitation for high-power LEDs, and several theories have been proposed as the dominant factor for the droop observed in LEDs. We will review the discussion for both leading theories on Auger recombination and carrier leakages, and we will present some possible solutions for removing the efficiency-droop. Novel approach based on low-cost and practical method will also be reviewed for addressing light extraction efficiency issue in nitride LEDs. Several interesting approaches for achieving white LEDs and novel growth methods for dislocation reduction technique will also be presented.

7602-53, Session 12

Role of interface roughness on lateral transport in InGaN/GaN LEDs: diffusion length, dislocation spacing, and radiative efficiency

I. Lu, Y. Wu, National Taiwan Univ. (Taiwan); J. M. Hinckley, J. Singh, Univ. of Michigan (United States)

Nitride based LEDs are increasing playing a dominant role in solid state lighting. It is known that in spite of a high dislocation density (10^{7}-10^{8} cm^{-2}) the radiative efficiency is quite high, especially at low current injection. The high performance of the LEDs suggests that dislocations are not of importance in LED performance. One may ask the question: Once in the wells, are the carriers unable to reach the dislocation? There have been few studies on the lateral transport of free carriers once they are in the InGaN quantum wells. This transport occurring under zero or very low electric field is important as it determines how carriers diffuse

towards regions of dislocations before they recombine radiatively or non-radiatively.

In a LED electrons and holes are injected from the contacts into the quantum wells where they thermalize rapidly (in picoseconds). The carriers diffuse laterally in the quantum wells (there is no lateral field). Some of these carriers can reach dislocations where they may suffer non-radiative recombination. Carriers also recombine radiatively and through defects. Carriers also leave the wells through leakage and Auger recombination. We have developed a Monte Carlo simulation program that includes all these effects and we will show bias dependent results. We will focus on the role of interface roughness in the quantum well on lateral transport and present results on the diffusion length in the lateral direction. The influence of quantum well with different indium composition, quantum well width, carrier density, and interface roughness are studied.

Our results show that in absence of any interface roughness the lateral mobility in In0.2Ga0.8N/GaN wells is 1800 cm^2/V.s. The lateral transport has a small bias dependence since the shape of the quantum well changes with forward bias conditions. For the perfect interface the lateral diffusion length is around 12 micrometers which is much greater than the dislocation spacing indicating that dislocations will be an important source of recombination if the interfaces are perfect. If the interface is described by islands that are 1 nm tall and 3 nm wide (values that are consistent with values needed to understand photoluminescence linewidth in InGaN/GaN wells) the mobility drops to only around 600 cm^2/V.s. The diffusion length then becomes smaller than the dislocation spacing. In some cases (larger interface roughness), the mobility can even drop to 100cm^2/Vs. Under these conditions the dislocations play a minimal role on LED performance. It will also depend on the radiative life time since longer life time will increase the diffusion length. With higher indium composition, the mobility drops more rapidly with larger interface roughness due to the much larger scattering potential and strong piezoelectric field that push the carrier toward the interface. The roles of interface roughness, dislocation, radiative recombination, and Auger scattering will be discussed in detail.

7602-54, Session 12

Reduction of the efficiency droop of InGaN quantum well light-emitting diodes by using an In0.04Ga0.96N pre-layer and trimethylindium treatment

H. Liu, P. Chen, H. Lin, J. Chyi, National Central Univ. (Taiwan)

Carrier localization in nanoscale In-rich regions plays an important role in efficiency roll-off behavior of InGaN-based light-emitting diodes (LEDs). In this work, we report a method to alleviate efficiency droop of InGaN LEDs as evidenced by the three samples, designated as A, B, and C, investigated. Sample A is a reference sample, which consists of ten undoped In0.16Ga0.84N (3 nm) quantum wells separated by Si doped GaN barrier (10 nm). Sample B has a composite quantum well active region, i.e. ten periods of In0.04Ga0.96N (2 nm) /In0.16Ga0.84N (3 nm)/GaN (10 nm). While sample C has the same active region as sample B, a TMIn treatment process at the In0.04GaN/In0.16GaN interface is adopted during the growth to smooth the interface. Temperature-dependent photoluminescence measurements are carried out to investigate the excitation-localization effect as well as the activation energy of nonradiative recombination. Based on the band-tail model, sample A, B and C has localization energy of 11.5 meV, 9.4 meV and 7.4 meV, respectively. The activation energy of integrated PL intensity of sample A, B and C at low temperature (below 100 K) is 30.4 meV, 12.6 meV and 12.1 meV, respectively. These results indicate that the degree of localization is reduced by the new quantum well structure and growth technique. Under pulsed operation, the droop point of sample B is extended from 30 A/cm2 to 60 A/cm2, while that of sample C is further extended from 60 A/cm2 to 80 A/cm2.

7602-55, Session 12

A measurement method of internal quantum efficiency in InGaN light-emitting diodes without any parameter assumptions

J. Shim, H. Kim, Hanyang Univ. (Korea, Republic of); H. Jung, W. Kim, EtaMax Co. (Korea, Republic of)

The external quantum efficiency (EQE) in InGaN LEDs is defined by the product of the internal quantum efficiency (IQE) and the light extraction efficiency (LEE). Since the EQE can be limited by the IQE or the LEE, it is important to evaluate the IQE and the LEE separately and improve both components individually.

Absolute intensity measurements by an integrating sphere with theoretical LEEs, carrier lifetime measurement by electrical pulse, analysis of the light power-current curve based on carrier rate equation, and the temperature dependent electroluminescence have been reported for the IQE measurements. One of limitations included in these methods is that some of the fundamental physical parameters are assumed and treated as constants with respect to carrier density in InGaN-based QWs.

A measurement method of the IQE just from the measured light power-current curve at room temperature without the aid of any internal physical parameter assumptions is developed for the first time. The proposed method utilizes only relative ratios of measured power experimentally so that it can be applied to any types of LEDs and its estimation error can be minimized. The method is theoretically based on the carrier rate equation with taking into account of carrier screening of the piezo-electric field and the carrier band filling. We applied our method to commercial grade blue InGaN multiple quantum well LEDs with the same fabrication processes except Au and Ag-base packages. Almost the same IQEs but different LEEs were estimated, which confirmed the validity of our method.

7602-56, Session 13

Development of high-power UV LEDs for epoxy curing applications

C. Tran, SemiLEDs Corp. (United States)

High power near-UV LEDs, with wavelengths from 365nm to 410nm, were realized with an external quantum efficiency from 12% to 45% for 365nm and 410nm, resp.

First the LED epitaxial layers were grown on a template structure consisting of GaN on sapphire. Then the template structure including sapphire were both removed in subsequent process steps, thus leaving only the LED epitaxial layers on top of an alloy base as a complete device. This method enables for short wavelength, AlGaN-only structures close to 365nm, to be grown on a thick GaN layer for high crystalline quality. Afterwards, the GaN layer will be completely removed, so no absorption by the GaN layer occurs. We show that the vertical LED design, coupled with the Silicon sub-mount package gives very good reliability that is suitable for many high power epoxy and polymer curing applications. UV LEDs are proven to be a good replacement for high power mercury lamps currently used in the market.

7602-57, Session 13

Original GaN-based LED structure on ZnO template by metal organic chemical deposition

R. Lin, Chung Gung Univ. (Taiwan); S. Yu, National Cheng-Kung Univ. (Taiwan)

In this study, we have successfully grown blue LED structure on ZnO template (deposited on sapphire substrate by atomic layer deposition, ALD) by atmospheric pressure metal-organic chemical vapor deposition (MOCVD). Although GaN semiconductor material is very similar to ZnO

in many ways, i.e. relatively small lattice mismatch ~1.8 % compared with traditional sapphire substrate~16 %, it still has a big challenge when GaN based LEDs structure grow on ZnO template at standard growth temperature near 1100 °. With too high a temperature and a long deposited time, it would cause reaction at GaN/ZnO interface which is a vital reason that degrades the GaN crystalline quality. In view of this, we introduced an optimized thin AlN cover layer on ZnO template protecting the underneath ZnO layer and then obtained a real work LED structure. Meanwhile, the HRXRD and TEM measurement characterized the epilayer crystalline structure. The optical properties also were carried out by photoluminescence and electroluminescence analysis. Finally, with a suitable fabrication of LED processing, the ZnO template film may has the potential as a sacrificial layer by chemical etching technic instead of conventional laser lifted-off.

7602-58, Session 13

Increasing light extraction efficiency of blue-light-emitting diodes a using moth-eye structure

T. Kondo, A. Suzuki, F. Teramae, T. Kitano, Y. Kaneko, R. Kawai, EL-SEED Corp. (Japan); K. Teshima, S. Maeda, S. Kamiyama, M. Iwaya, H. Amano, I. Akasaki, Meijo Univ. (Japan)

The moth-eye structure consists of periodic cones, with wavelengths order on the submicron scale, on the surface of optical components. To apply it to the surface of light-emitting diodes (LEDs), an increase in light extraction efficiency is necessary owing to the interference effect. The use of the moth-eye structure is a new approach that produces a pure interference effect, and has a possibility to realize higher light extraction efficiency than a conventional technique. In this study, we investigated the dependence of cone period in the moth-eye structure on the light extraction efficiency of nitride-based blue LEDs on the SiC surface. Because of the small period of the moth-eye structure, we used low-energy electron-beam projection lithography for patterning the back surface of the SiC substrate, which is capable of forming a periodic hole pattern at a very high speed. After transforming such a pattern to a metal mask by the lift-off technique, dry etching was carried out to form cones. To enhance the interference effect in the moth-eye plane, a reflector at another surface of the top epilayer was also adopted. At a cone period of 500 nm, the blue LED exhibited a more than three times higher output power than that with a flat surface. This improvement is much greater than the effect of a conventional roughened surface or a micron-scale textured surface. We will also show other applications of the moth-eye structure such as moth-eye patterned sapphire substrates and ITO contacts in nitride-based LEDs.

7602-59, Session 13

Internal quantum efficiency of m-plane InGaN on Si and GaN

J. Lee, X. Ni, M. Wu, X. Li, R. Shimada, U. Özgür, A. Baski, H. Morkoç, Virginia Commonwealth Univ. (United States); T. Paskova, G. Mulholland, K. Evans, Kyma Technologies, Inc. (United States)

High brightness InGaN light emitting diodes (LEDs) require high quantum efficiency and its retention at high injection levels. The efficiency drop with injection has been attributed, e.g. to polarization field on polar c-plane InGaN and the heavy effective hole mass which impedes high hole densities and transport in the active quantum wells. In this study, we carried out a comparative investigation of the internal quantum efficiency (IQE) of InGaN layers, representing the active regions used in LEDs, using resonant optical excitation for layers with polar (0001) orientation on c-plane sapphire, and nonpolar (1-100) m-plane orientation, the latter on m-plane bulk GaN and on specially patterned Si. The IQE values were extracted by analyzing the resonant photoluminescence (PL) intensity as a function of the excitation power. The data indicate that at comparable generated carrier concentrations the efficiency of the m-plane InGaN on Si is approximately a factor of 2 higher than that of the highly optimized c-plane layer. At the highest laser excitation level employed (corresponding carrier concentration n ~ 1.2 x 10^18 cm-3), the m-plane InGaN double heterostructure on Si has an IQE value of approximately 65%. We believe that the m-plane would remain inherently advantageous, particularly at high electrical injection levels, even with respect to highly optimized c-plane varieties. The observations could be attributed to the lack of polarization induced field and the predicted increased optical matrix elements.

7602-60, Session 14

Development of high-efficient InGaN-based blue LED for lighting applications

T. Hsu, M. Hsu, M. Hsieh, M. Jou, Epistar Corp. (Taiwan); T. Tang, Y. Chen, W. Shiao, C. Lin, W. Chang, C. Liao, K. Shen, C. Yang, National Taiwan Univ. (Taiwan)

After more than ten-years development, InGaN-based LED really exhibit high potential for application of general lighting. However there are still some technical issues to be overcome, such as internal quantum efficiency (IQE), light extraction and droop. For LED with significant higher efficiency, development of novel materials and structure might play an important role. In this paper, coalescence overgrowth high-quality GaN nanocolumns(NCs) on c-plane sapphire substrate with metal organic chemical vapor deposition is studied. The surface roughness of the overgrown layer in an area of 5x5 um2 is as small as 0.411 nm, which is only one-half that of the high-quality GaN thin-film template directly grown on sapphire substrDepth-dependent x-ray diffraction measurements near the surface of the overgrown layer shows that the dislocation density is reduced to the order of 107 cm−2, which is two to three orders of magnitude lower than those of ordinary GaN templates. With this improved crystal quality and also the enhanced light extraction, emission enhancement results of blue emitting InGaN/GaN QW and LED structures based on NCs growth and coalescence overgrowth are presented.

7602-61, Session 14

Efficiency enhancement of InGaN LEDs with an n-type AlGaN/GaN/InGaN current spreading layer

P. Chen, H. Liu, G. Lee, H. Lin, J. Chyi, National Central Univ. (Taiwan)

Uniform current spreading is an essential design consideration in high power InGaN LEDs for solid state lighting as current crowding increases with current. In this work, we report a novel InGaN light-emitting diode (LED) structure, which improves current spreading and thus the quantum efficiency. Three samples, designated as sample A, B, and C, are prepared. Sample A is a reference sample, which has a conventional MQW structure and an n-GaN buffer layer. Sample B has an additional n-Al0.1Ga0.9N blocking layer on the n-GaN buffer layer while sample C has a n-Al0.1Ga0.9N/GaN/In0.07Ga0.93N current spreading layer on the n-GaN buffer layer. LEDs with size of 45 mil×45 mil are fabricated on these samples for characterization. The n-Al0.1Ga0.9N/GaN/In0.07Ga0.93N structure is a double heterostructure and exhibits two layers of two-dimensional electron gas at the two hetero-interfaces due to the polarization-induced electric field. According to theoretical calculation, the structure induces a high electron concentration (3.49×1019cm-3/4.92×1019cm-3) in this layer. Its total electron concentration is higher than that in the n-Al0.1Ga0.9N/GaN (3.14×1019cm-3) structure and n-GaN/In0.07Ga0.93N (4.48×1019cm-3) structure used in conventional LEDs. The advantage of using this new current spreading layer is confirmed by the improved output power-current characteristics and uniform light emission images. The optical output power at 350 mA of sample A, B and C is 93.7 mW, 105.6 mW

and 115.2 mW, respectively, that is nearly 23 % improvement for the LEDs with this new current spreading layer.

7602-62, Session 14

High-quality AlN for deep UV applications

S. A. Nikishin, B. Borisov, M. Pandikunta, R. P. Dahal, J. Lin, H. Jiang, M. Holtz, Texas Tech Univ. (United States)

The optical and electrical properties of AlGaN based deep UV light emitting diodes and photodetectors (PDs) grown on c-plane sapphire are very sensitive to the material quality. Thick AlN is very attractive for fabricating metal-semiconductor-metal (MSM) solar-blind PDs due to the relative simplicity of forming high quality Schottky contacts. We report influence of growth conditions during gas source molecular beam epitaxy (GSMBE) with ammonia on structural and morphological properties of AlN. The density of inversion domains (IDs) varies depending on the growth condition from 10e9 cm-2 to 10e7 cm-2. To reduce the ID density we incorporated two AlN/GaN short period super lattices (SPSLs) into our structure with barrier and well thicknesses of ~ 2.0 and ~ 0.5 nm, respectively. The ID density, 10e6 cm-2, estimated from large scale, 10 x 10 µm2, atomic force microscope images was reduced by over one order of magnitude than in AlN layers grown without SPSLs. We found that insertion of SPSLs between nucleation and top AlN layer does not strongly influence either screw or edge dislocation density. The large areas, 0.50 x 0.55 mm2, MSM PDs on the samples with different ID density were fabricated. The reduction in ID density is found to improve the MSM PD leakage current and sensitivity. PDs with ID density 10e6 cm-2 exhibit a very low dark current 0.5 fA at zero bias which remains below 50 fA up to bias ± 30 V. The peak responsivity of 0.08 A/W was obtained at a wavelength ~202 nm.

7602-63, Session 14

Efficiency retention at high current injection levels in m-plane InGaN LEDs

X. Li, X. Ni, J. Lee, M. Wu, Ü. Özgür, H. Morkoc, Virginia Commonwealth Univ. (United States); T. Paskova, G. Mulholland, K. Evans, Kyma Technologies, Inc. (United States)

We investigated both the internal quantum efficiency (IQE) and external quantum efficiency (EQE) of an m-plane InGaN-based LED grown on an m-plane bulk GaN. According to photoluminescence (PL) measurements, the IQE values from the m-plane LED is approximately 1.7 times higher than a c-plane reference LED with the same structure (multiple-quantum well active region with 3nm In0.01Ga0.99N barriers) albeit on sapphire substrate. According to electroluminescence (EL) measurements, the external quantum efficiency (EQE) from both LEDs shows negligible droop under electrical injection due to the employment of thin In0.01Ga0.99N barriers in the active regions. Moreover, with the increase of the current, the EL intensity of the m-plane LED increases more rapidly than that from the c-plane LED, with the EL intensity reaching its peak value at ~150 Acm-2 for the m-plane LED and ~420 Acm-2 for the c-plane LED. The EQE values from the m-plane LED are ~1.6 times higher than its c-plane counterpart, which is consistent with the results obtained from the PL

7602-64, Session 15

AlGaInN heterostructures on semipolar side facets of selectively grown GaN stripes for optoelectronic applications

F. Scholz, T. Wunderer, M. Feneberg, K. Thonke, A. Chuvilin, U. Kaiser, Univ. Ulm (Germany); S. Metzner, F. Bertram, J. Christen, Otto-von-Guericke-Univ. Magdeburg (Germany)

In order to overcome the problems of reduced recombination probability due to internal piezoelectric fields in strained GaInN quantum wells, we have developed a method to grow semipolar GaInN-based LED structures on semipolar side facets of selectively grown GaN stripes with triangular cross-section. This enables to grow semipolar device structures over the full area of a 2” wafer while still making use of the well developed growth of optimized c-plane GaN buffer layers. We have studied stripe and hexagonally shaped mask geometries. Depending on the stripe direction and the growth conditions, different semipolar facets develop. We found a strongly facet dependent growth mechanism leading to very flat surfaces on {1-101} facets as opposed to their {11-22} counterparts along with a different indium incorporation efficiency. An increased indium uptake on semipolar {1-101} facets as compared to conventional c-plane layers helped to shift the LED emission to longer wavelengths beyond 500 nm in the green spectral range despite the significantly reduced field-dependent Stark shift. By photoluminescence (PL) investigations on pre-biased LED structures along with respective model calculations, we could directly determine the value of the reduced internal electric field. Hexagonally shaped mask geometries are more favourable for large area device applications. Moreover, the reduction of dislocations resulting from the heteroepitaxial process on sapphire may be more pronounced. However, by locally resolved cathodoluminescence, we found a quite strong local variation of the emission wavelength over the formed inverted pyramid facets which is also visible in locally resolved measurements of the carrier recombination times.

7602-65, Session 15

Fabrication of ultraviolet-C light source using MOVPE grown AlGaN layer on AlN/sapphire

H. Miyake, Mie Univ. (Japan)

AlGaN alloys have been promising GaN-based III-nitride materials for laser diodes and photodetectors covering ultraviolet region because of their direct energy band gap from 3.4 eV to 6.2 eV. However it is extremely difficult to grow high-quality AlGaN with high Al content directly. Meanwhile the technique of using high temperature-grown AlN film as an underlying layer for the growth of AlGaN has been also reported, but cathodeluminescence from the AlGaN is not enough for application of deep-UV light source. In this study, high-quality AlGaN with high-luminance-intensity in deep UV region was realized by inserting a AlN mole-fraction-control layer on AlN/sapphire template. Crystalline quality and cathodeluminescence of the AlGaN are discussed.

High-quality (0001) epitaxial AlN film with thickness of 0.8 m was directly grown on sapphire (0001) substrate by low-pressure metal organic vapor phase epitaxy (LP-MOVPE). Subsequently, AlxGa1-xN (0. 2<x<0. 9) was grown on the AlN by LP-MOVPE. The growth was performed at a pressure of 50 Torr and at temperatures from 1100 oC to 1300 oC.

No cracks appeared in fabricated the AlGaN with thickness of 1.0 micro meter on the underlying AlN. Atomically flat surfaces with single atomic step of approximately 0.1-0.2nm in height were observed in the AlGaN by AFM.Cathodeluminescence intensity of the AlGaN layer with AlN mole fraction layer is 3 times higher than that without the AlN mole fraction layer. We demonstrated fabrication of light sources in wavelength region of 240-260 nm (ultraviolet-C) using MOVPE grown AlGaN on a AlN/sapphire template. The AlGaN layer was excited by an electron beam with an accelerating voltage of 8 kV.

7602-66, Session 15

Electroluminescence characteristics of nonpolar a-plane ([11-20]) InGaN/GaN light-emitting diodes grown on r-plane sapphire substrates

D. H. Kim, B. G. Lee, W. H. Lee, D. J. Chae, J. W. Yang, K. C. Kim, H. M. An, Korea Univ. (Korea, Republic of); S. M. Hwang, Y.

G. Seo, Korea Electronics Technology Institute (Korea, Republic of); T. G. Kim, Korea Univ. (Korea, Republic of)

Recently, nonpolar GaN light-emitting diodes (LEDs) have received an attraction because of the potential for the improvement of device performance, as compared to polar GaN counterparts. These potentials would arise from the absence of built-in polarization-related electric fields and thereby higher radiative recombination rates in such material systems. However, the growth of nonpolar GaN LEDs on sapphire substrates is still challenging due to the high density of threading dislocations and basal stacking faults incurred during the crystal growth.

In this work, we report on the growth, fabrication, and device characteristics of nonpolar a-plane ([11-20]) InGaN/GaN LEDs grown on r-plane ([1022]) sapphire substrates by using multiple stage overgrown methods. In particular, the effect of the injection current on the light output power, emission wavelength, and linewidth in the electroluminescence (EL) emission spectra are investigated. Until now, we have observed a light output power of 94.7 uW at 20 mA under 3.54 V and a maximum light output power of 278.7 uW at 50 mA at 4.3 V. More details on the experimental results including current-voltage and the EL performance of the nonpolar a-plane InGaN/GaN LEDs will be presented.

7602-67, Session 15

Blue superluminescent light-emitting diodes

M. Rossetti, Exalos AG (Switzerland); E. Feltin, NOVAGAN s.a.r.l. (Switzerland); J. Carlin, A. Castiglia, G. Cosendey, N. Grandjean, Ecole Polytechnique Fédérale de Lausanne (Switzerland); J. Dorsaz, V. Laino, M. Duelk, C. Velez, Exalos AG (Switzerland)

Superluminescent light emitting diodes (SLEDs) are devices combining the beam directionality of laser diodes with the broadband emission of LEDs. Thanks to these specific properties, SLEDs are used today in the near-infrared for optical gyroscopes or optical coherence tomography (OCT). Short-wavelength SLEDs could have a major impact in biomedical applications by combining OCT and fluorescence measurements all-in-one system, or as speckle-suppressing light sources used in projection applications.

Here we report on the first demonstration of a GaN based SLED emitting in the blue-violet spectral region. The structure containing multiple InGaN QWs inside an AlGaN/GaN waveguide was grown by MOVPE on 2 inch free-standing GaN substrates. Index-guided single lateral mode SLEDs were fabricated by means of dry etching and thin film deposition techniques and lasing suppression was achieved by tilting of the ridge-waveguide with respect to the output facet.

At low currents the edge emission is mostly driven by spontaneous recombination with a spectral linewidth of 10-15 nm. For increasing injection, the spectra become narrower due to light amplification and exhibit a smooth Gaussian peak with a typical linewidth of 4-5 nm.

The light-current characteristics follow the exponential trend typical of light amplification (signature of superluminescent operation) with CW output powers up to 4 mW at 15kA/cm^2. The average (peak) power measured under pulsed injection reaches 20 mW (100 mW) at 20% duty cycle and for a current density of 30kA/c^m2. The emission is highly directional, which is desirable for projection applications and for coupling into optical fibers.

Conference 7603: Oxide-based Materials and Devices

Sunday-Wednesday 24-27 January 2010 • Part of Proceedings of SPIE Vol. 7603

Oxide-based Materials and Devices

7603-01, Session 1

Conduction in disordered thin films: application to ZnO

D. C. Look, Wright State Univ. (United States)

Thin semiconductor films grown on lattice-mismatched substrates are likely to be polycrystalline or disordered in some other way. Conduction in such films is in general dependent on the type and amount of disorder and also the thickness of the film. Although ZnO is usually n-type due to residual Al and Ga, acceptor states associated with threading dislocations and grain boundaries can trap the free electrons and even render the material semi-insulating. Such properties are often desirable for enhancement-mode field-effect transistors. For other applications, however, near-metallic conduction is needed, and this can be accomplished by doping with Al or Ga to enhance the donor concentration ND, or by introducing H to partially neutralize the acceptor concentration NA. To determine ND and NA in degenerate thin films, we have developed a detailed scattering model to fit temperature-dependent resistivity and magnetoresistivity (B,T) data. Note that the carrier concentration n is independent of temperature and is used as an input parameter. Interestingly, the magnetoresistance is negative up to about 200 K due to weak localization, a quantum interference effect. To test our model, we have measured n and (B,T) in PLD-grown, Ga-doped, forming-gas-annealed ZnO samples of thickness ranging from 3 - 285 nm. If we use a ZnO target containing 3-wt% Ga2O3, we get ND = 5.1 x 1020 and NA = 2.1 x 1020 cm-3, showing that about 45% of the Ga atoms in the target enter the ZnO lattice as donors. This important number is very difficult to obtain by any other means.

7603-02, Session 1

Theory of high field carrier transport and impact ionization in ZnO

F. Bertazzi, Boston Univ. (United States) and Politecnico di Torino (Italy); M. Penna, M. Goano, Politecnico di Torino (Italy); E. Bellotti, Boston Univ. (United States)

With the emergence of ZnO as a potential player in the wide band-gap semiconductor arena, it is critical to understand the material performance to be able to design and optimize electronic and optoelectronic devices. In this work we present a novel full band Monte Carlo model of high field carrier transport and impact ionization in wurtzite ZnO. The proposed Monte Carlo model is based on a fitting-parameter-free approach in which the carrier-phonon interaction is treated using the rigid pseudoion formalism, the electronic structure is calculated with a nonlocal empirical pseudopotential method and the phonon dispersion is determined with the linear response technique within density functional theory. Adjustable parameters such as deformation potential coefficients are eliminated by computing the electron and hole anisotropic deformation potentials directly from first-principle. On the same footing, the electron and hole impact ionization rates and the polar carrier-phonon interaction have been computed using the calculated ZnO electronic structure. The model also includes a novel approach for the treatment of electric-field-induced interband transitions. Since the only experimental information on the ZnO transport coefficients available is for low applied field strengths, first we show that the proposed model can reproduce the measured temperature dependent Hall mobility data. Subsequently we evaluate the carrier drift velocities for different crystallographic directions up to a field of 1MV/cm and we determine the direction dependent carrier ionization coefficients up to an applied field strength of 4MV/cm.

7603-03, Session 1

Ultrafast carrier relaxation and diffusion dynamics in ZnO systems

C. J. Stanton, C. J. Cook, Univ. of Florida (United States); S. Khan, Univ. of Illinois (United States); X. Wang, The Univ. of Texas at Austin (United States); Y. Jho, Gwangju Institute of Science and Technology (Korea, Republic of); D. H. Reitze, Univ. of Florida (United States)

While polycrystalline ZnO has been widely used in areas such as sunscreens or phosphors, only recently has high quality, bulk crystaline or epitaxial ZnO become available. This has opened up intriguing possibilities for new uses for ZnO owing to its wide band gap (3.37 eV) including applications in the production of blue or green lasers/diodes; high power devices; and more recently possible novel applications in the field of spintronics. We report on our calculations and measurements of the ultrafast carrier and exciton dynamics in ZnO materials. We have performed time-resolved differential reflectivity (TRDR) measurements of bulk ZnO, ZnO epilayers and nanorods as a function of temperature and excitation wavelength at the National High Magnetic Field Laboratory. Bi-exponential decays of the A and B exciton states are observed with fast (~ps scale) and slower (~50-100 ps scale) components, which depend strongly on excitation wavelength. Our theoretical calculations of the exciton and photoexcited carrier dynamics are based on a multi-state, coupled rate equation model. We compare our theoretical results with the experimental results to study the relaxation dynamics when pumping and probing near the A and B excitons. In addition to solving the coupled rate equations, we show that carrier diffusion can play an important part in explaining the experimental results.

7603-04, Session 1

Optical and vibrational properties of nonpolar a-plane versus polar c-plane ZnO

M. R. Wagner, M. Cobet, G. Callsen, R. Kirste, M. Kaiser, A. G. Hoffmann, Technische Univ. Berlin (Germany); S. Eisermann, S. Lautenschläger, J. Sann, B. K. Meyer, Justus-Liebig-Univ. Giessen (Germany)

Non-polar a-plane ZnO substrates for epitaxial growth introduce the prospect of high quality epilayers which do not suffer from piezoelectric fields and thereby enable the fabrication of efficient hetero-structures unaffected by the quantum confined Stark effect. However, many optical and structural properties of a-plane ZnO were not yet studied to the same extend of detail as in c-plane ZnO. In this contribution, we present a comprehensive comparison of the influence of internal piezoelectric and external stress fields on the optical properties of polar and non-polar ZnO substrates and epilayers. Micro-Raman spectroscopy reveals the presence of different strain distributions in the samples which also vary as a function of the polarity in the c-plane material. These strain levels are compared with the c- and a-lattice parameters determined by HRXRD. It is found that substrates from different suppliers exhibit large deviations of the lattice parameters. The influence of these variations on the excitonic-polaritonic transitions is studied by PL under uniaxial pressure and different pressure coefficients for the exciton-polaritons are calculated. The derived polariton dispersion of the different samples is compared to UV spectroscopic ellipsometry of the a- and c-plane samples.
Using synchrotron radiation, the dielectric function is determined in a straightforward manner. This technique delivers the whole set of intrinsic optical functions and information about the anisotropy between the two independent components for electric field vectors parallel and perpendicular to the optical c-axis. Distinct structures of the free exciton-polaritons allow the accurate determination of the valence band splittings, the band symmetry ordering and the longitudinal-transversal

separation of the polaritons. Finally, the effect of nitrogen doping in a-plane and c-plane ZnO on the incorporation of shallow N acceptors is studied. All results are compared concerning the influence of polar and non-polar material and suggestions for further improvements of non-polar growth will be provided.

7603-05, Session 2

Mechanisms of enhancement of visible light absorption in ZnO films for photoelectrochemical splitting of water

J. L. Pau Vizcaino, M. J. Hernández, M. Cervera, L. Wolff, J. Piqueras, Univ. Autónoma de Madrid (Spain)

Among all methods to produce hydrogen, photoelectrochemical (PEC) water splitting is possibly the cleanest way since it can rely on solar power to split water. Conductive oxides present excellent properties to perform as photoanodes in PEC cells: appropriate bandgap and flat band potential, high conductivity, and good corrosion resistance. However, their large bandgap makes them inefficient at producing hydrogen under solar illumination. In this work, mechanisms for enhancing visible light absorption in ZnO films such as metal and nitrogen doping, surface modification, and fabrication of novel structures are reviewed.

7603-06, Session 2

Growth and properties of nonpolar and polar MgZnO/ZnO quantum wells

H. Matsui, The Univ. of Tokyo (Japan)

Recently, low-dimensional physics based on oxide materials have been progressed due to the exact control of atomically flat heterointerfaces. Its spectacular breakthroughs have been achieved in optoelectronics with the use of MgZnO/ZnO heterostructures. Fundamental characteristics of quantum wells (QWs) have investigated for the polar directions. In contrast, A- and M-nonpolar ZnO surfaces show a polarization field in a surface plane that differs from Zn- and O-polarities, which gives an influence for layer growth and optoelectronic properties. M-nonpolar ZnO layer surfaces produce periodic arrays of nanowires naturally formed during homoepitaxial growth. Self-organization of one-dimensional (1D) nanostructures has attracted much attention, as this is expected to forming low-dimensional systems like quantum wires. Therefore, the low-dimensional nanostructures produce interesting quantum phenomena in terms of both scientific and practical applications and are one of the challenges in crystal growth technology.

In this presentation, we focus on growth and properties of nonpolar MgZnO/ZnO QWs, which are compared to polar MgZnO/ZnO quantum structures. Different from Zn- and O-polar surfaces with isotropic atomic structures, the M-nonpolar surface has anisotropic atom arrangements and shows optical anisotropy based on the excitonic selection rules and in-plane anisotropy of electron conductivity on MgZnO ZnO QWs. Furthermore, we introduce an interesting growth mode on A-nonpolar ZnO homoepitaxy, which is developed for MgZnO/ZnO quantum heterostructures with a V-grooved interface. These studies new quantum technology employed with surface nanostructures based on oxide materials.

7603-07, Session 2

Intersubband transitions in ZnO quantum wells

K. Ohtani, M. Belmoubarik, H. Ohno, Tohoku Univ. (Japan)

Intersubband transitions in ZnO/MgZnO quantum wells grown by plasma assisted molecular beam epitaxy are investigated by a photocurrent spectroscopy. Photocurrent peaks are observed in the energy range from 300 to 400 meV. Polarization-resolved photocurrent spectra show that these peaks are observed when the polarization of incident lights is TM mode. Calculation indicates that the photocurrent peaks are the intersubband transition from the first to the third subband in ZnO/MgZnO quantum wells.

7603-08, Session 2

Valence electronic structure of oxide semiconductors

C. F. McConville, P. D. C. King, T. D. Veal, Univ. of Warwick (United Kingdom); A. Schleife, F. Fuchs, F. Bechstedt, Friedrich-Schiller-Univ. Jena (Germany)

The valence band density of states for a number of oxide semiconductor materials have been studied using a combination of high resolution x-ray photoelectron spectroscopy and quasiparticle-corrected density functional theory calculations. In particular, we have investigated the occupied shallow semi-core levels structure of a range of different materials, including ZnO, CdO, MgO and In2O3. Good agreement was obtained between the experimental and theoretical results. The implications of these findings on the electronic structure of these oxide materials will be discussed.

7603-09, Session 3

Transparent conductive oxide for n-i-p thin film silicon solar cells

T. Söderström, F. Haug, C. Ballif, Ecole Polytechnique Fédérale de Lausanne (Switzerland)

Transparent conductive oxides (TCO) are used in thin film silicon solar cells to collect the current from the photovoltaic device. In addition, textured TCOs are also used to enhance the light in-coupling which is necessary for the mitigation of the light induced degradation of amorphous silicon and for the production throughput. For thin film silicon solar cells, the choice of TCO and its optimization focuses on having low resistivity (Rsq<10ohmsq), high transparency (Absorbance< 3%), and substrate root mean square (rms) roughness between 50-200 nm. So far, the best TCO for a:Si:H solar cells is ZnO deposited by low pressure chemical vapor deposition (ZnO LP-CVD) which grows naturally textured, typically with rms roughness of 70 nm for 2 microns thick films. The natural surface texture of the ZnO LP-CVD results in light scattering with high scattering angles in the silicon. We investigate the optical behavior of n-i-p single and multi-junction devices prepared with different front contacts. The back contact consists of a 2D periodic grid with moderate slope. The front contacts are either a 70 nm thick, nominally flat ITO or a rough 2 microns thick LP-CVD ZnO. We observe that, for a-Si:H, the cell performance depends critically on the combination of thin flat or thick rough front TCOs. Finally, we present the effect of LP-CVD ZnO as asymmetric intermediate reflector in the n-i-p tandem micromorph cell on low cost plastic substrate; in this device, textured ZnO is the key for increasing the stabilized efficiency 8.9% to 9.8%.

7603-10, Session 3

Opportunities and challenges of metal oxides in organic semiconductor devices

G. B. Murdoch, M. G. Helander, M. T. Greiner, Z. Wang, Z. Lu, Univ. of Toronto (Canada)

The use of metal oxides has recently become a focus area for researchers and industrialists within the field of organic electronics. The diversity of available metal oxides offers a large sample space for the creation novel oxide/organic, metal/oxide and oxide/oxide interfaces within devices. Metal oxides can be selected with conductivities ranging

from insulating to metallic, with various optical transparencies, and with diverse surface properties.

Highly transparent and conductive oxides such as ITO have found widespread use as electrode materials, allowing charge to be transported while allowing light to enter or exit organic devices. Recently, the use of ITO as the accepted standard transparent conductive oxide (TCO) material has become worrisome due to the rarity and high cost of Indium base metal. Proposed large-area organic photovoltaic and LED deployment will put a further strain on the global production of Indium, which is already facing high demand from flat panel display and television producers. In what follows, we present an overview of available TCO alternatives and demonstrate suitable ITO replacement materials/methods for small molecule, polymer, and colloidal quantum dot photovoltaic devices.

Oxides of lower conductivity have found use as ultrathin films incorporated into organic material stacks. In particular, the use of buffer layers between electrodes and organic layers, forming oxide/oxide/organic or metal/oxide/organic structures have been widely reported to lower device driving voltage in the case of OLEDs and improve power conversion efficiency when used in organic photovoltaics. Given the diversity of available oxides and organic materials, understanding the physics of these interfaces in terms of fundamental material parameters has become an important endeavour in order to enable rational interface design. We discuss the science and technology of metal oxides with a focus on recent improvements in organic LED and solar cell performance.

7603-12, Session 3

Growth and characterization of ZnO-based buffer layers for CIGS solar cells

T. Törndahl, A. Hultqvist, C. Platzer-Björkman, M. Edoff, Uppsala Univ. (Sweden)

Text

7603-13, Session 3

Aluminum-doped ZnO layers for thin film silicon solar cells

J. K. Rath, Utrecht Univ. (Netherlands)

Optical confinement plays an important role in case of thin film silicon solar cells due to its role in facilitating a near complete absorption of above band gap light in a photoactive layer that is not thick enough to sufficiently absorb light in a single pass. The limitation to the thickness arises mainly by lower mobilities and higher defect densities compared to the high efficiency cells such as c-Si. Recent advances in either varying the band gap of the materials through alloying or using of multi-junction structures have extended the absorption strength of the solar cells. Moreover, use of nano-dots to adapt the absorption characteristics and use of up-conversion or down conversion are the techniques to address this absorption issue from two directions. However, the deterioration of the electronic quality of the new materials, has so far limited such techniques to succeed and light trapping process is still a sought after method to enhance current in solar cells. We will discuss here the use of transmitting conducting oxide (TCO), mainly magnetron sputter deposited aluminum doped zinc oxide (ZnO:Al) layers, in thin film silicon solar cells where they are used at front, back and in between sub cells (intermediate layer) in a multi-junction structures.

Texture etching of ZnO:1%Al layers using diluted HCl solution provides excellent TCOs with crater type surface features for the front contact of superstrate type of thin film silicon solar cells, whichcan effectively replace the SnO2:F TCO, such as commercially available U-type Asahi TCO.. The texture etched ZnO:Al definitely gives superior performance than Asahi TCO in case of nanocrystalline silicon (nc-Si) type of solar cells. However, the sputter deposition condition or the structure of the ZnO:Al material that gives the best electrical properties is the not the same that gives the best etched texture for light scattering. The stress of the film changes from tensile to compressive with the increase in substrate temperature of sputter deposition and the rms roughness or the haze of the film seems to be have a correlation with the stress of the film prior to etching; the sample made at 250 oC is the most tensile and the etching rate and the evolved roughness is least at this condition whereas the sample made at 350 oC with a compressive stress character gives a high roughness. At present the ZnO:Al made at room temperature provides the best tradeoff between the electrical property and the scattering property of the texture etched layer. A current density of 24 mA/cm2 has been obtained for a nc-Si cell of 2200nm thick. To apply such a texturing technique to make rough ZnO:Al TCO layers on PET and PEN for solar cells on plastics, an addition step of embossing the plastic prior to the sputter deposition of the ZnO:Al layers was employed to release undue stress. The texture etching of such layers on plastics showed good electrical properties in addition to excellent scattering properties. As far as ZnO:Al as the back reflector is concerned, the scattering has to be predominantly at the metal oxide surface and not at the metal layers of a typical ZnO:Al/Ag back reflector. Use of thick, low doped ZnO:Al in combination with white reflectors, instead of metals, will be a possible trend to avoid surface plasmon absorption loss. We have successfully applied this concept using 0.5% Al doped ZnO to a superstrate type a-Si silicon solar cell using upconversion material at the back of the solar cell. In case of substrate type solar cells on plastics, the ZnO:Al layers that are used at the Ag/ZnO:Al back reflector as well as barrier layers, have to be thin and made at a low stress condition. Such a process resulted in ~6% efficiency of n-i-p a-Si solar cell on PET and PEN substrates. The paper will discuss all these issues that need to be addressed to achieve high efficiency thin film silicon solar cells.

7603-14, Session 3

Band gap engineering of ZnO for high efficiency CIGS based solar cells

C. Platzer-Björkman, A. Hultqvist, J. Pettersson, T. Törndahl, Uppsala Univ. (Sweden)

Thin film solar cells based on Cu(In,Ga)Se2, called CIGS, is one of the most promising technologies for low cost, high efficiency photovoltaics. The CIGS device is composed of four layers; Molybdenum back contact, CIGS p-type absorber, n-type buffer layer and doped ZnO top contact. The most common buffer layer is CdS, however it is desirable to find a Cd-free, large band gap alternative. In this presentation, the use of ZnO-based buffer layers deposited by atomic layer deposition, ALD is described. Efficiencies of over 18% are shown by using Zn(O,S) or (Zn,Mg)O by ALD followed by sputtered ZnO:Al. The role of the conduction band alignment across the heterojunction is discussed, and results for large band gap CuGaSe2 absorbers are presented. In addition, light-soaking effects for devices with (Zn,Mg)O-based buffer layers are related to measurements of persistent photoconductivity of ALD-(Zn,Mg)O thin films.

7603-15, Session 3

Self textured transparent conductive oxide film for efficiency improvement in solar cell

D. Y. Kim, Pohang Univ. of Science and Technology (Korea, Republic of); J. Yi, Sungkyunkwan Univ. (Korea, Republic of); H. Kim, Pohang Univ. of Science and Technology (Korea, Republic of)

In this article, we concentrated the thin film characteristics induced TMA pressure and the properties of solar cell device adopted AZO prepared by LPCVD films as electrode. AZO has a preferential orientation of (110) planes and was grown as the polycrystalline thin film. In order to improve efficiency of thin film solar cell it is very important role of both low electrical resistivity and highly diffused light ability of these films. We observed that the resistivity of AZO films decreased and its diffused transmittance is increased in comparison to undoped ZnO when the

TMA doping is introduced. In this study, we acquired the low resistivity of 6.3x10-3 ohm-cm and high haze factor of 43% through the TMA doping. The surface morphology of AZO film with high haze factor has a pyramid-like structure. The increase of resistivity as an increase of TMA pressure resulted in the consumption of free electron concentration due to large oxygen defects density evaluated by PL spectroscopy measurement. We demonstrated that solar cell having a high efficiency required the TCO film, of which properties included low resistivity due to low oxygen interstitial defects and high haze factor due to the Al doping and surface structure. From this study, we suggest that AZO films are possible to alternate SnO2:F TCO thin film to be commercially used for the fabrication of high efficiency microcrystalline or amorphous thin film solar cells.

7603-16, Session 3

Excitonic emission of ZnO nanoparticles

B. Masenelli, D. Tainoff, Univ. Claude Bernard Lyon 1 (France); P. Melinon, Univ. Claude-Bernard Lyon 1 (France)

Its intense emission in near UV and a large exciton binding energy make ZnO an attractive and widely studied material for the design of nanometric light sources. However, the size reduction induces effects, such as surface reconstruction, contamination...that are detrimental to the excitonic emission. Alongside the free excitonic emission, other features are present which are partly linked to defects or to specific dopants. The nature of some of them is still not precisely determined.

In the present contribution, we intend to address the fundamental topics regarding the link between the size reduction in ZnO nanoparticles and the modification of both the free excitonic emission and the defect related one. Analyzing uncapped, well crystallized and stoichiometric ZnO clusters produced in ultra high vacuum by LECBD (Low Energy Clustyer Beam Deposition: an adiabatic hyperquenching of a plasma) and comparing them to microcrystals as well as monocrystals, we first demonstrate the importance of the surface control (passivated or not). Second, we investigate the mechanism responsible for the emission at 3.31 eV, often used to assess p-doping (a long standing quest in ZnO). Eventually, we explore the relation between the size reduction and the excitonic emission dynamic (decay rate).

7603-17, Session 4

Cathodoluminescence and synchrotron-based x-ray absorption characterisation of iron in-diffusion in ZnO

C. Ton-That, M. Phillips, M. Foley, L. Lee Cheong Lem, G. McCredie, Univ. of Technology, Sydney (Australia)

Fe doped ZnO has been investigated using cathodoluminescence (CL), X-ray absorption spectroscopy (XAS), photoemission spectroscopy (PES). The incorporation of Fe was achieved by evaporating 200 nm Fe film onto the surface of a-plane ZnO single crystal (hydrothermally grown by the MTI Corporation) and subsequently annealing at 800ºC for up to 70 hours. CL spectra of the as-received ZnO crystal consists of the near band edge at 3.36 eV as well as broad defect luminescence bands centred at 2.0 eV (orange, OL) and 2.4 eV (green, GL). Following heat treatment, the broad OL peak was observed on the annealed Fe-free crystal but not on annealed Fe-coated crystal, which exhibited a strong GL peak. Depth-resolved CL demonstrated that Fe in-diffusion had occurred to at least 3 micron (the electron range in ZnO at 30 kV). The observed Fe 2p XAS spectra from the Fe in-diffusion sample and a Fe metal standard are completely different, ruling out the possibility of formation of Fe metal clusters in the bulk or on the crystal surface. Comparison with the X-ray adsorption edges of Fe reference oxides shows that Fe ions are incorporated on tetrahedral Zn cation sites and in the mixed Fe2+ - Fe3+ valence states. Furthermore, valence band PES of the Fe in-diffusion crystal revealed Fe 3d states locating close to the O 2p band, at ~ 3.7 eV below the Fermi level. Combined results from the techniques employed indicate the roles of oxygen vacancies and the charge transfer state of Fe in the OL and GL.

7603-18, Session 4

Hydrogen in ZnO

E. Lavrov, Technische Univ. Dresden (Germany)

A combined study of hydrogen in ZnO by means of Raman scattering, IR absorption, photoluminescence and photoconductivity is presented. Properties of two main hydrogen shallow donors are discussed. These are isolated bond-centered hydrogen and hydrogen bound to the oxygen vacancy. It is shown that isolated hydrogen in ZnO is not stable and migrating through the lattice forms electrically inactive interstitital molecule, which is responsible for the so-called “hidden” hydrogen. In addition, a variety of complexes acceptor-hydrogen in ZnO is considered.

7603-19, Session 4

Lattice location of the group V elements Sb, As, and P in ZnO

U. Wahl, Instituto Tecnológico e Nuclear (Portugal); J. G. Correia, European Organization for Nuclear Research (Switzerland); T. de Melo Mendonça, Univ. do Porto (Portugal); S. Decoster, Katholieke Univ. Leuven (Belgium)

Modifying the properties of ZnO by means of incorporating phosphorus, arsenic or antimony impurities is of interest since these group V elements have been reported in the literature among the few successful p-type dopants in this technologically promising II-VI compound. However, there is an ongoing debate whether the experimentally observed p-type character is due to P, As or Sb simply replacing oxygen or to the formation of more complicated defects: In particular the formation of electrically active acceptor complexes of the type As(Zn)/2V(Zn) or Sb(Zn)/2V(Zn) has been suggested to be responsible for the p-type behaviour.

The lattice location of ion-implanted Sb, As, and P in ZnO single crystals was investigated by means of the electron emission channeling technique using the radioactive isotopes 124Sb, 73As and 33P. It is found that Sb, As, and P preferentially occupy substitutional Zn sites while the possible fractions on substitutional O sites are a few percent at maximum, which is understandable from the relatively large ionic size of the heavy group V impurities.

While the presented results cannot settle the interesting issue whether substitutional As or Sb on oxygen sites or As(Zn)/2V(Zn) or Sb(Zn)/2V(Zn) complexes are responsible for the acceptor action, the fact that implanted Sb, As, and P prefer the substitutional Zn sites is clearly a strong argument in favour of the complex acceptor model, while it discourages the notion that As and Sb act as simple “chemical” acceptors in ZnO.

7603-20, Session 4

A detailed temperature dependent Hall study of As-doped ZnO thin films

S. Nagar, S. Chakrabarti, Indian Institute of Technology, Bombay (India)

ZnO has become a subject of intensive research for its potential application in the UV-VIS optoelectronics devices due to its wide bandgap (3.3 eV) and high exciton binding energy (60meV). Due to the presence of zinc interstitials and oxygen vacancies ZnO is intrinsically n-type. Thus, obtaining stable p-type ZnO behaviour has been a major hindrance and not widely reported. We are hereby reporting growth of stable p-type ZnO thin film by Pulsed Laser Deposition technique at temperatures of 300°C, 350°C and 400°C on semi-insulating GaAs substrates. The samples were then subjected to rapid thermal annealing at temperatures varying from 550°C to 700°C. The annealing was performed with an idea that As atoms from GaAs would diffuse in to the ZnO film and replace the oxygen atoms to get stable p-type behaviour. XRD results confirm deposition of ZnO films with the lower FWHM value for the annealed samples suggesting better crystallinity. AFM results report uniform deposition of the film having an rms roughness value between 7.6nm to 8.5nm. Temperature dependent Van der Pauw hall measurements (80K to 310K) performed on the samples revealed a transition of conductivity from n-type for as-grown samples to p-type for the annealed ones. The highest values of hole concentration and Hall mobility measured at 310K were found to be 8.49E19 cm-3 and 32.4 cm2/V-sec respectively. The authors acknowledge the SPM facility of IIT Bombay and DST for its financial assistance.

7603-22, Session 5

Complex oxide heterostructures grown by pulsed laser deposition

M. A. Brandt, H. von Wenckstern, M. Lorenz, H. Frenzel, G. Benndorf, M. Lange, M. Stölzel, C. Dietrich, J. Zippel, M. Grundmann, Univ. Leipzig (Germany)

The report focuses on functional ZnO based heterostructures with atomically abrupt surfaces and interfaces grown by pulsed laser deposition. The coupling of the electric polarization of this piezoelectric material with that of adjacent piezoelectric and ferroelectric layers was investigated. Unique effects are observed as two dimensional transport, quantum confinement, and the quantum confined stark effect. Control of the laser plasma kinetics allowed design of the interface sharpness. Thereby the exciton recombination lifetime was controlled yielding values previously only reached in MBE grown structures. Functional devices, such as transparent ferroelectric field effect transistors were fabricated, which represent nonvolatile memory elements.

7603-23, Session 5

Flash memory and spin-field-effect transistor using multiferroic oxides

C. Jia, J. Berakdar, Martin-Luther-Univ. Halle-Wittenberg (Germany)

We propose a modified spin-field-effect transistor fabricated in a two dimensional electron gas (2DEG) formed at the surface of multiferroic oxides with a transverse helical magnetic order. The topology of the oxide local magnetic moments induces a resonant momentum-dependent effective spin-orbit interaction acting on 2DEG. We show that spin polarization dephasing is strongly suppressed which is crucial for functionality. The carrier spin precession phase depend linearly on the magnetic spiral helicity. The latter is electrically controllable by virtue of the magento-electric effect. We also suggest a flash-memory device based on this structure.

7603-57, Session 5

Interfacial magnetoelectric coupling for electrically controllable spin-based properties

V. Garcia, M. Bibes, K. Bouzehouane, S. Fusil, A. Crassous, C. Deranlot, A. Barthelemy, Unité Mixte de Physique CNRS/Thales (France); N. Mathur, Univ. of Cambridge (United Kingdom); S. Valencia, F. Kronast, Helmholtz-Zentrum Berlin BESSY (France); S. Enouz-Vedrenne, Thales Research and Technology (France); L. Bocher, A. Gloter, D. Imhoff, Univ. Paris-Sud 11 (France)

At room temperature, we use piezoresponse force microscopy to show robust ferroelectricity in BaTiO3 ultrathin films, and conductive-tip atomic force microscopy to demonstrate the resistive readout of the polarization state via its influence on the tunnel current[1]. This giant electroresistance nondestructive readout paves the way towards ferroelectric memories with simplified architectures, higher densities and faster operation. Additionally, ferroelectric tunnel junctions with ferromagnetic electrodes were built to demonstrate local, large and non-volatile control of carrier spin polarization by switching ferroelectric polarization. Our results represent a giant interfacial type of magnetoelectric coupling and suggest a new low-power approach for spin-based information control.

1 Garcia, V. et al., Nature 460, 81 (2009)

7603-24, Session 6

Oxide thin films and devices for large-area electronics and optoelectronics

D. A. Keszler, S. T. Meyers, K. Jiang, J. K. Stowers, A. Telecky, Oregon State Univ. (United States)

Recent advances in the development of high-performance oxide semiconductors, dielectrics, and resists will be addressed. Emphasis will be placed on new thin-film materials produced via aqueous-solution processing. Applications including optical microcavities, thin-film transistors, and sub 10-nm patterning will be considered.

7603-25, Session 6

Photon-assisted synthesis of functional oxide thin films: mechanisms and applications to oxide electronics

S. Ramanathan, Harvard Univ. (United States)

Functional oxide thin films are of great interest in electronic and photonic technologies including ultra-fast switches. Developing novel routes for synthesis of oxide thin films with controlled structure and stoichiometry is of great importance. In this talk, we will discuss recent results from our on-going work on synthesis of ultra-thin crystalline functional oxides in rutile and fluorite phases utilizing photo-excitation. Techniques to manipulate interface structure and chemistry in oxides utilizing UV photons and their impact on functional properties will be presented. Mechanisms leading to oxygen incorporation under photon irradiation will be discussed. We will subsequently discuss metal-insulator transitions in vanadium oxide as a representative example where synthesis plays a determining role in the manifestation of strongly correlated phenomena.

7603-26, Session 6

ALD growth and properties of ZrOx/LaOx thin films

S. Abermann, C. Henkel, O. Bethge, E. Bertagnolli, Technische Univ. Wien (Austria)

High-performance devices for the sub-45-nm technology target equivalent oxide thickness values below 0.8 nm, requiring films of about 4 nm thickness or less for gate dielectrics with a k-value of 20 - 25. Here La_2O_3 is one potential candidate, but due to its hydroxylation tendency, the ALD-growth of La_2O_3 is challenging, and hence it is mainly deposited in combination with a second high-k oxide, like ZrO_2.

Atomic layer deposition (ALD) is a suitable technique to deposit uniform and smooth films and film-stacks in the few nm-range, with its initial growth behaviour strongly depending on the precursor reactivity with the substrate surface.

We present our results on the ALD-growth of ZrOx/LaOx high-k dielectric stacks on Si and Ge substrates. We show how applied precursor materials, stacking sequences, as well as substrate surface preparation

influence the resulting electrical and morphological properties of metal gate/high-k MOS devices.

7603-27, Session 6

Complex oxide heterostructures and superlattices: the role of interfaces

H. Habermeier, Max-Planck-Institut für Festkörperforschung (Germany)

Complex oxides showing electron correlation effects are characterized by a competition between lattice-, orbital-, charge- and spin ordering - all at similar energy scales. This opens a path to externally manipulate their properties by external fields. A recent concept is the preparation of thin film superlattices composed of constituents with different functionalities and to study their mutual interaction. At interfaces the growth properties of complex oxides are governed by the constraint of preserving charge neutrality and stoichiometry imposed by the ionic character of the constituents. In this context the self-doping of interfaces could turn the interface between two insulators into a metal. Changes in the bonding characteristics at the interface may affect the spin properties because of the strong interaction between orbital and spin degrees of freedom. Furthermore, electronic reconstruction at the interface and broken lattice symmetry modifies orbital physics at the interface. Consequently, the physical properties of an interface dominated sample will be different from those of its constituents. This concept opens a possibility for interface engineering and unexpected phenomena, which cannot be understood in terms of conventional band pictures, may thus appear. The combination of a ferromagnet and a superconductor is regarded as a prototype for this concept since these two ordering principles are antagonistic by nature and can not coexist in a homogeneous system. In this contribution the field will briefly be reviewed and recent results for charge transfer, orbital reconstruction and the different length scales for the interaction for YBCO/LCMO heterostructures will be given.

7603-28, Session 7

Interface control in BaTiO3 based supercapacitors

M. Maglione, C. Elissalde, C. U-Chan, Univ. Bordeaux 1 (France)

Core shell BaTiO3 based particles sintered using advanced processes provide a high control of grain boundaries in bulk composites. As a result supercapacitor behaviour was evidenced which came from the balance between inner grain conductivity and grain boundary dielectric barrier.

Apparent dielectric permittivities of more than 300 000 were obtained with dielectric losses lower than 10% at romm temperature and for an operating frequency of 100kHz. Such huge extrinsic permittivites were already reported but the losses were extreme as well which is a concern for the possible applications of these composite. We ascribe the lower losses reported here to the silica shell which continuously coats all of the BaTiO3 grains prior to the sintering of the composite.

7603-29, Session 7

Computational study of the deposition of metal-oxide thin films on strontium titanate: morphology and growth modes

J. L. Wohlwend, Univ. of Florida (United States); C. N. Boswell, Univ. of California, Berkeley (United States); S. R. Phillpot, S. B. Sinnott, Univ. of Florida (United States)

Classical molecular dynamics simulations are used to examine the growth of SrTiO3 (STO), SrO and TiO2 thin films. They consider the deposition of SrO and TiO2 molecules and STO clusters onto STO (001). The role of surface termination layer (SrO vs. TiO2), incident energy, incident particle size and deposition scheme is investigated. SrO thin films grow in a layer-by-layer fashion while TiO2 thin films exhibit a kinetically limited 3D growth mode. These growth modes are predicted to be a consequence of the mobility and interaction energy of each particle (SrO or TiO2) with the substrate.

For STO thin film deposition two schemes are investigated, alternating monolayer deposition (AMD) and cluster deposition. AMD consists of depositing alternating SrO and TiO2 monolayers, SrTiO3 cluster deposition considers the deposition of 1, 2, 3, and 4-unit stoichiometric STO clusters all having incident energies of 1.0 eV/atom. On the whole, some layer-by-layer growth is predicted to occur on both terminations with films grown on TiO2 termination having a more ordered structure. The prevalent defects observed in the first deposited layer on TiO2-terminated STO are Sr vacancies, TiO2 inclusions and Ti substitutions, these are characterized and their effect on subsequent layers is investigated.

To further elucidate the growth modes observed, temperature accelerated dynamics is used to predict energy barriers associated with diffusion mechanisms of adatoms and ad-dimers on (100) SrTiO3. We observe two surface diffusion mechanisms depending on substrate termination. On TiO2 termination, an oxygen exchange mechanism is favored whereas on SrO termination, hopping mechanisms dominate.

7603-30, Session 7

Enhanced transport properties in LaMnO grown on STO

P. Orgiani, Univ. degli studi di Salerno (Italy); C. Aruta, Istituto Nazionale di Fisica Nucleare (Italy); R. Ciancio, Istituto Nazionale per la Fisica della Materia (Italy); A. Galdi, L. Maritato, Univ. degli Studi di Salerno (Italy)

We report on structural, magnetic, and transport properties of LaMnO (LMO) thin films, epitaxially grown on STO substrates by MBE, as a function of the La/Mn stoichiometry and the oxygen content. Optimal oxygenated LMO films (with x=0.88) show a metal-insulator transitions temperature TMI=387K. Also in presence of a La/Mn slight unbalance (namely, x=0.98), LMO films show a very high TMI=370K. However, LMO samples with La/Mn ratio larger than 1, show severely depressed conducting properties, being insulating for x>1.10. All these findings clearly demonstrate that the lanthanum deficiency is a very efficient way to dope manganites, as in the case of bivalent cation-substitution. Moreover our work provides fundamental knowledge of the LMO physical properties as a function of extrinsic effects (i.e. effects of heavy-ion and/or oxygen stoichiometry) in view of better understanding of novel interface phenomenon with strongly electron correlated manganite compounds.

7603-31, Session 7

Plasmonic effects on the laser-induced metal-insulator transition of vanadium dioxide

D. W. Ferrara, E. R. MacQuarrie, J. Nag, Vanderbilt Univ. (United States); A. Kaye, Vanderbilt Univ. (United States) and ITT Advanced Engineering and Sciences (United States); R. F. Haglund, Jr., Vanderbilt Univ. (United States)

Vanadium dioxide (VO2) is a strongly-correlated electron material with a well-known semi-conducting to metallic phase transition that can be induced thermally, optically, or electrically. When switched to the high-temperature (T > 68OC) metallic phase, the greatest contrast in the optical properties occurs at wavelengths longer than the near-infrared. In the visible, however, upon switching for wavelengths between ~500 nm to 1000 nm, VO2 transmits more light in the metallic phase. By coating lithographically prepared arrays of gold nanoparticles (NPs) of diameters 100 nm - 200 nm and array spacing 350 nm - 500 nm with 60 nm thick films of VO2 via pulsed laser deposition, a hybrid Au-VO2 structure was created. Due to the sensitivity of the Au particle-plasmon resonance (PPR), a temperature dependent shift in the PPR can be generated by switching the VO2 from one phase to another. The hybrid structure therefore functions as a tunable metamaterial. We have measured the switching behavior of VO2 and Au-VO2 structures using millisecond laser pulses in order to study both optical and thermal mechanisms of the phase transition. Transient absorption measurements were done using a chopped 780 nm pump laser in order to correspond to the PPR resonance of the Au NPs and 1550 nm CW probe. Results show that the presence of Au NPs lowers the threshold laser power required to induce the phase transition. Apparently the Au NPs localize heating, thus requiring less laser energy to switch the material. Finite element modeling was performed to better understand the complex thermodynamics of the structure.

7603-32, Session 7

Properties of anatase Nb-doped TiO2 transparent conductor

T. Hitosugi, Tohoku Univ. (Japan)

We here report the development and properties of TiO2-based transparent conducting oxides. Transparent films exhibiting a resistivity of 6.4×10^-4 Ohm cm can be obtained on glass substrates by crystallizing amorphous films. These films have characteristics unique to the TiO2-based transparent conducting oxide, such as high refractive index, durable in reduced atmosphere, high chemical stability and so on. We discuss on possible application of this film to GaN based light emitting diodes and solar cells.

7603-11, Session 8

Review on optical and electrical properties of InGaZnO

H. J. Kim, Yonsei Univ. (Korea, Republic of)

Oxide semiconductors became one of the potential elements for large area electronics such as a channel for thin film transistors. Optical and electrical properties were modified by alloying or doping of several oxide materials; In2O3, ZnO, Ga2O3, and SnO2. The excellent properties achieved at the ternary or quaternary alloys could be explained by the role of each materials as a carrier controller, a conduction path etc. The metal oxide semiconductors were generally deposited by vacuum process but recently, alternative ways, like a sol-gel or an ink-jet printing, are suggested. In this review, diverse approaches on oxide semiconductors are shown, and an in-depth discussion of the optical and electrical properties alternation in metal oxide alloy fabricated by various methods is given.

7603-33, Session 8

Paper-e: the electronics of future

E. M. C. Fortunato, P. Barquinha, L. Pereira, G. Gonçalves, N. M. R. Correia, R. Martins, CENIMAT, Univ. Nova de Lisboa (Portugal) and CEMOP/Uninova (Portugal)

The aim of this paper is to present data concerning the use of non conventional electronics, away from silicon fully recyclable, as it is the case of nanoscale based devices processed with and on the paper. A comparison of the today's recycling silicon based electronics bottlenecks with the ones facing the future, fully green based will be discussed, having as starting point the paper transistor and the pleura of electronic circuits that can be processed based on this discover.

7603-34, Session 8

High-performance transparent thin film transistor with atomic layer deposition ZnO-based active channel layer

H. Kim, Yonsei Univ. (Korea, Republic of); S. Lim, J. Kim, D. Y. Kim, Pohang Univ. of Science and Technology (Korea, Republic of)

ZnO is studied rigorously as an active layer for transparent thin film transistor (TFT) due to its transparency and high mobility. Atomic layer deposition (ALD) has several advantages such as low growth temperature and large area uniformity for display process. In this study, we investigated the applications of ALD for fabrication of high performance transparent TFT devices. While low temperature growth was possible below 150 °C, ALD ZnO using water as a reactant produced conductive ZnO films, which have too high carrier concentration to be used as an active channel layer. By using NH4OH as a single source for reactant and nitrogen doping, ZnO:N with carrier concentration down to 10^13 / cm^3 level was deposited. TFTs were fabricated by using ALD ZnO:N as an active layer and ALD Al2O3 as a gate insulator. High performance TFT devices with high saturation mobilities up to 20 cm^2/Vsec and high on/off ratio (>10^7) were fabricated on both glass and polymer substrates. By changing nitrogen concentration, the device properties such as threshold voltage (VTH) and DC bias stability were significantly changed. Also, the effects of bending on the device properties of ZnO:N TFT on the flexible PEN substrate were investigated. It was found out that the VTH change by bending was originated from the piezoelectric effect of ZnO:N. Additionally, we investigated the film properties and device application of plasma enhanced ALD (PE-ALD) ZnO. In contrast to thermal ALD, PE-ALD ZnO with oxygen plasma as a reactant was very resistive. The effects of UV light exposure to the PE-ALD ZnO films and the device properties of PE-ALD ZnO based TFT devices were investigated.

7603-35, Session 8

Complementary use of organic and oxide semiconductors

J. H. Na, M. Kitamura, Y. Arakawa, The Univ. of Tokyo (Japan)

Contrast to a p-type conductivity of most organic semiconductors, most oxide semiconductors have a n-type conductivity. The absent of each counterpart has limited their device applications such as complementary circuits and optoelectronic p-n junction devices. One of possible options is a complementary use of these materials, allowing us to have more flexibility in fabricating such devices. Here, complementary use of p-type organic and n-type oxide semiconductors is presented. First, we demonstrate complementary inverters using pentacene and InGaZnO transistors with field-effect mobilities of 0.6 and 17.1 cm2/V s, respectively. The inverter exhibits good voltage transfer characteristics with a high gain of ~56. Complementary 5-stage ring oscillators composed of the inverters shows an output frequency of 200 Hz at 10 V, corresponding a propagation delay of 1 ms. Second, we demonstrates a hybrid p-n junction light-emitting diode using N,N'-diphenyl-N,N'-bis(1-naphthyl)-1,1'-biphenyl-4,4'-diamine (-NPD) and sputtered ZnO. The hybrid junction shows a current rectifying characteristic similar with conventional p-n junction diodes. The device performance, such as turn-on voltage and efficiency, is enhanced by post-deposition annealing of as-sputtered ZnO film. X-ray diffraction measurement indicates that the relaxation of intrinsic stress in as-sputtered ZnO film is related to the improvement. Electroluminescence from the device was seen clearly with the naked in normal room light under forward bias. We found that the electroluminescence bands from the device agree well with the photoluminescence peaks from -NPD and ZnO, implying the radiative recombination of injected charges occurs in both components of the junction.

7603-36, Session 8

Materials engineering for solution-processed InGaZnO thin film transistors

J. Lim, H. Lee, M. R. Moon, J. H. Shim, J. H. Choi, J. Joo, K. Park, D. Jung, H. Kim, Sungkyunkwan Univ. (Korea, Republic of)

This study presents the results of a study on fabricating ZnO-based thin film transistors via a sol-gel route. We compared the device performance of ZnO-TFT and InGaZnO-TFT.

7603-37, Session 9

Floating gate memory paper transistor

R. Ferrão de Paiva Martins, P. Barquinha, L. Pereira, G. Gonçalves, I. Ferreira, E. M. C. Fortunato, CENIMAT, Univ. Nova de Lisboa (Portugal) and CEMOP/Uninova (Portugal)

Here we report architecture for a non-volatile floating gate memory n-type transistor based on natural cellulose paper and oxide semiconductors. The device is built using the hybrid integration of natural cellulose fibers (pine and eucalyptus fibers embedded in an ionic resin), which act simultaneously as substrate and gate dielectric, with amorphous multicomponent oxides such as GIZO and IZO, which are used as gate and channel layers, respectively. This is complemented by the use of continuous patterned metal layers as source/drain electrodes.

7603-38, Session 9

Oxide thin film transistors on novel flexible substrates

S. J. Pearton, W. Lim, E. Douglas, F. Ren, Univ. of Florida (United States); Y. W. Heo, Kyungpook National Univ. (Korea, Republic of); D. P. Norton, Univ. of Florida (United States)

Since the introduction of crystalline and amorphous oxide semiconductor-based thin-film transistors in 2003 and 2004, respectively, a wide variety of n-type oxide materials have appeared to be the promising candidates for channel layer, including binary oxides (ZnO, SnO_2, and In_2O_3) and several amorphous multi-component oxides (ZnSnO, InZnO, InGaO, and InGaZnO). These amorphous oxide-based TFTs operate in both depletion and enhancement-mode and exhibit excellent saturation drain currents with good electrical and optical properties (high on-to-off ratio, low subthreshold gate-voltage swing, large mobility, high transparency. The high performances presented by these TFTs associated to a high electron mobility, at least two orders of magnitude higher than that of conventional amorphous silicon TFTs and a low threshold voltage, opens new doors for applications in flexible, wearable, disposable portable electronics as well as battery-powered applications. In this talk we will review our progress in making $InGaZnO_4$ TFTs on novel substrates,including cellulose paper,clean room tape and plastic.The devices show surprisingly good dc performance. The remaining issues such as surface encapsulation,low temperature dielectrics and roll-up stability will be discussed.

7603-39, Session 9

Photosensor application of amorphous InZnO-based thin film transistor

P. Liu, Y. Chou, L. Teng, National Chiao Tung Univ. (Taiwan)

Thin film transistor (TFT) structure with novel photosensitive semiconductor will be promisingly integrated in a display panel with pixel array circuits for photosensor applications. The adoption of TFT-based photosensor device also can realize the system-on-panel (SoP) concept and sense the ambient light brightness as well as give the feedback to the backlight system adjusting the backlight intensity for the power-saving green displays. Amorphous indium zinc oxide (a-IZO)-based semiconductors have been paid much attention due to possessing uniform amorphous phase and high field-effect carrier mobility characteristics. In this work, we studied the photosensitivity of a-IZO-based TFTs to ultraviolet light and a slow recoverability of electrical characteristics is observed after removing the light source. This mechanism for the photoreaction is well explained by the dynamic equilibrium of charge exchange reaction between O_2(g) and O_2^- in the backchannel region of IZO-based films. An electrical trigger using charge pumping method is also used to confirm the proposed mechanism and accelerate photoreaction recoverability for the first time. Using knowledge of photoreaction behavior, an operation scheme of photosensing elements consist of a-IZO TFTs is also demonstrated in this paper.

7603-40, Session 9

TCO nanostructures for excitonic solar cells

A. Vomiero, G. Faglia, C. Baratto, A. Braga, E. Comini, I. Concina, M. Ferroni, V. Galstyan, G. Jimenez, I. Kholmanov, N. Poli, A. Ponzoni, S. Todros, G. Sberveglieri, INFM-CNR, Univ. degli Studi di Brescia (Italy)

Third generation solar cells promise to have a series of benefits with respect to traditional counterparts, such as low cost, “green energy” due to application of non toxic materials, improved efficiency, while maintaining acceptable long term stability.

Excitonic solar cells (either dye- or quantum dot-sensitized) are strong candidates for development in the field. While dye sensitized cells have a 20-years history of development and are nowadays competitive with respect to poly- and amorphous-silicon cells in terms of overall cell efficiency and stability, quantum dot solar cells are at the very beginning of their functional exploitation, and only poor performances have been gained up to now. However, for both the systems, an intense development is ongoing to enhance the overall photoconversion efficiency. Among the very recent advances in excitonic cells, remarkable interest has been paid towards integration of single crystal nanowires of transparent conducting oxides in photoanodes. Pioneering works indicated the possibility to obtain a photoelectrochemical system in which electronic transport takes place along the single crystalline backbone of 1-dimensional transparent nanostructures. Thanks to the high electron mobility in single crystal nanowires (about 100 times higher than in polycrystalline network) this solution eliminates the detrimental drawback of polycrystalline photoanodes in which a single electron has to pass thousands of grain boundaries before reaching the anode, with high recombination probability. In principle this benefit could result in unprecedented cell efficiency, but only limited results have been obtained for nanowire-based cells up to now.

One of the most critical points is the very limited grafting ability of the sensitizers (both dye molecules and quantum dots) on the nanowire bundle surface, which affects the optical density of the active layer. Engineered networks of mixed polycrystal powders and single crystalline nanowires can merge the beneficial properties of both the systems, allowing high optical density of the active layer, which results in nearly complete light absorption, while maintaining direct electron path, which minimizes recombination processes. Such systems can be profitably applied in both dye- and quantum dot- base solar cells. Improved efficiency has been proven in these kinds of cells with respect to the polycrystalline traditional counterparts.

The beneficial effect of the composite network will be analyzed and discussed from the viewpoint of the functional features of the cells either dye- or quantum dot-sensitized.

7603-41, Session 9

ZnO for transparent electronics grown by pulsed laser deposition

D. J. Rogers, F. H. Teherani, V. E. Sandana, Nanovation (France)

No abstract available.

7603-42, Session 10

Applications of zinc oxide to UV photonics

M. D. Gerhold, U.S. Army Research Office (United States)

ZnO is a remarkable photonic material with a excitonic binding energy of 60 meV - far exceeding the thermal energy of electrons at room temperature. Excitonic lasing appears to have been demonstrated with electrical injection of ZnO nanopillars on Si and numerous reports of two-photon and optically pumped nanowire lasers have been made. Based on the material advantages of easy processing, abundant supply, wide-bandgap alloying range, radiation resistance, etc. further research in ZnO may be warranted. In this talk emphasis will be given to the deep-UV photonics markets and an overview given related mainly to GaN LEDs and photonics. ZnO and other wide-bandgap oxide semiconductors show potential for deep-UV photonics as well which will be related to the commercial applications along with competing technologies that are on the market. AlGaN LEDs have progressed greatly in the past 12 months in the deep UV but there still exists gaps in the 200-300 nm range for research in lasers, photodetectors, and LEDs. Potential applications for deep-UV photonic devices include: water purification and surface sterilization, photoluminescence and SERS spectroscopy based biomolecule and chemical sensing, UV engineering of plants and foods, and niche areas relevant to the military and other sensing modalities. Motivation for research in wide-bandgap oxide semiconductors and discussion of progress related to pushing systems developments for these applications will be given.

7603-43, Session 10

Optical properties of metal-semiconductor-metal (MSM) UV photodetectors on ZnO films

L. Li, Univ. of Missouri-Columbia (United States); Y. Ryu, MOXtronics, Inc. (United States); H. White, P. Yu, Univ. of Missouri-Columbia (United States)

Among wide and direct bandgap materials that are sensitive to photons in the UV region, ZnO is a promising photonic material because of its unique properties. Based on the lateral interdigitated back-to-back Schottky contact structure, MSM photodetectors have substantially lower parasitic capacitance compared with vertical p-i-n photodetectors, which leads to be a very high speed photodetection device. Previously, we reported results of MSM ZnO UV photodetectors where ZnO films were fabricated by hybrid beam deposition (HBD). An annealing process at a high temperature in a gas environment can decrease contact resistance, and increase adhesive force. It may also remove surface defects created in the fabrication process. In this paper, we report optical characteristics of MSM ZnO UV photodetectors for which the ZnO films and gases were used to anneal the device at a high temperature. The MSM ZnO photodetectors consist of two interdigitated electrodes with Ti and Au metals on n-type ZnO. The electrodes on the ZnO MSM diode are finger-shaped, and the distance between the fingers is 40 microns, and the width and length of an electrode finger are 40 microns and 800 microns. The device displays fast pulse response with very short rise times and relatively long relaxation times when applied by a bias. The long exponential decay tail indicates an RC time constant limited response, and it is found that the time constant is 10 micro-sec. at 20 V, which is smaller than 29 micro-sec. for MSM ZnO photodetectors without the gas annealing process.

7603-44, Session 10

Molecular beam epitaxial growth of Ternary cubic oxide semiconductors for deep ultraviolet applications

W. V. Schoenfeld, J. W. Mares, R. C. Boutwell, M. Falanga, A. Scheurer, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States)

There is currently a growing need for deep-UV (DUV) semiconductors that can address various applications such as solar blind detection (SBD), water/air sterilization, and DUV fluorescent lifetime imaging. Despite the considerable progress that has been made with wurtzite nitride and oxide semiconductors, current DUV devices still fall short of the efficiencies that have enjoyed in the visible wavelength region and are complicated by the naturally occurring piezoelectric and spontaneous polarization fields that are inherent in polar wurtzite films. We will report on a new approach towards the DUV region using several ternary cubic oxide semiconductors that offer lattice matching to commercially available MgO substrates. Molecular beam epitaxy was used to grow high quality NiMgO epilayers on MgO over the entire compositional range, as verified by RBS, with good stoichiometry and intrinsic carrier concentrations in the 10^13/cm^3 range. Transmission spectroscopy validated the ability to tune its energy gap across the 250 - 350 nm region while maintaining a root-mean square roughness ranging from 0.7 to 120 Å. Results from several other ternaries will also be presented along with initial efforts to fabricate metal-semiconductor-metal photodetectors using these compounds.

7603-45, Session 10

Growth and characterization of wide bandgap ZnMgAlO thin films lattice-matched to ZnO substrate

I. Kim, B. Lee, Chonnam National Univ. (Korea, Republic of)

Zinc oxide (ZnO) has been widely used as an active material for ultraviolet (UV) light emitting devices because of its direct band gap and high exciton binding energy. For the optoelectronics application, one of the key issues is the energy band gap (Eg) engineering to realize hetero-junction devices. Ternary ZnMgO films have been mainly studied to obtain Eg higher than that of ZnO (3.3 eV), which have to endure mismatch in the lattice constant as large as 2 % to obtain Eg of ~4.0 eV.

In this work, quaternary ZnMgAlO films lattice matched to ZnO were grown by the magnetron sputter technique. Structural and optical properties of samples were characterized by transmission electron microscopy, scanning electron microscopy, X-ray diffraction (XRD) and cathodo-luminescence (CL). The CL measurement showed UV emission peaks at 4.0 eV for the Zn0.83Mg0.12Al0.05O/ZnO films and 3.7 eV for the Zn0.91Mg0.07Al0.02O/ZnO films. The XRD clearly indicated that the films are lattice matched to the ZnO substrates; the (0002) and (0004) peaks appear at the same position, 34.42 and 72.56 . The electron microscopy inspection indicated that the films are of single crystalline.

Further details on the film properties as well as characteristics of the multi-quantum-wells fabricated from the quaternary films will be discussed during the presentation.

7603-46, Session 10

Progress in ZnO template substrates for GaN-based alloys grown by MOVPE

A. Ougazzaden, Georgia Institute of Technology Lorraine (France); D. J. Rogers, F. H. Teherani, V. E. Sandana, Nanovation (France); G. Orsal, T. Moudakir, S. Gautier, Ctr. National de la Recherche Scientifique (France); F. Jomard, Univ. de Versailles

Saint-Quentin-en Yvelines (France); M. Abid, Georgia Institute of Technology Lorraine (France); M. Molinari, M. Troyon, Univ. de Reims Champagne-Ardenne (France); N. Fressengeas, Ctr. National de la Recherche Scientifique (France); P. Voss, Georgia Institute of Technology Lorraine (France)

Recently, the GaN and ZnO materials systems have attracted considerable attention because of their use in a broad range of emerging applications including light-emitting diodes and solar cells. GaN and ZnO are similar materials with direct wide bandgaps, wurtzite crystal structure, high thermal stability and comparable thermal expansion coefficients. GaN has the advantage, however, of a mature know-how for p-type doping, while ZnO has proven to be more crystallographically compliant to non-native substrates than GaN. To exploit both of these advantages, ZnO layers have been proposed as buffer layers for the regrowth of GaN-based p-n devices on amorphous and mismatched substrates.

GaN and InGaN layers were grown on ZnO-buffered silicon and sapphire by metalorganic vapour phase epitaxy (MOVPE). In order to prevent ZnO surface degradation, the growth conditions were optimized using pressure/temperature MOVPE approach with N2 as a carrier gas and a mixture of dimethylhydrazine and ammonia as nitrogen source.

Scanning Electron Microscopy (SEM) of cross-sections, High Resolution X-Ray Diffraction (HR-XRD), Secondary Ion Mass Spectroscopy (SIMS) and Cathodoluminescence (CL) studies suggest that single phase InGaN layers with about 21.5% indium were grown with no evidence of back-etching of the ZnO templates. The materials quality of GaN/InGaN structures were investigated as function of the nature of the substrates (Si, Al203), thickness of the ZnO buffer layer as well as the chemical and in-situ pre-growth treatments. The results of these studies will be presented and discussed.

7603-47, Session 10

Hybrid flexible ZnO nanorods ultraviolet LEDs

J. Chen, L. Aé, M. C. Lux-Steiner, Helmholtz-Zentrum Berlin für Materialien und Energie GmbH (Germany)

We report the fabrication and operation of hybrid flexible vertical nano scale diodes. The diodes, formed by n-type ZnO and p-type CuSCN, were embedded in a 6 µm polymer foil, provided with vertical cylindrical openings of about 100 nm, by using a low temperature solution-based electrochemical deposition technique. Electrical measurements show diode function with sound device characteristics at operation temperatures up to 70 °C. Both the temperature dependent current-voltage characteristics and the application for the heterojunction ultraviolet light-emitting diodes are discussed. It is a promising structure for fabricating of large-area ZnO based heterojunction ultraviolet LEDs.

7603-48, Session 11

Multifunctional ZnO and its nanostructures for optoelectronic devices

Y. Lu, Rutgers, The State Univ. of New Jersey (United States)

No abstract available.

7603-49, Session 11

ZnO nanowires: optical properties, LEDs and lasers

F. Capasso, Harvard Univ. (United States)

No abstract available.

7603-50, Session 11

Nanopatterned optical and magnetic La0.7Sr0.3MnO3 arrays: synthesis, fabrication, and properties

W. Su, National Taiwan Univ. (Taiwan)

We have fabricated La0.7Sr0.3MnO3 periodic arrays exhibiting tunable optical properties and magnetic properties using nontoxic and environmentally friendly electron beam resist made from La0.7Sr0.3MnO3 sol-gel precursor. We studied their unique optical properties by using the spectral microreflectometer and their magnetic properties using the superconducting quantum interference device and magnetic force microscopy. Additionally, the resist has the ability to demonstrate both positive and negative resist behaviors depending on the electron beam dosage. With these special characteristics, we can fabricate periodic structure on a thin film possessing controlled optical reflectance properties in the wavelength range of 300 nm to 800 nm with one fixed design electron beam pattern without changing the structural parameters but changing the electron beam dosage only. The surface potential of patterned La0.7Sr0.3MnO3 measured by KFM is very useful to identify the chemical compositions and mechanism of the dual function of La0.7Sr0.3MnO3 resist. The magnetic properties of the patterned La0.7Sr0.3MnO3 can be clearly observed by post-sintering the sample at 900 °C for 4 hours after electron beam writing. Our approach provides an uncomplicated route for the fabrication of nanometer scale magnetic patterns, which serve as the building blocks in the search for novel properties of periodic arrays.

7603-51, Session 11

Multi-layered water quality sensor based on RuO2 nanostructures

S. Zhuiykov, Commonwealth Scientific and Industrial Research Organisation (Australia)

The multilayered nanostrcutured RuO2-based sensing electrodes were prepared for water quality sensors on the ceramic sensor substrates. XRD, SEM, EDX were used for analysis of their morphology. Long-term stability trial shown that bio-fouling can be one of the main destructive factors affecting the performance of the sensors in the long run. the technology used in the multi-layer implementation provides fundamental properties for minituarization, reasonable accuracy and low cost. The complete sensor system also includes electronic acquisition and signal conditioning capabilities.

7603-52, Session 12

Nanolithography for oxide nano-arrays and their application in medical devices

R. Luttge, Univ. Twente (Netherlands)

An overview of nanolithographic techniques for oxide nanoarrays will be presented. Using patterning techniques such as lithography, normally we aim for structural elements that can be integrated into one functional device or system demanding some level of ordering throughout the manufacturing process. Oxide nanoarrays (of pillars, holes or wires) have shown unique properties already and their specific design brings about the opportunity to modify and tune device performance. Moreover, these nanostructures can deliver new functionalities specifically at the interface with biological material. Investigating these novel phenomena, subsequently, we can look for medical applications where this unique property of the smallest manufactured element is repetitively used such as, for example using photonic crystals in medical diagnostic devices. Bio-inspired templated nanoarrays will be described in perspective to other massively parallel nanolithography techniques currently discussed in the scientific literature.

7603-53, Session 12

Synthesis and characterization of phosphorus-doped ZnO nanocrystals by nanoparticle-assisted pulsed laser deposition

T. Okada, Kyushu Univ. (Japan)

Realization of p-type ZnO crystals has been the key issue in the application to UV light-emitting devices. Now, substantial research work is currently carried out on ZnO doping. In this presentation, the synthesis and characterization of phosphorus-doped ZnO nanowires and nanowalls grown by a novel high-pressure nanoparticle-assisted pulsed-laser deposition (NAPLD) method will be discussed based on XRD, SEM, TEM, low temperature PL and lifetime measurements. It was also found that the ZnO nanowalls show excellent field emission property.

7603-54, Session 12

Effect of surface modification on the optical properties nanocrystalline zinc oxide materials

D. M. Steeves, U.S. Army Soldier Systems Ctr. (United States); J. Singh, J. Im, J. E. Whitten, Univ. of Massachusetts Lowell (United States); J. W. Soares, U.S. Army Soldier Systems Ctr. (United States)

The wide band gap and unique photoluminescence spectrum of nanocrystalline zinc oxide (nano-ZnO) make it useful for a variety of photonics and sensor applications. Toward the goal of modifying the electronic structure and optical properties of nano-ZnO, the nano-ZnO surface was modified with electron withdrawing organosilanes, 1H,1H,2H,2H-perfluorodecyltriethoxysilane (PFDS) and pentafluorophenyltriethoxysilane (PFS), and a partially conjugated heterobifunctional molecule, p-maleimidophenyl isothiocyanate (PMPI). FTIR spectroscopy and XPS confirmed the presence of the modifiers on the nano-ZnO surface and verified covalent attachment. Photoluminescence (PL) spectroscopy was performed to evaluate the influence of the modifiers on the nano-ZnO inherent optical behavior. An increase in the nano-ZnO near-band edge emission (UV) was evident for all three modifiers, despite their differing electronic structures, while the defect emission (visible) remained unchanged. The influence of size/shape of the nanocrystalline ZnO was examined by reacting spherical nanoparticles, average diameter of 20 nm, with PFDS. Similar post-modification PL behavior as the nanorods was exhibited, although the inherent PL of the spheres differs from the nanorods. The results from these studies will be presented and compared to results obtained previously for thiol-modified nano-ZnO to elucidate the role of modifier structure on surface-modified nano-ZnO optical behavior.

7603-55, Session 12

Inorganic light emitting device based on ZnO nanoparticles

E. Neshataeva, T. Kuemmell, Univ. Duisburg-Essen (Germany); A. Ebbers, Evonik Degussa GmbH (Germany); G. Bacher, Univ. Duisburg-Essen (Germany)

-

7603-56, Session 12

Solid-state white light source from ZnO-porous silicon nanocomposites

R. G. Singh, Univ. of Delhi (India); F. Singh, Inter Univ. Accelerator Ctr. (India); V. Agarwal, Univ. Autónoma del Estado de Morelos (Mexico); D. Kanjilal, Inter Univ. Accelerator Ctr. (India); R. M. Mehra, Univ. of Delhi (India)

Development of solid-state white light source across the extended visible region of electromagnetic spectrum from ZnO-Porous silicon nanocomposite is reported. Such outstanding emission has considerable implications in the development of advanced luminescent materials. Nanocrystallites of ZnO were grown inside the spongy structures of porous silicon by chemical route of sol-gel spin coating. The property of the material arises from versatile interactions among the host structure of porous silicon and ZnO. This type of solid-state white light source has the potential to revolutionize the world of lighting such as control panel, backlighting, panel indication, decorative illumination, emergency lighting, animated signal and flat penal display. The origin of observed extended white light emission from 1.4 to 3.3 eV is discussed by developing an energy band diagram. There is a considerable interest in the development of advanced luminescent materials for a variety of applications such as indicators, control panel, signs decor light, backlighting, panel indication, decorative illumination, emergency lighting, animated signal and flat penal display. The coming future is a little better into focus on the exciting luminescent characteristics of the template based nanocomposite of ZnO may lead to futuristic bright light source. The properties of the material arise from complex interactions among the host structure of porous silicon (PS) and ZnO. The various defects and surface states on interface of ZnO-PS are strongly dependent on the width of interface. The potential applications of SSWLS are immense because of their distinctive properties such as low power consumption, high efficiency, long life time, drastically reduced operating costs, green house gases and lack of toxic mercury.

7603-58, Poster Session

Characterization of ZnO UV photoconductors on the 6H-SiC substrate

L. Li, Univ. of Missouri-Columbia (United States); Y. Ryu, MOXtronics, Inc. (United States); H. White, P. Yu, Univ. of Missouri-Columbia (United States)

Optical properties of ZnO semiconductors are similar to those of GaN-based semiconductors, which show potential in UV light detection. Due to internal photoelectrical gain and fabrication simplicity of photoconductors, ZnO UV photoconductors were grown on 6H-SiC substrates by hybrid beam deposition. Electrical characterization, spectral response, and temporal response were studied for the photoconductors with interdigitated top contacts that are finger-haped Ti/Au ohmic contacts. The responsivity was measured by exciting with a He-Cd laser (325 nm). Spectral response measurements were performed from 250nm to 700nm under a bias voltage. The spectral responsivity remained nearly constant from 250 nm to 372 nm, and dropped by three orders of magnitude within 10 nm fro 372nm. The detector was measured to have a responsivity of 0.37A/W at the wavelength of 364nm under a 0.5V bias, and the bias-dependent responsivity was performed. The photoconductors show a responsivity that is highly dependent on incident power. We also explored the responsivity dependence on the optical power for different chopping frequencies, and the responsivity becomes flatter with increased the modulation frequency. The relationship between response time and bias was measured. The time response showed a persistent photoconductivity effect that depicted a slow and non-exponential transient response, that is responsible for the frequency dependent responsivity for the photoconductors. A reasonable explanation of slow photocurrent decay is due to the recombination of electrons in the deep levels located at extended defects or dislocations in the ZnO photoconductors.

7603-59, Poster Session

Structural and electrical properties of rectifying p-ZnO/n+-InP heterojunction

A. Mandal, S. Chakrabarti, Indian Institute of Technology (India)

ZnO thin films were deposited over n+ InP by Pulsed Laser Deposition (PLD) technique at 400ºC in an oxygen ambient of 75mTorr followed by Rapid Thermal Annealing (RTA) at the temperatures 450ºC, 500ºC, 550ºC, 600ºC and 650ºC respectively. XRD results revealed that the full width at half maxima (FWHM) of the annealed samples were narrower (0.1673º) compared to that of the as grown sample (0.3264º) and is attributed to the improved recrystallization for the c-axis oriented ZnO films. A lower strain (~ -.36%), lesser biaxial compressive stress (~ -1.633 GPa) and increased crystallite size (46.45 nm to 90.6 nm) were observed for the annealed samples. AFM images depicted surface roughness of the ZnO films varying between 7.257 nm to 21.483nm (root-mean-square). Absorption coefficients, calculated from the UV/VIS spectroscopy in reflection mode were found to decrease with annealing temperatures from 6.97 μm-1 (for as-grown sample) to 2.82 μm-1 (sample annealed at 650ºC) at 360 nm. The optical band gap was calculated to be about 3.23 eV. P-type ZnO film, grown under the same condition (annealed at 550ºC) over semi insulating InP had a high hole concentration of 2.95E19 cm-3 and Hall mobility of 8.63 cm2/V-s at room temperature. Current rectification ratio (IF/IR) |V|=1.5 of 17.2 was measured from the I-V characteristics of the p-ZnO/n+-InP heterojunction diode fabricated with the ZnO film annealed at 550ºC. We acknowledge Central SPM Facility of IIT Bombay for AFM study and DST for financial assistance.

7603-60, Poster Session

Atomic layer epitaxy of ZnO and TiO2 thin films on c-plane sapphire substrate for novel oxide soft x-ray mirrors

M. Murata, Y. Tanaka, H. Kunagai, A. Kobayashi, Osaka City Univ. (Japan); T. Shinagawa, Osaka Municipal Technical Research Institute (Japan)

Zinc oxide(ZnO) and titanium dioxide(TiO2) thin films are applicable for the novel oxide soft x-ray mirrors at the “water-window”(=2.3-4.4 nm) wavelengths. This is because oxygen of these oxide films is transparent for these wavelengths. Therefore, we have fabricated TiO2/ZnO multilayer mirror and demonstrated the high reflectivity at the wavelength. Our theoretical calculation also indicated that these multilayer mirrors can have the high reflectance of nearly 50% at the wavelength of 2.73 nm.

For the fabrication of TiO2/ZnO multilayer mirrors, thin ZnO and TiO2 films should be controlled precisely. Those films were grown on the c-plane(0001) sapphire substrate by means of atomic layer epitaxy(ALE) technique, which involves the sequential surface chemical reactions between Zn(CH2CH3)2 and H2O and between TiCl4 and H2O, respectively. Especially, these surface chemical reactions provide the self-limiting nature of adsorptions so that the thicknesses of the deposited layers should be controlled precisely.

Both Wurtzite ZnO(0001) and Rutile TiO2(200) films were grown with self-limiting natures epitaxially on c-plane(0001) sapphire substrates in our experiments at 450K.

In the presentation, ALE of Wurtzite ZnO(0001) and Rutile TiO2(200) on the c-plane sapphire substrate as well as the performance characteristics of TiO2/ZnO multilayer mirrors will be shown in detail.

7603-61, Poster Session

p-n homojunction zinc oxide nanowires-based light-emitting device

P. Gilet, A. L. Bavencove, Commissariat à l’Énergie Atomique (France); P. Ferret, Lab. d’Electronique de Technologie de l’Information (France); J. Garcia, M. Lafossas, F. Levy, P. Noel, P. Marotel, N. Olivier, Commissariat à l’Énergie Atomique (France); E. Pougeoise, Lab. d’Electronique de Technologie de l’Information (France); E. Latu-romain, R. Thierry, G. Feuillet, Commissariat à l’Énergie Atomique (France); D. Le Si Dang, Univ. Joseph Fourier (France)

In this communication, we report on the electroluminescence from p-n homojunctions in vertically aligned ZnO nanowires (NWs). The samples were grown by catalyst free MOCVD on sapphire substrates. As or P were used as p-type dopants whereas no specific dopants are used for n-type doping . The nanowires have been embedded and contacted by n- and p-type electrodes (Ti/Au and Ni/Au respectively) through a technological integration process.

Room temperature I-V characteristic of the devices exhibits diode like behaviour which unambiguously confirms the achievement of p-type doping in the nanowires. Light emission is clearly visible for low voltage bias (i.e. below 10V) and has been recorded with an UV CCD camera. The electroluminescence spectra clearly indicate well resolved room temperature band edge emission at 385nm. Threshold Voltage around 3V have been measured for a 350x350μm^2 device. Since first observations (within one month), no ageing effect has been noticed. One band is present at lower energy (around 2eV) but with lower intensity (three times) and is attributed to the defect band of the material. Local optical spectroscopy measurements (Photoluminescence and Cathodoluminescence) will be compared to macroscopic electroluminescence spectra of integrated NWs in order to discuss about the specific signature of p-type doping. Scanning Probe Microscopy (SPM) characterizations were performed on reference samples containing p type dopants in the Scanning Capacitance Microscopy (SCM) mode. These measurements reveal p-type space charge regions and add one more evidence of p-type doping achievement.

7603-62, Poster Session

Post-annealing of p-type ZnO:Sb thin film grown by pulsed laser deposition

Y. Yata, T. Sakano, M. Obara, Keio Univ. (Japan)

We present the effect of post-annealing on the p-type ZnO:Sb thin film. The post-annealing is an important process to achieve p-type conduction in ZnO thin film, which is usually applied to activate the dopant through the formation of acceptor complex. We used an Sb dopant in ZnO. The minimum annealing temperature necessary to activate Sb in ZnO is believed to be 700~800 C. However, annealing at such high temperatures may cause detrimental effects such as the formation of defects and unwanted compounds. This phenomenon becomes more crucial when the annealing time is prolonged. This negative effect will arise from the film being applied too much energy to the film at high annealing temperatures.

In this paper, it is shown that by using different annealing temperatures, the characteristic of ZnO:Sb grown by PLD is controllable to minimize the negative effects. We first show that p-type conduction can be achieved only for the films grown at a certain temperature range even with post-annealing. The film grown at 600 C, and annealed at 700 C for 60 min has shown a hole concentration of 1.4 x 10^17 cm-3 and a reasonable mobility of 6.7 cm2/Vs. Then, we present the reason why changing the total energy applied to the film and the annealing parameters improve the film characteristic. Decreasing the annealing time, which subsequently reduces thermal exposure, have improved Hall-effect measurement results.

7603-63, Poster Session

Highly transparent and conductive Tantalum-doped ZnO films prepared by radio frequency sputtering

Y. An, Z. Song, Y. Wang, Jilin Univ. (China)

Tantalum-doped ZnO (TZO) transparent conductive films are deposited on glass substrates by radio frequency (RF) sputtering at 300 oC. The influence of sputtering power on the structural, morphologic, electrical, and optical properties of TZO films is investigated by X-ray diffraction (XRD), Field emission scanning electron microscopy (FESEM), Hall measurement, and optical transmission spectroscopy. The minimum resistivity of 4.1×10−4 Ω cm is obtained from the film grown at the sputtering power of 150 W. The average optical transmittance of the films is over 93%, and the film optical band gap is about 3.53 eV.

7603-64, Poster Session

Change in properties of spray pyrolysed ZnO thin film due to co doping of fluorine with metals

T. V. Vimal Kumar, C. Sudha Kartha, K. P. Vijayakumar, Cochin Univ. of Science & Technology (India)

Thin film of ZnO have been deposited using various techniques including chemical spray pyrolysis which is quite simple, inexpensive and suitable for large area deposition. Addition of impurities often induced dramatic change in the electrical and optical properties of wide-band-gap semiconductors. In this paper, we present results of systematic studies on the effect of doping with Indium, Aluminium and Flourine . .The films exhibited luminescence in two regions-near band edge (NBE) (~380 nm) and in the blue- green (~503 nm). Intensity of the near band edge emission increased with fluorine doping while it decreased with metal doping .However there were no observable changes in the band gap of the doped samples. Transmission of the sample in the visible region increased after the co-doping of fluorine. XRD studies revealed that crystallinity of ZnO films decreased with fluorine doping. Resistivity of the sample became 10-2 Ohm cm with fluorine doping But co doping with metals resulted in 10-3 Ohm cm. Scanning electron microscope (SEM) analysis of the films revealed that fluorine doping greatly affect the surface morphology of the film , which is useful in photovoltaic application.

7603-65, Poster Session

Structural and optical properties of TiO2 thin films annealed in O2 and N2 gases flow

S. H. Kim, T. U. Kim, G. Oh, H. Ki, D. Kim, H. J. J. Kim, H. J. Ko, M. Han, S. Hann, H. Kim, Korea Photonics Technology Institute (Korea, Republic of)

TiO2 is an important oxide-based semiconductor material used in photocatalysis, photovoltaic cells, MOSFET gate dielectrics, and sensors. Here, TiO2 thin films were prepared by ion-assisted electron-beam evaporation on glass substrates at room temperature. The samples were annealed by rapid thermal annealing system at different temperatures of 300 to 700 in O2 and N2 gases flow. Crystalline phase and optical transmittance were investigated using X-ray diffraction and UV-VIS-NIR spectrophotometer. The as-deposited films are amorphous phase. The TiO2 films annealed with N2 gas are (110) rutile and (101) anatase phases, but with O2 gas are (110) rutile phase. The increase in temperature would result in more observable anatase and rutile phases. However, phase transition temperature was not shown in this case. The transmittance percentage and optical band gap of the TiO2 films annealed in O2 gas flow are higher than those of the TiO2 films annealed in N2 gas flow. The as-deposited films have a low optical band gap of 3.250 eV. As annealing treatment of 300 ~ 500 , the optical band gaps of the TiO2 thin films are increased to 3.281 and 3.271 eV in O2 and N2 gases flow, respectively. At 600 , the band gap begins to decrease to 3.277 and 3.257 eV in O2 and N2 gases flow, respectively. The decrease of the band gap results from the increase of the annealing temperature. Here, these characteristics can show that the films annealed in O2 and N2 gases flow become more crystalline.

7603-66, Poster Session

Physical properties of MgZnO film grown by RF magnetron sputtering using ZnO/MgO (80/20 wt%) target

K. Hsueh, Vanung Univ. (Taiwan); C. Tun, National Synchrotron Radiation Research Ctr. (Taiwan); H. Chiu, Chang Gung Univ. (Taiwan)

In this work, we report on an investigation of the characteristics of MgZnO films which were deposited on top of the sapphire by RF magnetron sputtering system using ZnO/MgO (80/20 wt%) 6 inch target. All MgZnO films used in this study were grown by RF sputtering method (HELIX) on c-face sapphire substrates.

The XPS was performed by a Thermo VG-Scientific/ Sigma Probe instrument. The XPS results by varying the etching time were shown. The red line in the XPS results is the surface of MgZnO. The contents of MgZnO were also estimated by varying the etching depth.

The transmittance spectrum of MgZnO film is obtained. In this study, the MgZnO film show high transparency with transmittances over 85% in the visible region (400 ~ 700nm) and the sharp absorption edge is visible in UV region due to the Mg content. The absorption edges of MgZnO shift toward the short wavelength compared with the previous report, implying that band gaps can be tuned by changing the Mg content of MgZnO layer.

We summarized the Hall measurement on the MgZnO samples which were deposited at RF power of 100W and 200W, respectively. The results show that the Hall measurement of MgZnO films which were deposited at lower RF power magnetron sputtering obtained the higher n-type doping concentration, but the resistivity and mobility are not a strong function of the RF power and annealing temperatures.

7603-67, Poster Session

Comparison of ZnO nanostructures grown using pulsed laser deposition on various substrates

V. E. Sandana, D. J. Rogers, F. H. Teherani, Nanovation (France)

This paper compares the forms and properties of ZnO grown by Pulsed Laser Deposition (PLD) nanostructures prepared using three different substrate: Silicon 111 (Si 111), c-Saphir (c-Al2O3) and c-ZnO bulk crystal. 2 kinds of of ZnO nanostructures were investigated, including nanorods, and nanoneedles aside with some novel features, such as “bevelling” of nanowires. The nanostructures grown by PLD were better crystallized with the relatively lowest density of defects.

Conference 7604: Integrated Optics: Devices, Materials, and Technologies XIV

Monday-Wednesday 25-27 January 2010 • Part of Proceedings of SPIE Vol. 7604

Integrated Optics: Devices, Materials, and Technologies XIV

7604-01, Session 1

Integrated photonic devices for advanced modulation formats

Y. Hibino, NTT Photonics Labs. (Japan)

Internet protocol (IP) data traffic explosively increases with diffusion of broadband access environment such as fiber to the home (FTTH), and asynchronous digital subscriber line (ADSL) which enable video on demand services, video chat, and so on. In Japan, the IP data traffic is increased by about twice per year, and its tendency will be continued after this. Very large capacity backbone network is required to support the huge traffic volume from the access networks. For this purpose, optical transmission schemes for channel rates of 100 Gb/s or higher in wavelength-division multiplexed (WDM) systems are now being widely studied. The combination of polarization division multiplexing (PDM) and spectrally efficient modulation formats, such as quadrature phase-shift keying (QPSK), with digital coherent detection techniques is emerging as one of the most promising solutions, because of the high sensitivity. This technology also enable to attain the high tolerance to fiber dispersion and band filtering in the add/drop nodes. To realize the digital coherent detection techniques, high-speed analog-digital converters (ADCs) and large-scale digital signal processors (DSPs) are key components, and have been developed extensively. In addition, it will become essential to integrate various photonic components such as modulators, PDM components, and photo-diodes (PDs) with trans-impedance amplifiers (TIAs) to reduce the optical transceiver cost. This is because the components are complicated, and must be packaged in a small space. This paper mainly reviews the recent progress on integrated photonic devices for advanced modulation formats.

7604-02, Session 1

High-performance optical waveguides based on boron/phosphorous-doped silicon oxynitride

F. Sun, G. Sengo, A. Driessen, K. Worhoff, Univ. Twente (Netherlands)

Silicon oxynitride (SiON) is a highly attractive material for integrated optics, due to its excellent properties such as high transparency, adjustable refractive index and good stability. In general, the growth of SiON layers by plasma enhanced chemical vapor deposition (PECVD) is followed by an high temperature annealing step in order to remove hydrogen and achieve low propagation losses in the 1.5- m wavelength window. The high annealing temperature (>1000°C) required for sufficient hydrogen removal induces, however, side effects like significant inter-layer diffusion and micro-cracks resulting in deterioration of the device performances.

In this paper compositional and optical properties of as-deposited and annealed boron/phosphorous (B/P) doped SiON layers were investigated. The doped layers have been fabricated by introducing PH3 and B2H6 gaseous precursors into the PECVD process. Hydrogen contents of the samples have been studied by Fourier transform infrared (FTIR) spectroscopy. Compared with undoped films, a 70% reduction of the hydrogen content was measured in as-deposited B/P doped SiON layers. Further reduction beyond the FTIR detection limit was achieved upon annealing at temperatures as low as 700°C. Optical loss measurements of slab waveguides by moving prism method have confirmed the hydrogen elimination, where propagation losses as low as 0.2dB/cm have been demonstrated.

Besides hydrogen reduction the reflow properties of B/P doped SiON are also highly relevant for the realization of low-loss integrated optical circuits. Reactively ion etched channel waveguides have been reflown applying temperatures from 700°C to 900°C. Significant reduction of the sidewall roughness has been confirmed by scanning electron microscope.

7604-03, Session 1

Diamond-based waveguides and devices: fabrication and design

M. P. Hiscocks, The Univ. of New South Wales (Australia); C. Su, K. Ganesan, B. C. Gibson, A. D. Greentree, The Univ. of Melbourne (Australia); F. J. Ladouceur, The Univ. of New South Wales (Australia); S. D. Prawer, The Univ. of Melbourne (Australia)

Diamond is an attractive material candidate for a range of photonics applications due to its outstanding properties including high thermal conductivity, wide transparency window and high refractive index. In photonic devices an additional feature of interest is the ability of diamond to generate single photons on demand at room temperature when certain types of lattice defects are optically pumped. Recent advances in the production of artificial diamonds with high purities have made diamond a more accessible material for research.

We have developed a scalable process for fabricating photonic devices in diamond using reactive ion etching (RIE) and photolithography as well as using ion implantation to provide vertical confinement. Applying this we have demonstrated a few-moded waveguide with a large cross section for easier coupling to optical fibre. The characterisation of these waveguides, in particular their propagation, bend and coupling losses, has not been completed as of yet due to the difficulties cleaving/cutting diamonds. We intend to show how we surmounted this technical issue and present our latest characterisation results for single-moded waveguides.

We also examine the application of diamond waveguides to other photonic applications in particular low mode volume cavities produced in diamond using a slot-waveguide design. These cavities may be used to enhance the single photon emission efficiency of a diamond defect centre and other quantum interactions can be investigated by producing 1D or 2D coupled arrays of these resonators.

7604-04, Session 1

Waveguides based on TeGe thick films for spatial interferometry

E. Barthélémy, S. Albert, C. Vigreux-Bercovici, A. Pradel, Univ. Montpellier 2 (France)

Due to their unique property of transmission in the infrared region, chalcogenide glasses are very promising materials for the realisation of infrared integrate optics micro-components. These components are particularly attractive for infrared applications as environmental metrology for the detection of pollutant gases or spatial interferometry for the detection of exoplanetary systems.

The first step in the fabrication of infrared micro-components is the realization of single-mode waveguides. In such a case TeGe thick films need to be deposited on TeGeGa bulk glass substrate. The chosen method of deposition of these TeGe thick films is the thermal co-evaporation, method rarely used to produce chalcogenide films. The fabrication of chalcogenide waveguides based on the stacking of TeGe thick films on TeGeGa glass substrates will be described. The testing of theses waveguides will be presented. In particular, the first transmission measurements at 10.6 µm will be discussed.

In conclusion, the feasibility of micro-components based on the stacking of chalcogenide films deposited on a chalcogenide glass is demonstrated, opening the door to applications related to detection in the mid- and thermal infrared spectral domains.

7604-05, Session 1

Fabrication and characterization of garnet/SOI strip-loaded waveguides for integrated optical isolator applications

L. Bi, J. Hu, L. C. Kimerling, C. A. Ross, Massachusetts Institute of Technology (United States)

Integration of magneto-optical isolators on a semiconductor platform is a fundamental difficulty for integrated photonics. Although widely used in fiber optical communication systems, integration of magneto-optical isolators onto semiconductor substrates remains challenging so far. In this study, we report a novel strategy to integrate magneto-optical oxides on a SOI platform based on a strip-loaded waveguide structure. By using conventional waveguide fabrication and thin film deposition techniques, we can fabricate a strip-loaded waveguide with high magneto-optical non-reciprocal phase shift (NRPS). As a demonstration, Y3Fe5O12 (yttrium iron garnet, YIG)/SOI waveguides are fabricated. A 450 nm wide silicon channel waveguide is firstly formed by electron-beam lithography and reactive ion etching of a 220nm SOI layer. Then an 80 nm thick YIG layer is deposited on the SOI wafer at 450°C by pulsed laser deposition followed by a rapid thermal annealing process at 850°C for 5 min to cause crystallization(>95 vol.%). The YIG layer has an in-plane magnetization easy axis with saturation field as low as 100Oe. By tuning the mode profile with a top cladding layer, an NRPS difference of 54.9 deg/cm between forward propagating and backward propagating waves of the TM fundamental mode at 1550 nm wavelength can be achieved by simulation. The transmission insertion loss, the NRPS and the figure of merit of this device will be discussed. This fabrication technique offers a compact, low cost, non-material-selective and etching-free route for integrating magneto-optical materials on a silicon platform, therefore providing a promising integration strategy for optical isolators.

7604-06, Session 1

Microfluidics and thin-film processes: a recipe for organic integrated photonics based on 3D microresonators

N. Huby, D. Pluchon, M. Belloul, A. Moreac, N. Coulon, Univ. de Rennes 1 (France); E. Gaviot, Univ. du Mans (France); P. Panizza, B. Beche, A. Saint-Jalmes, Univ. de Rennes 1 (France)

We report on the design and realization of photonic integrated devices based on 3D organic microresonators. This has been achieved by combining microfluidics techniques and thin-film processes. The microfluidic device and the control of the flow rates of the continuous and dispersed phases allow the fabrication of organic microresonators with diameter ranging from 30 to 200 m. The resonance of the sphere in air has been first investigated by using the Raman spectroscopy set-up demonstrating the appropriate photonic properties. Then the microresonators have been integrated on an organic chip made of the photosensitive resin SU-8 and positioned at the extremity of a taper and alongside a rib waveguide. The realization of these structures by thin-film processes needs one step UV-lithography leading to 6 m width and 30 m height. Both devices have proved the efficient evanescent coupling leading to the excitation of the whispering gallery modes confined at the surface of the organic 3D microresonators. Finally, a band-stop filter has been used to detect the resonance spectra of the resonators once integrated.

7604-07, Session 2

Rare-earth-ion-doped Al2O3 for integrated optical amplification and lasing

K. Wörhoff, M. Pollnau, L. Agazzi, J. D. B. Bradley, Univ. Twente (Netherlands)

Amorphous Al2O3 is a highly attractive host material for active integrated optics applications. We have developed and optimized Si-compatible technology for the fabrication of rare-earth-ion-doped Al2O3 waveguides. Planar waveguides are grown reliably and reproducibly on thermally oxidized Si-wafers exploiting reactive co-sputtering. As-deposited layers are uniform over the substrate area and have a refractive index and propagation losses of 1.64(3±1) and 0.11±0.05 dB/cm at = 1.5 m, respectively. Channel waveguides with steep and smooth sidewalls are fabricated by ICP reactive ion etching utilizing BCl3/HBr chemistry in combination with standard lithography. The quality of the etching process has been demonstrated by uncladded channel waveguides having optical losses as low as 0.21±0.05 dB/cm. The excellent optical performance in combination with the controlled channel waveguide fabrication and the high refractive index add to the high potential of this material in compact integrated optical applications.

Rare-earth ions have been incorporated into the growing Al2O3 layers by co-sputtering from a metallic Er target. Waveguides with Er concentrations varying from 0.27 to 4.22 1020 cm-3 have been investigated. The exponential tails of the decay curves of the 4I13/2 level range from 7.5 ms to 6.1 ms at the lowest and highest Er concentration, respectively. For optimum Er concentrations in the range of 1 to 2 1020 cm-3, internal net gain was obtained over a wavelength range of 80 nm (1500-1580 nm). A peak gain of 2.0 dB/cm was measured at 1533 nm. Upon optimization of the amplifier length, net gain of more than 20 dB throughout the C-band is predicted. Based on the gain properties novel, integrated amplifier and laser devices have been designed and realized. The device performance is investigated.

7604-08, Session 2

Application of waveguide amplifiers in optical networks

S. Taccheo, K. Ennser, Swansea Univ. (United Kingdom)

We review potential applications of waveguide amplifiers in optical networks. We present application were such a devices may give give clear advantages.

Since waveguide amplifiers maybe integrated with other optoelectronc compontents they use will reduce the overall footprint and may also reduce overall installation costs.

In addition waveguide amplifiers, compared to semiconductor optical amplifiers, offer better perfomance in term of gain and noise figure allowing to extend the reach of optical networks.

We show potential high gain with excellent power consumption efficiency.

7604-09, Session 2

Optofluidic FRET dye laser controlled by DNA scaffold

Y. Sun, C. Wu, X. Fan, Univ. of Missouri, Columbia (United States)

We report the development of optofluidic ring resonator (OFRR) dye laser through the fluorescent resonance energy transfer (FRET) between oligonucleotide labeled donor molecule and its complementary oligonucleotide labeled acceptor molecule. The OFRR is a thin-walled fused silica capillary with a diameter around 80 um and a few centimeters in length. The capillary cross-section forms a ring resonator supporting the high-Q whispering gallery modes (WGMs) with evanescent field penetrating into the capillary core, where gain medium flows through

the OFRR capillary. In the OFRR FRET dye laser, the distance between donor and acceptor is strictly controlled by the base pair number of DNA scaffold, which in turn determines the FRET efficiency. In this study, we have investigated the lasing emission spectrum, threshold, and lasing power conversion efficiency regarding to donor/acceptor concentration, donor to acceptor ratio, and donor acceptor distance, respectively, by using the designed DNA scaffold structure. Cascade FRET lasing has also been explored by using three dye molecules labeled with oligonucleotide. The energy transfer between three individual FRET pairs can be controlled by the oligonucleotide length. The study shows a lasing threshold of pump energy density as low as 5 uJ/mm2 and the lowest concentration supporting FRET lasing is 2.5 uM.

7604-10, Session 2

Demonstration of excitation-wavelength-independent concentration of sensitized Er3+ ions in as-deposited and low-temperature-annealed Si-rich SiO2 films

O. Savchyn, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States); R. M. Todi, K. R. Coffey, L. K. Ono, B. Roldan Cuenya, Univ. of Central Florida (United States); P. G. Kik, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States)

Currently significant amount of work is dedicated to the realization of a silicon-based laser for optical interconnects. One of the possible ways of realizing such a device is to use the emission not from silicon itself but rather from the optical centers incorporated into silicon-based matrixes. Erbium ions incorporated in Si-rich SiO2 with their typical emission at 1.5 um can serve this purpose. Due to the narrow absorption lines of erbium characterized by low absorption cross sections, sensitization of erbium in SiO2 is required. Silicon nanocrystals incorporated in erbium-doped SiO2 have been thought to be the dominant source of erbium excitation. However, recently it has been demonstrated by our group that not silicon nanocrystals but rather silicon-excess-related luminescence centers are responsible for indirect excitation of erbium in Si-rich SiO2.

In the current study erbium sensitization is demonstrated in as-deposited erbium-doped Si-rich SiO2, thus excluding the presence of Si-nanocrystal-mediated excitation of erbium in these samples. The erbium absorption cross section in as-deposited and samples annealed at 600oC is shown to be similar within a factor 3 under 355 nm and 532 nm excitation. The density of excitable erbium ions is demonstrated to be excitation wavelength independent, and thus the shape of the erbium excitation spectra is shown to be governed by a wavelength-dependent erbium absorption cross-section. The results of the study demonstrate the possibility of efficient excitation of this gain medium in a broad range of wavelengths.

7604-11, Session 2

Low threshold Er3+/Yb3+ co-doped microcavity laser

H. Hsu, The Univ. of Southern California (United States); C. Cai, California Institute of Technology (United States); A. M. Armani, The Univ. of Southern California (United States)

Whispering gallery mode devices are able to efficiently confine light within the periphery at specific wavelengths, known as the resonant frequency of the device. The common figure of merit for optical cavities is the quality factor or Q of the cavity which describes the photon lifetime within the cavity. In high-Q cavities, the long photon lifetimes result in a large circulating optical intensity which enables these devices to have numerous applications throughout science and engineering.

By incorporating a rare earth dopant into the device, the build-up intensity can be leveraged to form a low-threshold laser. This effect has previously been demonstrated with Er3+ and Yb3+. In the present study, Er3+ and Yb3+ were combined to form a co-doped microlaser. In this device, which is pumped at 980nm, Yb3+ is a sensitizer, improving the lasing efficiency of the Er3+ ions. The planar array of co-doped toroidal microcavity lasers was fabricated using two different methods. The first approach was based on coating a silica toroid with a thin layer of Er3+/Yb3+ sol-gel, also known as the surface functionalization method. The second approach involved spinning and directly patterning several layers of Er3+/Yb3+ co-doped sol-gel.

Using tapered optical fiber coupling, the Q factor of the devices was determined at 633nm, which is sufficiently far from the absorption of Er3+ and Yb3+. Both methods obtained Q factors greater than 1E7 at 633nm. Using a 980nm pump laser, either single or multi-mode lasing at 1530nm could be obtained with less than a 10microW threshold.

7604-12, Session 3

Large-scale simulations in the realm of nano-optics

C. Rockstuhl, C. Menzel, T. Paul, S. Fahr, F. L. Lederer, C. Helgert, C. Etrich, T. Pertsch, Friedrich-Schiller-Univ. Jena (Germany)

The realm of nanooptics is usually characterized by the interaction of light with structures having relevant feature sizes that are much smaller than the wavelength. To model such problems, a large variety of different methods exists. However, most of these methods either require a periodic arrangement of a unit cell (as it occurs, e.g., for metamaterials) or can handle only single entities (as it occurs e.g. in the analysis of plasmonic nanoantennas). But there exists a great variety of functional devices which may have either a spatial extent much larger than the wavelength and which comprises structural details with sizes in the order of a fraction of the wavelength or they may consist of an amorphous arrangement of strongly scattering entities where each has a nanometric spatial extent. Such structures require a large scale simulation where the fine details are properly retained.

In this contribution we outline our latest research on such devices. Presenting several examples, we show how simulations support the physical understanding of these devices and outline how they can be used to strengthen our understanding on how light is guided and/or localized in nanooptical elements. Our discussion will include the example of randomly textured surfaces used for solar cells, where guided modes excited in the light absorbing layers strongly affect the solar cell efficiency. Other presented examples are amorphous metamaterials and stochastically arranged nanoantennas. We will motivate the use of computational experiments by the unprecedented insights we obtain into the functionality of such optical components.

7604-13, Session 3

Propagation analysis of low-optical overlap modes in nanoscale III-V and amorphous membrane waveguides

R. D. Whaley, Jr., K. Manoharan, A. Solam, Ohio Univ. (United States); G. Lifante, Univ. Autónoma de Madrid (Spain)

Low optical overlap modes (LOOMs) are defined as guided modes in which the optical modal fill factor is on the order of 1% or less. Because the interaction of the optical field with the core region is so weak, these types of modes can potentially be used in integration schemes that require ultra low-loss. In addition, due to the extended nature of the primary electric field, the interaction cross-section of such a mode with a potential chemical analyte can greatly enhance the sensitivity of evanescent wave chemical sensors. For this work, we have considered nanoscale membrane LOOM waveguides, composed of both InP (for 1.55 μm analysis) and amorphous ZnO (for 550 nm analysis) each with a primary membrane thickness of 50 nm. Using analytical tools such as

effective index methods, we have calculated the mode profiles of quasi-TE and quasi-TM modes and obtained both the modal fill factor and optical confinement factor for each polarization. We then investigated the accuracy of the analytical tools by reevaluating the modal and confinement results through the use of finite element modeling (FEM) and semi-vectorial beam propagation (BPM) numerical analysis. The applicability of each of these numerical tools within the framework of this nanoscale, extended-mode regime is discussed. Finally, we present an analysis of the fabrication restrictions for such structures, investigating the tolerances required to maintain single LOOM propagation without incurring excessive loss due to modal coupling.

7604-14, Session 3

Finite element method for accurate 3D simulation of plasmonic waveguide devices

L. W. Zschiedrich, Zuse Institute Berlin (Germany); F. Schmidt, S. Burger, JCMwave GmbH (Germany)

Plasmon-based waveguiding structures allow for transport and manipulation of light at subwavelength scales. Fast and accurate 3D Maxwell solvers are needed for designing structural parameters of, e.g., waveguide bends and splitters.

Due to the multi-scale nature of the corresponding field distributions, accurate computation of the properties of such devices can be numerically challenging. We have developed finite-element method (FEM) based solvers for the Maxwell eigenvalue and for the Maxwell scattering problems.

The method is based on higher order vectorial elements, adaptive unstructured grids, and on a rigorous treatment of transparent boundaries. The method has been applied to plasmonic devices like plasmonic antennas, gratings and waveguides [1,2,3].

Here we present 3D simulations of light propagation in plasmonic waveguides, including bends and splitters. We investigate the accuracy of the simulations in a convergence analysis of the numerical results.

[1] J. Hoffmann, C. Hafner, P. Leidenberger, J. Hesselbarth, S. Burger, “Comparison of electromagnetic field solvers for the 3D analysis of plasmonic nano antennas”, Proc. SPIE Vol. 7390, 73900J (2009).

[2] S. Burger, L. Zschiedrich, J. Pomplun, F. Schmidt, B. Kettner, D. Lockau, “3D Finite-Element Simulations of Enhanced Light Transmission Through Arrays of Holes in Metal Films”, Proc. SPIE Vol. 7390, 73900H (2009).

[3] H. W. Lee, M. A. Schmidt, H. K. Tyagi, L. Prill Sempere, P. St. J. Russell, “Polarization-dependent coupling to plasmon modes on submicron gold wire in photonic crystal fiber”, Appl. Phys. Lett. 93, 111102 (2008).

7604-15, Session 3

Compact WDM using a multi-channel directional-coupler and partial image revivals

R. J. McCosker, G. E. Town, Macquarie Univ. (Australia)

We describe a compact 1×2 wavelength-division-multiplexer based on a multi-channel directional-coupler (MCDC) using partial image revivals. Using supermode theory, an MCDC is described as a composite waveguide structure and then analyzed in terms of multi-mode interference and the principle of self-imaging. In an MCDC, bringing the waveguides closer together increases waveguide coupling, resulting in a quicker transfer of energy between the waveguides and hence shorter mirror- and self-image lengths. However, as the waveguides get close enough together, non-nearest neighbor coupling results in the corresponding image lengths becoming much longer, rather than shorter. Nonetheless, we can take advantage of the partial image revivals that occur at the beginning and end of the self-image process. We now have the advantage of the increased coupling and hence shorter image lengths, but with the disadvantage that the images are partial, which means that most but not all the energy is focused at the required image revival point. This results in a trade-off between device size and isolation ratio, where although we use the partial self-image revival at 1.55 μm wavelength for a compact device, the trade-off is a reduced isolation ratio when compared to 1.3 μm wavelength where a complete mirror-image is present. The design of a compact device in SU-8 with a polymer (UFC-170) cladding is described with a footprint of only 12.8×780 μm. The transmission characteristics of the device are determined using a 3-D Beam Propagation Method. The results demonstrate insertion losses of 0.03/0.3 dB, isolation ratios of 25.1/13.6 dB and 3-dB bandwidths of 8.5/11 nm at 1.3/1.55 μm, respectively.

7604-16, Session 3

Coupled mode analysis for graded index multiwaveguide systems

K. C. Patra, E. K. Sharma, S. Shrivastava, Univ. of Delhi (India)

In this paper, we present the modified scalar coupled mode analysis for the diffused N waveguide directional coupler. Some of the applications of the graded index multi-waveguide coupler include power splitters/ dividers, multiplexers/ demultiplexers, filters etc. All of these applications result from the evanescent field coupling between adjacent waveguides. Here, we analyze this evanescent field coupling for any given graded index Multi-Waveguide Systems. In a two step procedure, the propagation characteristics of individual waveguides have been obtained first using the simple and completely analytical variational procedure. Gaussian trial fields having only a single variational parameter have been used to obtain the fields and effective indices of the individual waveguides. Consequent upon obtaining the individual waveguide characteristics, the complete scalar coupled mode theory has been developed to obtain the supermodes corresponding to the coupled waveguide configuration consisting of N graded index waveguides. The field propagation along z-direction has also been studied in detail. Completely generalized and accurate analytical expressions for all coupling coefficients, perturbation correction terms and nonorthogonality terms involved in the analysis are presented. A comparison with the numerically intensive though exact multilayer staircase procedure has been carried out. The excellent agreement between the two procedures justifies the use of this simple formulation, especially for repetitive calculations as required for design optimization. Further to this, a detailed analysis wherein the effect of various interaction terms on the accuracy of the propagation characteristics of the multi-waveguide coupler are presented.

7604-17, Session 4

Generic packaging concepts in the frame of network of excellence ePIXnet

T. Tekin, L. Zimmermann, Technische Univ. Berlin (Germany); H. Schröder, Fraunhofer-Institut für Zuverlässigkeit und Mikrointegration (Germany); P. Dumon, W. Bogaerts, Univ. Gent (Belgium); J. V. Galan, P. Sanchis, Univ. Politécnica de Valencia (Spain); W. Whelan-Curtin, D. M. Beggs, Univ. of St. Andrews (United Kingdom)

Generic packaging concepts for silicon photonics have been developed in the frame of EU-funded Network of Excellence ePIXnet (FP6). Three approaches for Silicon photonic packaging will be presented within this paper. Two concepts provide solutions for fiber array coupling to high-index contrast photonic wire waveguide gratings. Third concept is the integration of inverted taper-based fiber coupling structure with silicon etched V-grooves. Using standardized SOI chip designs and commercial available assembly parts, the packaging concepts allow for small footprint or flexible use in an R&D environment.

The tolerances of the used assembly parts and the alignment sensitivity of the SOI chip were analyzed, respectively. The demonstrated interconnections have an enormous potential as a smart, low cost, compact package for silicon photonics. The work presented here has resulted from cooperation within the European Network of Excellence ePIXnet. The work is continuing partly in the framework of the European funded integrated project HELIOS.

7604-18, Session 4

Quantum well intermixing in AlInGaAs MQW structures through impurity-free vacancy method

K. Lee, J. R. O'Callaghan, B. J. Roycroft, H. Yang, Tyndall National Institute (Ireland); F. H. Peters, Tyndall National Institute (Ireland) and Univ. College Cork (Ireland); B. Corbett, Tyndall National Institute (Ireland)

Lasers fabricated with AlInGaAs-based heterostructures have shown superior performances over InGaAsP at higher temperatures; therefore, AlInGaAs have great potential as a means of realising photonic integrated circuits. To achieve the monolithic integration, a post-growth bandgap engineering technique like quantum well intermixing (QWI) can be employed to avoid complex selective area regrowth process steps. Here, we report QWI on AlInGaAs-MQWs using the impurity-free vacancy diffusion (IFVD) method with dielectric capping layers.

The AlInGaAs-MQW laser structures were grown on (100) n-doped InP substrate by metal-organic vapor phase epitaxy (MOVPE). The as-grown photoluminescence (PL) peak is ~ 1521 nm. The dielectric capping layers including 80-nm-thick SiNx and 200-nm-thick SiO2 were deposited by plasma-enhanced chemical vapour deposition (PECVD). Samples of the laser structure capped with different dielectric layers were then annealed by rapid thermal annealing (RTA) at temperatures between 650 and 750 ˚C for times ranging from 30 to 120 seconds. After RTA treatment and removal of the capping and contact layers, PL measurements were carried out using a 1042 nm-wavelength pump source.

The measured PL shifts generally increase with annealing temperature and duration. The SiO2 cap does not induce significant atomic interdiffusion, but the SiNx capping layer causes a larger degree of intermixing than SiO2. The PL shift with SiNx capping can be up to 110 nm, but is less than 11 nm with SiO2 as capping at 750 °C annealing temperature. Based on this technique, the broad-area lasers with 110 nm wavelength blueshift are being fabricated and characterized.

7604-19, Session 4

Monolithic integration of optical mode-size converter and high-speed electro-absorption modulators using laterally undercut waveguide

Y. Chiu, F. Lin, T. Wu, H. Yan, J. Wu, National Sun Yat-Sen Univ. (Taiwan)

A new monolithic integration scheme of fabricating optical spot-size converter (SSC) is realized in this work. High-speed electroabsorption modulator (EAM) is used to integrate such SSC. By laterally tapering the active region of an optical waveguide through undercut active region, a vertically asymmetric waveguide coupler can be defined to form an SSC, where the top is a tapered active waveguide, and the bottom is a large core of passive waveguide mode-matched to single-mode fiber (SMF). Through the top tapered active waveguide, the effective index can be gradually varied in the propagation direction, momentarily matching the bottom low-index passive waveguide. It not only performs the resonant coupling in such asymmetric waveguide coupler, but also locks the transferred power by the tapered structure.

InGaAsP/InP multiple quantum wells are used as active region of active waveguide. Based on the highly selective etching properties between InGaAsP and InP, the tapered active waveguide can be fabricated by a method, called selectively undercut-etching-active-region (UEAR), enabling the processing of narrow waveguide structure (up to submicron) by general wet etching on a large waveguide. It also leads to good microwave performance of waveguide. By taking this advantage, a SSC-integrated EAM can perform high-speed as well as low-insertion loss properties. A mode transfer efficiency of 70% is obtained in such SSC. By narrowing waveguide by UEAR, higher than 40GHz of -3dB electrical-to-optical (EO) response is attained in EAM.

7604-20, Session 4

The erasing phenomenon in the DBR laser diode with an outer gain section monolithically integrated at the grating side

Y. Liu, Y. Cheng, S. Liang, B. Wang, L. Zhao, W. Wang, Institute of Semiconductors (China)

It is found that the gain section monolithically integrated with a distributed Bragg reflector (DBR) Laser diode (LD) at the DBR side has an erasing effect on the distributed Bragg reflector when the Bragg wavelength and the LD gain curve peak are dismatched in our divice, which has an structure with a DBR section sandwiched by two gain sections. When the injection current of front gain section is fixed above the threshold current, the operation mode of the device can be varied by the working conditions of the other sections. As the injection current of the back gain section is low, the device still shows a DBR LD operation. However, when the injection current of the back gain section is increased above the threshold the device starts to show a FP LD operation and when the device works in the FP LD mode, if a negative bias voltage or a large injection current is applied to the grating section, the device will turn to the DBR LD operation again. So this phenomenon can be controlled so that the device can work either as a normal DBR LD or a Quasi-FP LD, and may have some potential use in future which is still in research. A model with equivalent grating approximate is proposed and the numerical calculation based on transfer matrix method and mode competition theory is also performed which can explain the experiment results very well.

7604-21, Session 5

Leaky mode resonance photonics: technology for biosensors, optical components, MEMS, and plasmonics

R. Magnusson, The Univ. of Texas at Arlington (United States)

Resonant leaky modes can be induced on dielectric, semiconductor, and metallic periodic layers patterned in one- or two-dimensional formats. Potential applications include bandpass and bandstop filters, laser mirrors, ultrasensitive biosensors, absorption enhancement in solar cells, security devices, tunable filters, nanoelectromechanical display pixels, dispersion/slow-light elements, and others. As there is now a growing realization worldwide of the utility of these devices, it is of interest to summarize their physical basis and present the attendant applicability in photonic devices and systems. In particular, we have invented and implemented highly accurate, label-free, guided-mode resonance biosensors that are being commercialized. The sensor is based on the high parametric sensitivity inherent in the fundamental resonance effect. As an attaching biomolecular layer changes the parameters of the resonance element, the resonance frequency changes. A target analyte interacting with a bio-selective layer on the sensor can thus be identified without additional processing or use of foreign tags. Another promising pursuit in this field is development of optical components including wideband mirrors, filters, and polarizers. We have experimentally realized such devices that exhibit minimal layer count relative to their classical counterparts. Theoretical modeling has shown that wideband tuning of these filters is achievable by perturbing the structural symmetry using nano/microelectromechanical methods. MEMS-tuned resonance elements may be useful as pixels in spatial light modulators, tunable lasers, and multispectral imaging applications. Finally, mixed metallic/

dielectric resonance elements exhibit simultaneous plasmonic and leaky-mode resonance effects. Their design and chief characteristics will be described.

7604-22, Session 5

High-speed optical filtering using active resonant subwavelength gratings

A. V. Gin, S. A. Kemme, R. R. Boye, A. R. Ellis, D. W. Peters, J. R. Ihlefeld, J. R. Wendt, L. H. Marshall, Sandia National Labs. (United States); T. R. Carter, Sandia Staffing Alliance, LLC (United States); S. Samora, LMATA Government Services LLC (United States)

In this work, we describe the most recent work towards the device modeling, fabrication, testing and system integration of active resonant subwavelength grating (RSG) devices. Passive RSG devices have been a subject of interest in subwavelength-structured surfaces (SWS) in recent years due to their narrow spectral response and high quality filtering performance. Modulating the bias voltage of interdigitated metal electrodes over an electrooptic thin film material enables the RSG components to act as actively tunable high-speed optical filters. The filter characteristics of the device can be engineered using the geometry of the device grating and underlying materials.

Using electron beam lithography and other specialized etch techniques, we have fabricated interdigitated metal electrodes on an insulating layer and BaTiO3 thin film on sapphire substrate. With bias voltages of up to 50V, spectral red shifts of several nanometers are measured, as well as significant changes in the reflected and transmitted signal intensities around the 1.55um band.

Due to their small size and lack of moving parts, these devices are attractive for high speed spectral sensing applications. We will discuss the most recent high-speed testing results as well as the system integration aspects of this project. The system components outlined will include the detector and preamplifier circuitry, high-speed voltage waveform generator and data capture setup.

7604-23, Session 5

Deep-subwavelength focusing and steering of light in an aperiodic metallic waveguide array

L. Verslegers, P. B. Catrysse, Z. Yu, S. Fan, Stanford Univ. (United States)

The study of waveguide array structures has been of fundamental interest in demonstrating optical analogues of semi-classical electron dynamics, as well as for numerous linear and nonlinear optics applications. Previous work has mainly focused on dielectric waveguide arrays. Here, we numerically demonstrate that an aperiodic metallic waveguide array consisting of subwavelength slits in gold can focus an incident plane wave into a single slit. We show that the behavior of this structure can be understood, predicted qualitatively and, to a large degree, even designed for, using Hamiltonian optics. In this focusing scheme, for an incident beam at a free space wavelength of , most of the incident power can be concentrated into a focal spot with a deep-subwavelength dimension that can be as small as /100 and with a focal distance that is several wavelengths long. In contrast to previous works on focusing in metallic waveguide arrays, which all use periodic structures, our aperiodic approach uses an incident wave that is neither amplitude nor phase modulated to focus the light with a structure that has a simple planar geometry. Moreover, we demonstrate that the focusing behavior can be controlled by changing either the incident wavelength, or the angle of incidence, thus providing the capability of nanoscale beam steering. These novel planar structures, with their ability to focus and steer over a wide range of wavelengths (from about 600 nm to beyond 4 μm), can find applications in wavelength division multiplexing, spectroscopy and lithography.

7604-24, Session 5

Application of resonant subwavelength gratings to a rotary position encoder

R. R. Boye, D. W. Peters, J. R. Wendt, R. J. Shul, Sandia National Labs. (United States); S. Samora, S. G. Rich, LMATA Government Services, LLC (United States); A. L. Lentine, R. A. Kellogg, Sandia National Labs. (United States)

Resonant subwavelength gratings (RSG) have proven to be excellent devices for producing narrow resonances useful for filtering applications. In this paper we discuss the use of RSGs in a rotary position encoder intended for use in harsh environments. To avoid problems with routing electrical signals to the encoder, a single fiber optic line is used to address the device with multiplexed wavelengths corresponding to position bits. Each wavelength has a corresponding RSG that is patterned in the appropriate position locations. A demonstration device utilizing RSGs with TiO2 and SiO2 films on a silicon substrate will be presented. The design and modeling effort provided several RSGs with resonances addressable by a single tunable laser source. Since multimode fiber is used to route the optical signals, the gratings were designed to be polarization insensitive. Additionally, the individual RSGs accommodate significant wavelength shifts to simplify the integration of the encoder system. The fabrication of the devices was based on electron beam lithography and details of this work will be presented. Measurements of the individual RSGs as well as a demonstration of the determination of rotary position using these gratings will be shown. Finally, future work including the extension of this demonstration to RSGs designed for fabrication directly on a titanium substrate will be discussed.

7604-25, Session 5

Mechanical-strain tuned polymer Bragg reflectors for the tunable laser application

K. Kim, M. Oh, J. Kim, Pusan National Univ. (Korea, Republic of)

A tunable wavelength laser with an external feedback is demonstrated based on strain tuning of the flexible Bragg reflection waveguide. By the feedback of the Bragg reflection wavelength from the polymer Bragg reflector into broadband light source, a certain wavelength is raised. The highly elastic property of flexible polymer device enables direct tuning of Bragg reflection wavelength by controlling the imposed strain, and provides much wider tuning range than the silica fiber Bragg gratings or the thermooptic tuned polymer devices. By compressing and stretching the flexible polymer device, the Bragg reflection wavelength is tuned continuously over 80 nm. The external feedback laser based on the flexible Bragg grating wavelength filter is characterized over a 65 nm tuning range from 1509 nm to 1574 nm for the tensile and the compressive strain which is induced approximately 20,000 μ , respectively.

7604-26, Session 6

Towards nonlinear photonic wires in lithium niobate

H. Hu, L. Gui, R. Ricken, W. Sohler, Univ. Paderborn (Germany)

The development of wafer-scale (up to 3`` diameter) smart-cut lithium niobate (LN) single-crystal films is reported. The fabrication method is similar to the smart cut process widely used for silicon-on-insulator (SOI) fabrication. A Z-cut LN sample, implanted by 250 keV He ions, is crystal-bonded to a SiO2 layer of 1.8 μm thickness deposited by plasma enhanced chemical vapour deposition (PECVD) on another Z-cut handle sample. The bonded pair of samples splits along the He-implanted layer by annealing leaving a single crystal LN film of 900 nm thickness on top of the SiO2/LN substrate.

Such “LNOI” wafers are an ideal platform to develop waveguides of

high refractive index contrast and of (sub-) micro¬meter cross section dimensions (“photonic wires”). They are fabricated by Argon-ion beam milling with an etch rate of 7.6 nm/min; photo-resist stripes serve as etch masks. Such waveguides allow a further device miniaturization, e.g. of modulators, and a high integration density due to small bending radii.

LN photonic wires are of particular interest for nonlinear integrated optics. Due to a high guided mode intensity, most efficient nonlinear interactions result. E. g., a (2) wavelength conversion efficiency can be expected which surpasses that of conventional (e.g. Ti-doped) waveguides by more than one order of magnitude. However, to exploit the largest nonlinear coefficient and to allow quasi-phase matching (QPM), periodic poling (PP) of the waveguides is necessary. Therefore, novel “local” poling techniques are currently developed.

7604-27, Session 6

Silicon-organic hybrid nanophotonics

M. Hochberg, T. W. Baehr-Jones, Univ. of Washington (United States)

Silicon is the most important material in the world for building electronics, and the silicon platform gives access to nanoscale feature sizes at extraordinarily low cost. In the past few years, it has become clear that silicon is also an ideal material system for controlling light on the nanoscale. Silicon photonics is a very rapidly evolving field, and we’re now witnessing an explosion of second-generation applications for this technology that reach beyond simply transmitting and receiving digital data. We will present recent work on integrating ultrafast nonlinear optical polymers into the silicon platform, in order to create systems where light can be used to manipulate light. The combination of the nanoscale features available in silicon with the very high activity nonlinear polymers opens the possibility of creating significantly enhanced all-optical and electrooptic devices.

7604-28, Session 6

Electro-optic modulation in optical waveguides written by quasi-solitonic propagation in doped photopolymers

H. Ibn El Ahrach, Institut de Physique et Chimie des Matériaux de Strasbourg (France); S. Kamoun, A. Jemal, Ecole Nationale Supérieure de Chimie de Paris (France); J. Vola, L. Mager, A. F. Fort, Institut de Physique et Chimie des Matériaux de Strasbourg (France)

The Light Induced Self Written (LISW) waveguide propagation in photopolymerizable materials has allowed the fabrication of permanent optical waveguides with lengths up to a few millimetres. This process has been applied to the fabrication of tips for Scanning Near Field Microscopy (SNOM) or to the connexion of optical fibers and integrated optical waveguides (SOLNET process). The great advantage of this technique is that the connexion problem is greatly simplified. Up to now, the demonstrated devices have only been passive ones. But, the photopolymerizable material can be easily functionalized by the simple addition of small molecules with specific properties (fluorescence, non linear optical responses...). It is therefore possible to insert an arbitrary function in an optical circuit by through a proper formulation of a connecting part and then built an active device. We present here the functionalization of the LISW waveguide by 4’-n-pentyl-4- cyanobiphenyl (5CB). This molecule is a nematic precursor, but here the amount of 5CB as been kept in the solubility limits to avoid phase separation and light diffusion. The molecule exhibits a permanent dipole and a linear polarization anisotropy enabling the modulation of the guest/host material birefringence by the application of an electric field. The efficiency of the material and the performance in terms of phase modulation are measured in an interferometric setup. This demonstration of phase modulation opens the path to other devices such as TE-TM mode converters and polarization based electro-optic intensity modulators.

7604-29, Session 6

High-density integrated optics in ion-sliced lithium niobate thin films

G. Poberaj, M. P. Koechlin, F. Sulser, P. P. Gunter, ETH Zürich (Switzerland)

For very-large-scale integration of photonic devices compact electro-optical modulators, switches, and wavelength division multiplexers have to be realized. Optical microring resonators and photonic bandgap structures have been proposed for these applications. In one of our approaches we have developed an improved method for the reproducible fabrication of sub-micrometer thick $LiNbO_3$ films with an area of several cm^2. This method exploits the controlled exfoliation of He^+ implanted thin layers from a bulk $LiNbO_3$ crystal (crystal ion slicing) supported by wafer bonding using an adhesive polymer benzocyclobutene (BCB). The $LiNbO_3$/BCB composites have a high refractive index contrast ($\Delta n=0.65$). They possess chemical inertness and mechanical stability allowing further processing steps like lithographic structuring, dicing, and chemical-mechanical polishing. All these properties make the fabricated $LiNbO_3$ thin films very attractive as a platform for photonics chips.

We have realized a high-resolution laser lithography system for fast prototyping of integrated optics devices. We realized electro-optically tunable microring resonators in $LiNbO_3$ thin films with a free spectral range of 7 nm, a quality factor of 10’000, and a tunability of > 1 pm/V at wavelengths around 1.55 µm. Combining the laser lithography patterning and focused ion beam milling we have fabricated also first planar photonic crystal structures in ion-sliced $LiNbO_3$ thin films. Triangular lattices of holes with a diameter of 240 nm and a separation of 500 nm exhibit a photonic bandgap with an extinction ratio of 15 dB in the telecom wavelength range.

7604-30, Session 7

Tg: the reversible door to fabrication of novel glass photonic devices and integrated circuits

A. B. Seddon, D. Furniss, Z. G. Lian, W. J. Pan, T. M. Benson, The Univ. of Nottingham (United Kingdom)

Tg (the glass transition) is the key advantage glasses have over crystalline materials for fabrication of photonic devices. Heating the glass above Tg to access the supercooled liquid temperature region allows shaping. Cooling back through Tg allows the shaping to be retained. Novel glasses may be shaped from the micro-scale to the nano-scale: for photonic signal transmission and processing to photonic crystal arrays for dispersion management. Hence Tg is a reversible door to fabrication of novel glass photonic devices and integrated circuits. This paper will illustrate this claim by reviewing our recent work on hot embossing to make novel glass waveguides and other photonic devices.

7604-31, Session 7

Fabrication and optimization of Tantalum pentoxide waveguides for optical micropropulsion

B. S. Ahluwalia, O. G. Hellesø, Univ. of Tromsø (Norway); A. Z. Subramanian, N. M. B. Perney, N. P. Sessions, J. S. Wilkinson, Univ. of Southampton (United Kingdom)

Design, fabrication and optimization of high refractive index (2.1 @ 1070 nm wavelength), sub-micron thickness (200 nm) Tantalum Pentoxide (Ta_2O_5) waveguides is reported. Optimization of fabrication parameters reduces the propagation loss to ~ 1dB/cm @ 1070 nm for Ta_2O_5 waveguides. Tantalum pentoxide waveguides were found to be stable for high power applications with no significant absorption peaks over a large range of wavelengths (600-1700 nm). Based on its high refractive index contrast and sub-micron thickness Ta_2O_5 waveguides provide high intensity in the evanescent field. These combinations are useful for efficient optical propelling of micro-particles. Tantalum pentoxide waveguide is reported to propel micro-particles (8 micron in diameter) with velocity higher than previously reported (50 μ/s) with the guided power of only 20mW. Different designs of Tantalum pentoxide waveguides rib and strip structures were fabricated to compare their potential for optical guiding of particles.

7604-32, Session 7

Fabrication of buried-type waveguide with optical gates by nano-ion-exchange method

T. Yano, E. Shokatsu, H. Segawa, S. Shibata, Tokyo Institute of Technology (Japan)

Buried-type optical waveguide with blanches for the gate of optical signals was fabricated by nano ion-exchange method using the probe of atomic force microscope (AFM) as an electrode. 2-step procedure of the electric field-assisted Ag/Na-ion exchange (using the Ag metal film prepared by photolithography) followed by K/Na one (using the organic-inorganic hybrid electrolyte) was applied to prepare the waveguide structure inside the glass substrate (core dimension: 30 μmW x 5 μmH, n=1.61(core), 1.505-1.523(clad)). Pt-coated AFM probe as a cathode was attached to the glass surface of the waveguide which had Ag metal as an anode on the back side, and applied DC voltage to extract Ag^+ ions in the core. Ag^+ ions underneath the probe were partially drawn towards the glass surface, where the amount of the drawn Ag ions was controlled by monitoring the electric current through the probe. The protruding high index regions from the core towards the glass surface were examined how they work as the optical gate by introducing the light signal with the wavelength of 700-850 nm from Ti:sapphire laser into the waveguide. Emitted light from the gates was observed and their intensities were evaluated. The gate prepared by 1nC treatment permitted the passage of 700nm light but prohibited one of 850 nm light.

7604-33, Session 7

Refractive index engineering by fast ion implantations: a generic method for constructing multicomponents electro-optical circuits

A. J. Agranat, A. Gumennik, H. Ilan, The Hebrew Univ. of Jerusalem (Israel)

Refractive index engineering (RIEng) by ion implantations in electrooptical substrates is a generic methodology for constructing multi-component integrated circuits of electrooptic and nanophotonic devices with sub-wavelength features operating in the visible - near IR wavelengths. RIEng exploits the fact that ions that are incident at high energies on a substrate of oxygen Perovskites form within the depth of the substrate a well confined layer of Frenkel defects which cause the layer to be partially amorphized. The refractive index in this layer differs significantly from that of the crystalline substrate. The essence of the method is to perform spatially selective implantations for sculpting complex 3D pre-designed patterns with reduced refractive index within the volume of the substrate.

Sculpting 3D structures is enabled by combining three techniques that form a complete toolbox for constructing the circuits: (i) Lateral patterning: defining the lateral distribution of the amorphization by performing the implantation through a “stopping mask” which causes the amorphized region to replicate the contour of the topography of the mask; (ii) Longitudinal patterning: determining the depth of the amorphized region by controlling the energy of the implanted ions; and (iii) Selective etching: selective etching of the amorphized material that were created by the implantation process.

A number of devices that were constructed in a substrate of potassium lithium tantalate niobate will be described, including an optical wire, a channel waveguide array, and a ring resonator. It will also be shown that the devices are thermally stable after being subjected to an annealing process.

7604-34, Session 7

Highly photorefractive Eu^{3+} activated sol-gel SiO_2-SnO_2 thin film waveguides

S. Berneschi, Istituto di Fisica Applicata Nello Carrara (Italy); S. N. B. Bhaktha, Lab. de Physique de la Matière Condensée (France); A. Chiappini, A. Chiasera, M. Ferrari, Istituto di Fotonica e Nanotecnologie (Italy); C. Kinowski, S. Turrell, Lab. de Spectrochimie Infrarouge et Raman (France); C. Trono, M. Brenci, I. Cacciari, G. Nunzi Conti, S. Pelli, G. C. Righini, Istituto di Fisica Applicata Nello Carrara (Italy)

Rare-earth activated optical waveguides today represent a key structure in many commercial devices for communications and sensing. Among all the fabrication processes used in technology, UV laser writing in photorefractive materials gained an ever-growing interest due to its simplicity and relatively low cost. Even if germanium ions were the most used elements as photosensitive dopants in silica materials, tin ions represent a promising alternative because many devices, such as Bragg gratings, present a higher thermal stability in this matrix rather than in germanium-silica network.

Here we report on the photorefractive properties of tin-silica slab waveguides. Europium was introduced as a rare-earth and an optical probe of the glass structure. The thin films were deposited on vitreous-SiO_2 by means of a sol-gel route and dip-coating technique. The basic composition of the amorphous binary systems was 75 SiO_2 - 25 SnO_2 mol% and they were activated by 1 mol% of Eu^{3+} ions[1]. The optical characterization of the guiding structures pointed out low propagation losses (around 0.5 dB/cm at 633 nm) and a high refractive index modulation, as large as - 1.5 * 10-3 under the UV irradiation of a KrF excimer laser source at l = 248 nm, suitable for the writing of waveguide gratings.

[1] S.N.B. Bhaktha, F. Beclin, M. Bouazaoui, B. Capoen, A. Chiasera, M. Ferrari, C. Kinowski, G.C. Righini, O. Robbe, S. Turrell, “Enhanced fluorescence from Eu^{3+} in low-loss silica glass-ceramic waveguides with high SnO_2 content”, Appl. Phys. Lett. 93, 211904-1 - 211904-3 (2008).

7604-35, Session 8

Enhanced fluorescence sensing by nano-apertures

S. Blair, The Univ. of Utah (United States)

The next generation of molecular diagnostics tools (e.g. microarrays, sequencing systems) are targeted to have single molecule sensitivity. Surface-enhanced fluorescence can be a key enabling factor in achieving this goal. Large-scale arrays of apertured plasmonic structures, in particular, meet the requirements of enhanced fluorescence and background isolation, along with compatibility with existing instrumentation and surface chemistry. The simplest such embodiment is an array of sub-wavelength apertures in a metal film, with which fluorescence enhancement was demonstrated first using Au. We have also been working with structures in Al, which provide more balanced enhancement throughout the visible spectrum, opening up a wider range of applications. Significant fluorescence enhancements can be obtained using commercial two-color microarray scanners, consistent with calculations. Tuning of the relative enhancements can be accomplished by adjusting the shape of the apertures.

7604-36, Session 8

Realization of a compact static Fourier transform spectrometer in glass integrated optics

B. Martin, Institut de Microélectronique Électromagnétisme et Photonique (France) and MINATEC (France); A. Morand, Institut de Microélectronique Électromagnétisme et Photonique (France); L. Jocou, Lab. d'Astrophysique de l'Observatoire de Grenoble (France); G. Grosa, Institut de Microélectronique Électromagnétisme et Photonique (France); P. Y. Kern, Lab. d'Astrophysique de l'Observatoire de Grenoble (France); P. Benech, Institut de Microélectronique Électromagnétisme et Photonique (France); E. P. Le Coarer, Lab. d'Astrophysique de l'Observatoire de Grenoble (France)

For analysing the proprieties of optical light emitted, reflected or scattered, we often use spectrometers. In the last years, researches were focused on compact spectrometer in order to be easily used. They are actually composed of different optical components which are either dispersive grating or moveable mirror. Here, the realization and characterization of the leaky loop integrated Fourier transform spectrometer (LLIFTS) in glass integrated optics are described. The objectives are to obtain a compact component also with no moveable parts and costless. The principle of the LLIFTS lies on a two-beam interferometer in planar design using a leaky loop waveguide structure. The light leaking from the bend waveguide in the loop is coupled in a plane waveguide of few centimetres long. This radiated part induces an interference pattern at the end of the component. The optical spectrum is then obtained after an inverse Fourier transform of the interference pattern. Thanks by the loop radius, the gap evolution between the plane waveguide and the loop, the leaky loop structure has the advantage of controlling the shape of the interference pattern. The LLIFTS has been realized using the Silver/Sodium ion exchange technology which only requires a single lithography step. A mask has been designed considering a numerical model recently developed. Interference patterns have been measured in the wavelength range from 1500 and 1630 nm. Wavelength resolution of 11 nm has been reached with a 2.1 cm plane waveguide long. Measurement results with monochromatic and polychromatic optical sources are shown.

7604-37, Session 8

Design of metamaterial-based photonic sensors for pressure measurement

R. Aylo, P. P. Banerjee, Univ. of Dayton (United States); A. K. Ghosh, P. Verma, Univ. of Oklahoma (United States)

Transmission and reflection spectra of periodic and random stacks comprising positive index materials and metamaterials have been extensively studied [Aylo et al, SPIE Proc. 7029 (2008), SPIE Proc. 7392 (2009)]. We have shown that for photonic crystal structures, comprising periodic alternating layers of double negative index and positive index materials, one may expect an additional unique transmission bandgap (reflection bandpass), which does not depend on the incident angle. Random stacks of positive and negative index materials have also been studied with a view to identifying the bandgap, and possible extension to homogeneous structures, such as liquid crystals doped with nanoparticles. In this paper, we investigate the effectiveness of periodic stacks of postive and negative index materials for sensing of pressure. Both TE and TM incidence are investigated, as well as periodic stacks comprising double or single negative index materials along with positive index materials. Realistic dispersion relations for the permittivity and permeability of the metamaterials are chosen. A figure of merit is defined to characterize the sensitivity of these sensors, and its dependence on initial layer thickness, number of layers, etc., is studied. The optimum design and the tolerance of such a sensor system are investigated.

7604-38, Session 8

Fiber-based optical Fabry-Pérot gas sensor for fast and on-column detection

J. Liu, Y. Sun, X. Fan, Univ. of Missouri, Columbia (United States)

A versatile, compact, and sensitive fiber-based optical Fabry-Pérot (FP) gas sensor is described in this paper. The sensor probe is composed of a silver layer and a vapor-sensitive polymer layer that are sequentially deposited on the cleaved fiber endface to form an FP cavity. The interference spectrum generating from the reflected light at the silver-polymer and polymer-air interfaces changes upon the absorption of gas analytes. This structure enables using any polymer as sensing layer, regardless of the polymer refractive index (RI), which significantly enhances the sensor versatility. Two kinds of polymers of polyethylene glycol (PEG) 400 (RI=1.465-1.469) and Norland Optical Adhesive (NOA) 81 (RI=1.53-1.56) are used as the gas sensing polymer in the experiment, and show drastically different sensor response to various gas analytes. In addition, we demonstrate the potential of the proposed FP sensor to be developed as micro-gas chromotgraphy (GC). In experiment, we incorporate the FP sensor with commercially available GC system and carry out on-column detection, by inserting the sensing probe of the FP sensor into a hole drilled on the wall of the capillary, which is connected to the GC injection port through the GC column. The FP sensor exhibits fast detection within several seconds, and the estimated detection limit can be as low as several nano-grams.

7604-39, Session 8

Stationary wave integrated Fourier transform spectrometer (SWIFTS)

J. Ferrand, Lab. d'Astrophysique de l'Observatoire de Grenoble (France); G. Custillon, Ecole Nationale Supérieure d'Electronique et de Radioélectricité de Grenoble (France); G. Leblond, Univ. de Technologie Troyes (France); F. Thomas, T. Moulin, E. Le Coarer, Lab. d'Astrophysique de l'Observatoire de Grenoble (France); A. Morand, Institut de Microélectronique Électromagnétisme et Photonique (France); S. Blaize, Univ. de Technologie Troyes (France); A. Cheli, Lab. d'Astrophysique de l'Observatoire de Grenoble (France)

The size and the weight of current spectrometers is a serious issue regarding various applications, however the technologies used in existing spectrometers they prevent them from substantial improvement. SWIFTS (Stationary Wave Integrated Fourier Transform Spectrometer) is a new family of spectrometers based on a very promising technology. It is an original way to fully sample the Fourier interferogram obtained in a waveguide by either a reflection (SWIFTS Lippmann) or counter-propagative (SWIFTS Gabor) interference phenomenon. The sampling is simultaneously done without any moving part thanks to "nano-detectors" located in the evanescent field of the waveguide. It allows a dramatic reduction of the size and the weight of spectrometers while conserving, even improving, their performances.

Here, we present the development status of this new kind of spectrometers and the first results obtained with existing technical solutions for the "nano-detectors" in visible and near infrared.

7604-40, Session 8

Integrated optical chip in fiber optic gyros

V. P. Chunduru, V. Ramisetty, Osmania Univ. (India)

Fiber optic gyroscope is an important development in the field of fiber optic sensors. It is now considered an alternative technology to the mechanical and laser gyroscopes for the inertial guidance and control applications. The advantages of FOG over mechanical gyroscopes

are many like instantaneous operation, wide dynamic range, no g-sensitivity, maintenance free, and capability to withstand high shock and vibration and so on. The advantages over laser gyroscopes includes cost effectiveness, light weight, low power consumption and improved ruggedness. The optical gyroscope principle was first demonstrated by Sagnac in 1913. Optical gyroscopes implemented so far use Sagnac effect, which states that an optical path difference induced by counter propagating beams in a rotating reference frame is proportional to the absolute rotation. Fiber optic gyroscope is a completely static, pure optical gyroscope, with a high resolution and other advantages. In order to make the Fiber optic gyroscope be smaller in size, more reliable and sensitive, this paper presents a new type of interference integrated optical chip

The main requirement of a FOG is perfect reciprocity, i.e. in the absence of rotation, the counter propagating beams inside the fiber must travel identical paths thus resulting in zero phase shift. The phase shift in a Sagnac interferometer not only comprises of a non-reciprocal sources that set practical performance limits. These non-reciprocal sources generate random time varying output resulting in a bias drift even under zero rotation rates, which causes serious problems in present day gyroscope. In a FOG the reciprocal configuration ensures the bias stability, signal processing is used to obtain maximum sensitivity, a broad band source is used to eliminate the effect of back scattering, polarization coupling and Kerr effect and the closed loop operation is used to linearize the scale factor and improve its stability.

7604-41, Session 9

Extreme-parameter plasmonics

N. Engheta, Univ. of Pennsylvania (United States)

In this talk, I discuss the merging of two phenomena, namely, the extreme-parameter metamaterials with the plasmonic optics. Each of these fields has seen unprecedented developments in recent years. The field of plasmonic optics deals with interaction of electromagnetic waves with metallic nanostructures and metallic surfaces, in which the collective oscillation of conduction electrons couples with the optical signals, resulting in enhancement and confinement of optical fields. It is well known that in such structures surface plasmon polaritons (SPP) can be developed as a surface wave along the interface between the noble metals and dielectric regions. Such SPP guided waves possess wave numbers that are larger than the free space wave numbers, and thus their apparent wavelength along the interface is shorter than that of the free space. This is one of the attractive features of SPP waves in plasmonics optics, since it provides the opportunity for the confinement and subwavelength variation of optical fields. In other words, the shorter the apparent SPP wavelength, the better. The field of metamaterials also offers a variety of exciting features and characteristics. Metamaterials are composite structures with unconventional material parameters that are not readily available in nature. In the field of metamaterials, negative-index metamaterials (NIM) have received most attention in recent years in engineering and physics communities. However, other classes of metamaterials may also possess exciting features. Among those, one can mention materials with extreme values for relative permittivities (or permeability), e.g., epsilon-near-zero (ENZ) or epsilon-very-large (EVL) materials. Some of these materials are available in nature, for example SiC around 10.3 microns possesses near zero permittivity, and others may be designed and engineered as metamaterials in order to have effective permittivity near zero at desired frequencies. Such epsilon-near-zero (ENZ) materials may offer new possibilities for the design of novel devices and components in microwave and optical frequencies. In ENZ materials, the refractive index is near zero, resulting in essentially uniform phase and very long apparent wavelengths for electromagnetic waves in such media. Here in ENZ materials, in contrast with SPP waves along plasmonic surfaces, the wavelength in the medium is very long. We have been interested in exploring the merging of these two seemingly opposite features, by combining ENZ metamaterials that can support very long wavelengths with the SPP waves in plasmonic optics that can exhibit shorter wavelengths. Such “ENZ-based plasmonics”, or “extreme-parameter plasmonics” can lead to exciting results in supercoupling and anomalous tunneling, novel optical interconnects, molecular emission enhancement, unusual Purcell effects for extended plasmonic waveguides, and optical nanocircuit boards for metactronics, to name a few. In this talk, I give an overview of some of our recent work in these areas.

7604-42, Session 9

Experimental characterization of dispersion in plasmonic nanostripes for integrated DNA sensing

P. Steinvurzel, T. Yang, K. B. Crozier, Harvard Univ. (United States)

Rectangular metal stripes for which both cross-sectional dimensions are on the nanoscale support plasmonic modes with strongly confined fields. The guiding regions of these structures are not along the flat edges, as in conventional plasmon strip waveguides, but at the corners. Plasmonic nanostripe modes have been proposed as the illumination source in microfluidic direct linear analysis of DNA, where fluorescently labeled DNA strands can be interrogated by flowing over the stripe. In a waveguide coupled geometry, the stripe provides both excellent dark-field illumination, suppressing background noise, and high field localization, enabling better spatial resolution and discrimination of multiple tag sites. In this work, we experimentally fabricate arrays of such stripes on glass substrates in order measure their optical properties. Using a prism coupled geometry, we experimentally characterize the dispersion of plasmon modes in 50-150 nm wide metal stripes at a glass/water interface. Our measured data are verified by numerical simulations. Since the corners of the stripe provide mode guidance, we model the effects of having rounded corners, as well as cross-sectional and axial non-uniformities, and compare these with the morphological imperfections of our fabricated stripes as characterized by atomic force microscopy. We also investigate how the stripe design affects the strength, center wavelength, and bandwidth of the plasmon mode excitation in a when coupled to a diffused ion channel waveguide.

7604-44, Session 9

Nanoplasmonic couplers and modulators based on metal-insulator-metal structures

Z. Lu, R. Yang, R. A. Wahsheh, M. A. G. Abushagur, Rochester Institute of Technology (United States)

Plasmonics studies surface waves propagating on the interface between metal and insulator. From the theory of surface plasmons (SP), subwavelength structure can support propagation mode with negligible radiation loss. Metal-insulator-metal (MIM) configuration is an important example of plasmonic waveguide, which can achieve both deep-subwavelength field confinement and acceptable loss for integrated optics application. Recently, two-dimensional direct-coupling has been proposed to effectively convert power between optical and plasmonic modes, predicting highly compactable nanoplasmonic couplers working in broadband for on-chip optical circuits. Here we demonstrate a “slot-to-slot” direct coupling scheme by conventional semiconductor fabrication methods. The novel extension of direct-coupling, which introduces a dielectric slot inside a dielectric waveguide, is firstly studied by 2D FDTD simulation. 70% coupling efficiency is obtained when a dielectric slot mode (optical) is coupled into a 1-micron long plasmonic slot waveguide and then back to dielectric slot mode. The 2D model is then modified to fit into a 3D quasi-MIM prototype that can be easily demonstrated, for which 47% coupling efficiency is achieved through FDTD simulation. Based on a silicon-on-insulator platform, a two-stepped fabrication process is developed with e-beam lithography and thin-film lift-off. By normalizing the output power of the plasmonic coupler to a bare silicon slot waveguide, 36% coupling efficiency is achieved when the device (with 500-nm-long quasi-MIM) is probed by 1520-nm laser. We are currently investigating how the output would be modulated when the device is pumped by visible light to change the optical property of metal.

7604-47, Session 9

Guided subwavelength optical mode with slow group velocity supported by a periodic plasmonic waveguide

L. Yang, C. Min, G. Veronis, Louisiana State Univ. (United States)

We introduce a periodic plasmonic waveguiding structure which supports a guided subwavelength optical mode with slow group velocity at a tunable wavelength range and with a tunable slowdown factor. The structure consists of a metal-dielectric-metal (MDM) waveguide side-coupled to a periodic array of MDM stub resonators. Both the MDM waveguide and MDM stub resonators have deep subwavelength widths. We show that such a structure supports a guided optical mode with slow group velocity. The wavelength range in which slow light propagation is achieved can be tuned by adjusting the MDM stub resonator length and the periodicity of the structure. We also show that the slowdown factor increases as the periodicity of the structure decreases, and that light can be slowed down by several orders of magnitude. We find that there is a tradeoff between the slowdown factor and the propagation length of the supported optical mode. In addition, for a given slowdown factor and operating wavelength, the propagation length of the optical mode in the periodic plasmonic waveguide is much larger than the propagation length of the mode supported by a conventional MDM waveguide, in which the slowdown factor can be tuned by adjusting the dielectric layer width. Finally, we show that light can be coupled efficiently from a conventional MDM waveguide to such a periodic plasmonic waveguide. Such slow-light plasmonic waveguides could be potentially used in nonlinear and sensing applications. We use a characteristic impedance model and transmission line theory to account for their behavior.

7604-43, Session 10

Efficient sensitivity analysis of surface plasmon waveguide structures

M. A. Swillam, M. H. Bakr, X. Li, McMaster Univ. (Canada)

We propose a novel approach for efficient sensitivity analysis and design optimization of Surface Plasmon Polaritons (SPPs) -based waveguide structures. Using our approach, from one simulation only, the response and the sensitivity of this response with respect to all the design parameters can be obtained regardless of their number. This approach has been utilized to analyze and propose novel designs of different structures.

It has been exploited to design a novel SPP metal waveguide loaded on silicon on insulator (SOI) for subwavelength applications. In this design, the material is utilized due to its wide application in electronic circuits. It also allows for strong guiding and hence subwavelength light confinement. The utilized metal is gold (Au) at a wavelength of 1.55 m. The effect of the different design parameters of this structure on the propagation length of the fundamental TM mode is efficiently studied using the proposed approach [1]. The imaginary distance 3D ADI BPM is utilized to calculate the propagation length. The sensitivity information is then estimated using the adjoint variable method without any additional simulations.

The same approach is also utilized to propose an optimized design of new 1x3 SPP power splitter/combiner using metal on insulator. In this design, the multimode interference phenomenon is utilized. In this design, the target is to minimize the insertion loss for practical applications. The optimized design has both a low insertion loss of 1.5 dB and a compact size.

[1] M. A. Swillam, M. H. Bakr, and X. Li, “Efficient 3D sensitivity analysis of surface plasmon waveguide structures,” Optics Express, vol. 16, no. 21, pp. 16371-16381, Oct. 2008.

7604-45, Session 10

Optimal plasmonic focusing through matching plasmonic lens structure to illumination conditions

Q. Zhan, W. Chen, Univ. of Dayton (United States); D. C. Abeysinghe, Univ. of Cincinnati (United States); R. L. Nelson, Air Force Research Lab. (United States)

As a wave phenomenon, surface plasmon polaritons (SPPs) can be focused using metallic plasmonic lens structures. This allows the generation of strongly localized plasmonic field in a controllable manner. Combined with its strong field enhancement, focused SPPs may find applications in more efficient coupling for plasmonic circuits, local electromagnetic field concentration, high resolution imaging, biochemical sensing and thin film characterization etc. The challenges are to optimize the focus shape, size and strength. In this talk, I will present our recent works to achieve optimal plasmonic focusing by matching the plasmonic lens structure to illumination beam properties, especially the spatial polarization distribution across the beam profile. It is known that surface plasmon excitation has strong dependence on the state of polarization of the incident photons. This polarization sensitivity leads to the interesting possibility of spatially engineering the state of polarization across the laser beam in order to match to the plasmon coupling condition so that optimal plasmonic excitation can be achieved. Specific examples using linear polarization, circular polarization and radial polarization will be shown with their matching plasmonic lens structures. Both numerical modeling and experimental confirmation of the optimal plasmon focusing will be presented. Potentail applications of these plasmonic focusing structures will be discussed.

7604-46, Session 10

Manipulation of near-field polarization and locations by far-field excitation

S. Chen, A. A. Lazarides, Duke Univ. (United States)

Metal nanoparticle assemblies of designed structure are investigated as substrates for polarization manipulation in the near field region. Gold nanoparticles are known for their optical response due to the excitation of surface plasmons. Surface plasmons in coupled particles can strongly modulate light either in the far or near field region. The most common near field application of coupled particles is as field enhancing substrates for amplifying signals of molecules, for example, Raman signals, IR signals or fluorescence signals. However, the capabilities of metal nanoparticle assemblies can be extended beyond field amplification. Groups of particles can function as small antennas which convert far field excitation into localized fields with specific polarization. Through simulations we demonstrate that the near field polarization can be controlled through suitable design of nanoparticle configuration. The amplified near field with controlled polarization can be switched on and off by only changing the polarization of the excitation. The benefit of this configuration is that no probe excitation or other localized excitation is needed. The far field signal is converted into specific spots with designed polarization, which is not necessarily the same as excitation. Polarization is manipulated through coupling of different surface plasmon modes. This polarization control extends down to the few nanometer scale and may be applied to integrated plasmonic circuits where the far field signals are converted and transported into specific near field regions in which the polarization is modulated.

7604-48, Poster Session

Detailed observation of optical intensity and frequency signal transmission in random metal-dielectric film

M. Fukuda, K. Yamaguchi, Toyohashi Univ. of Technology (Japan)

A novel random metal-dielectric film structure has been proposed and its optical signal transmission properties have also been experimentally confirmed [1]. The random metal-dielectric film was composed of silver paste and submicron-sized fused silica balls with diameters ranging from 300 to 1000 nm. In the film, silica balls were randomly embedded in silver.

In this paper, we present some new experimental AM- and FM-signal transmission results in detail. The FM-signal transmission was carried out in a 40-nm-thick random metal dielectric film, where no direct propagating light was monitored with an infrared camera. This optical power confinement within the film is important to reduce back ground optical noise induced by the direct transmission (or leak) light for OEIC applications. The modulated light emitted from a 1550-nm-band laser diode was incident to the film. The optical near field, which is generated at the film surface by the light transmitted in the film, was coupled into an optical fiber probe, and then mixed with light from a local oscillator for optical heterodyne detection. The AM-FM side-bands corresponding to the various modulation signals were clearly monitored on the both side of beat spectra. The peak intensity of each side-band was nearly determined by FM- and AM-modulation component in laser cavity. From these results, we confirmed that AM- and FM-signals can be transmitted through the film without any distortion.

[1] M. Fukuda. et al., IEEE Photon. Technol. Lett., vol. 20, no. 8, pp. 590-592, April 2008.

7604-49, Poster Session

Lowloss plasmonic sharp splitter and bend

Z. Shi, V. Kochergin, Luna Innovations, Inc. (United States)

Plasmonic waveguides have potential applications in large-density optical integrated circuits and optical interconnections for high-speed chip communications. In this paper we presented the numerical simulation results of very sharp plasmonic splitters and bend for silver-dielectrics-silver plasmonic waveguides using finite-element analysis in Comsol. The simulated plasmonic waveguide has a width of 100nm. The simulation results show that sharp plasmonic splitter and bend have very low insertion losses at NIR wavelength regime, which has not been observed in conventional dielectric waveguides. The unique transmission performance offered by the plasmonic splitters and bends will find themselves many new applications in the optical integrated circuits and the optical interconnections.

7604-50, Poster Session

Label-free biosensors with enhanced sensitivity based on polymer waveguide Bragg reflectors

J. Kim, K. Kim, M. Oh, Pusan National Univ. (Korea, Republic of)

Label-free biosensors based on polymeric waveguides with Bragg reflection grating are demonstrated for the purpose of the highly sensitive protein detectors. Due to the unique processibility of the polymers in terms of nano-imprinting and the injection molding, the polymer waveguide devices has large potential to provide cost-effective solution for the disposable biosensors as long as robust immunoassay process is developed which is compatible with the polymer devices. Fluotinated polymer materials with the lowest refractive index, which is close to that of the saline solution, is incorporated for the sensor waveguide in order to increase the effective index modulation efficiency. The large contrast waveguide consisting of low index polymer exhibits enhanced sensitivity of detecting cover index variation by 1.9 times compared to the small contrast sensors. The Bragg reflectors with a 3-dB bandwidth of 0.9 nm was fabricated by using a laser interferometry and a dry etching of core layer by 50 nm. For the quantitative analysis of the capture antibody immobilization protocol, a colorimetric method using an amine linkable chromophore molecule is investigated, and then the density of amin groups binding with immobilized receptor is found to be 2.5 groups/nm2. The immunoassay experiment detecting the concentration of anti-biotin is performed by measuring the peak wavelength shift of the Bragg reflection sensors. By using blocking buffer, it is possible to obtain stable saturated output signal by preventing the nonspecific binding. In the experiment to measure the anti-biotin concentration, the sensor exhibited logarithmic response for the lower concentration less than 100 nM and a linear response for the higher concentration.

Conference 7605: Optoelectronic Integrated Circuits XII

Wednesday-Thursday 27-28 January 2010 • Part of Proceedings of SPIE Vol. 7605

Optoelectronic Integrated Circuits XII

7605-01, Session 1

Hybrid organic-inorganic photonic bandgap structures for lasing and switching applications

R. F. Mahrt, T. Stoeferle, S. Schoenenberger, N. Moll, IBM Zürich Research Lab. (Switzerland); T. Wahlbrink, J. Bolten, AMO GmbH (Germany)

All-optical signal processing and short distance optical interconnects are gaining enormous interest due to the steady increase of bandwidth demand in telecommunication and IT industries. The required level of opto-electronic integration demands small form factor device structures and new materials with highly nonlinear optical properties. If successful, lasers and switches based on hybrid organic-inorganic materials could become important due to their integration potential on arbitrary substrates.

Here, we present the design of an optimized mixed-order photonic crystal structure for lasing/switching applications. The lasing properties of this two-dimensional photonic crystal structure with an organic gain material are investigated theoretically and experimentally. A feedback structure fabricated in a thin film of high index material increases both the index contrast from the gain material as well as the optical confinement. Furthermore, by combining first order photonic crystal structures with second order ones losses occurring at the edge of the second order structure are dramatically reduced leading to a lower laser threshold and/or to a much smaller footprint of the laser.

7605-02, Session 1

New perspectives and applications of silicon nanophotonics

I. Rendina, Consiglio Nazionale delle Ricerche (Italy)

The high cost of photonic components and their assembly is a major obstacle to their exploitation. Silicon photonics is a way to solve the problem. It is aimed to the development of a small number of silicon-based elementary components to be realized with low cost integration technologies compatible with microelectronic VLSI processes. In this comunication, we report some new results we are having in the study of negative refractive index silicon photonic crystals based structures, whose exploitation has led to the first experimental demonstration, to our knowledge, of "optical antimatter", and on new experiments on Raman emission in silicon nanocrystals, showing a significant increase of the optical gain with respect to the case of crystalline silicon.

7605-03, Session 1

Monolithic integration photonic crystal devices integrated with photodiodes

C. Chen, W. Y. Chiu, National Central Univ. (Taiwan)

We demonstrate the monolithic integration of photonic crystal waveguides, a photonic crystal demultiplexer, a conventional waveguide and photodiodes. InGaAsP-based materials are chosen for the fabrication of the device to obtain high absorption efficiency at the operating wavelengths. The refractive index of the guiding material is designed to be higher than that of the cladding layer to obtain the vertical confinement in the input/output conventional slab waveguides. For the photodiodes, the partially p-doped photo-absorption layer is adopted to accelerate the diffusion of the electron form absorption layer to the depletion layer. The photonic crystal demultiplexer consists of hexagonally arranged air holes. The inputted light at the wavelengths of 1530nm and 1550nm can be separated by the demultiplexing system. The operation speed can be upto 22GHz.

7605-04, Session 2

InP photonic integrated circuits for optical switching and processing

Y. Nakano, T. Tanemura, The Univ. of Tokyo (Japan)

invited presentation

7605-05, Session 2

System-in-package technologies for photonics

T. Tekin, TU Berlin Microperipheric Technologies (Germany)

The System-in-Package (SiP) technology is announced as one of the key technologies, which enables the continued increase in functional density and decrease in cost per function required to maintain the progress of electronics by utilizing the three dimensions (3D) through innovation in packaging and interconnect technology. A key bottleneck to the realization of high-performance microelectronic systems, including SiP, is the lack of low latency, high-bandwidth, and high density off-chip interconnects. Photonics could overcome these challenges and leverage low-latency and high bandwidth communication within next generation architectures. In this paper state-of-the-art approaches will be discussed and the requirements in 3D integration perspective of converging platforms will be addressed.

Selected Refs:

Gordon E. Moore, "Cramming More Components onto Integrated Circuits," Electronics, pp. 114-117, April 19, 1965.

International Technology Roadmap for Semiconductors (ITRS) 2007, http://public.itrs.net.

Zhang, G.Q.; van Roosmalen, F.; Graef, M.; The paradigm of "more than Moore" Electronic Packaging Technology, 2005 6th International Conference on 30 Aug.-2 Sept. 2005 Page(s):17 - 24.

D. A. B. Miller, "Rationale and challenges for optical interconnects to electronic chips," Proceedings of the IEEE, vol. 88, pp. 728-749, 2000.

H. Dawei, T. Sze, A. Landin, R. Lytel, and H. L. Davidson, "Optical interconnects: out of the box forever?," IEEE J. Selected Topics in Quantum Electronics, vol. 9, pp. 614-623, 2003.

Gunn, C., CMOS Photonics for High-Speed Interconnects, Micro, IEEE Computer society, vol. 26, 2006.

7605-06, Session 2

Development of optical polymer waveguide devices

K. Chiang, City Univ. of Hong Kong (Hong Kong, China)

Low-cost planar lightwave circuits based on optical polymer waveguide devices hold promise for the next generation of optical communication systems. Over the years, we have devoted significant research effort to the development of polymer waveguide devices with the objective of exploring the many unique properties of polymer for the realization of new functional devices. For example, we have demonstrated zero-birefringence waveguides and polarization-insensitive directional couplers, where the stress and geometry effects in polymer thin films are balanced through careful waveguide design and thermal tuning. Using a long-period waveguide grating as the basic structure, we have demonstrated a range of tunable broadband filters, including band-rejection filters, bandpass filters, and add/drop multiplexers, where the large thermo-optic coefficient of polymer together with the high temperature sensitivity of the grating design allows an exceedingly wide wavelength range to be tuned thermally. Using vertical optical couplers as building blocks, we have demonstrated compact polarization splitters, thermo-optic switches, and dynamic power splitters. These three-dimensional devices take advantage of the fact that multi-layer structures can be formed easily with polymer. In addition to the conventional fabrication processes based on photolithography and reactive-ion etching, we have implemented a ultra-violet writing technique and an imprinting technique to enhance our waveguide fabrication capacity. Recently, we have proposed a new bottom-heating approach for the realization of thermo-optic waveguide devices, which can minimize the possibility of damaging the polymer waveguide due to electrode deposition and facilitate electric wiring and device packaging. This paper presents a review of these research activities.

7605-07, Session 2

Simple and reliable evaluation method of multimode polymer optical waveguides

O. Sugihara, F. S. Tan, T. Kaino, Tohoku Univ. (Japan); M. Kagami, M. Yonemura, A. Kawasaki, Toyota Central Research and Development Labs., Inc. (Japan)

Polymer optical chip containing a combination of 45 -angled cut waveguide, Y-splitter and S-bend structures was designed and fabricated for simple and reliable evaluation of multi-mode waveguides. Effect of mode scramblers was investigated as an appropriate input condition for standardization of measurement of optical characteristics of multi-mode waveguides.

7605-08, Session 3

Silicon photonics for on-chip interconnects and telecommunications

L. Chen, Alcatel-Lucent Bell Labs. (United States); K. Preston, M. F. Lipson, Cornell Univ. (United States); C. R. Doerr, Y. Chen, Alcatel-Lucent Bell Labs. (United States)

Silicon photonics has been a rapidly emerging field in recent years, driven by its low manufacturing cost and high level of integration. One particular application is optical interconnects for on- and off-chip communications in future multi-processor computers, to partially replace today's copper link with photonic links providing larger bandwidth at lower power consumption. Another area of application is in telecommunications where a large number of functionalities such as filtering, switching, multiplexing/demultiplexing and detecting can be integrated on a single chip.

In this talk I will summarize our work on fast germanium detectors with response time of only 8.8 ps, and their integration with cascaded silicon micro-ring resonators for multi-channel receivers. I will also discuss our recent demonstration of an on-chip optical interconnect link with monolithically-integrated, micrometer-scale silicon modulators and germanium detectors, and its operation at a link budget of 120 fJ/bit at 3 Gbps. At the end I will also briefly discuss some silicon photonic devices we are currently developing for telecommunications.

7605-09, Session 3

Gathering effect on dark current for CMOS fully integrated PIN-photodiodes

J. Teva-Merono, I. Jonak-Auer, J. Kraft, J. Siegert, F. Schrank, E. Wachmann, austriamicrosystems AG (Austria)

This paper presents the design and characterization of silicon based PIN photodiodes integrated in a CMOS commercial process. In particular, the dark current of the PIN photodiodes is investigated after reporting an increase on the dark current values due to the additional implementation of a guard ring. The gathering design consists on adjacent n+/p+/n+ diffusions and it is classified according to the distance of the p+ anode to the p+ guard ring diffusion (named L), which turned out to be the most relevant parameter in the parasitic dark current. Values of dark density current reported are: 11.9pA/cm2 for a guardless photodiode in contrast to 38.4pA/cm2 and 144.2pA/cm2 for photodiodes with guard ring distances of L=82.5μm and L=33μm, respectively. In fact, the p+ diffusion of the anode together with the n+ and p+ diffusions of the gathering, create a parasitic PNP- transistor that is supposed to be the root cause for this increase on the dark current values. It is suspected that holes are injected from the p+ guard ring diffusion to the p+ anode diffusion, increasing the dark current. In fact, the collector current is dependent on the base width neutral region, which allows to compute the dark current for each guard ring design. An analytical model has been developed and implemented, and the dark current measurements are reproduced with excellent agreement for different guard ring designs and for a wide temperature range.

7605-10, Session 3

Design and manufacture of quantum-confined punch-through SOI light sources

A. W. Bogalecki, INSiAVA (Pty) Ltd. (South Africa); M. du Plessis, Univ. of Pretoria (South Africa)

To investigate quantum confinement effects on silicon (Si) light source electroluminescence (EL) properties like quantum efficiency, external power efficiency and spectral emission, thin Si finger junctions with thicknesses down to 8 nm were designed and manufactured in a fully customized silicon-on-insulator (SOI) semiconductor production technology.

Optical simulations were employed in the design phase to maximize the externally available optical power.

The device design, mask layout and manufacturing process had to incorporate various effects of material and equipment limitations and physical phenomena like impurity redistribution occurring during the physical manufacturing process.

Since commonly available photolithography is unusable to consistently define and align nanometre-scale line-widths accurately and electron-beam lithography (EBL) by itself is too time-expensive to expose complete wafers, the wafer manufacturing process employed a selective combination of photolithography and EBL.

The SOI wafers were manufactured in the clean-rooms of both the Carl and Emily Fuchs Institute for Microelectronics (CEFIM) at the University of Pretoria (UP) and the Georgia Institute of Technology's Microelectronic Research Centre (MiRC), which made a JEOL JBX-9300FS electron-beam pattern generator (EPG) available.

Since no standard process recipe could be employed, the complete design and manufacturing process is based on self-obtained equipment characterization data and material properties.

The presentation on this topic will summarize the technical objectives, approach, chip and process design, physical manufacture, process control and measurement of the nanometre-scale SOI light sources.

7605-26, Poster Session

A novel fabrication process of polymeric photonic crystal

S. Oh, C. Kim, Pusan National Univ. (Korea, Republic of); E. Lee, Inha Univ. (Korea, Republic of); M. Y. Jeong, Pusan National Univ. (Korea, Republic of)

Photonic crystals(PCs) are recently fabricated by NIL(Nano Imprint Lithography) on the polymer with low index because of its simplicity and short process time and ease of precise manufacturing. But, PCs require the high dimensional accuracy due to optical characteristics of PCs . The dimensional accuracy of PCs using NIL depends on the stamp. NIL stamps are usually fabricated by EBL, lift off and etching process. The damage of PC structures happens during the lift off process due to tearing and ripping problem. So, we report on novel fabrication of NIL stamp using PMGI/PMMA bi-layer lift off technique. We can control the extent of the undercut in the support layer through independent development of PMGI and PMMA. We simulate the band structure of a triangle lattice with a polymer refractive index of 1.495. From the simulation results, we derive that dimensional accuracy of PCs should be maintained below ±30nm. We make the original pattern by EBL. An optimal dose for achieving this dimension on the PMMA is determined by dose test experiment and has 150μC/cm2 at the aperture 10μm and EHT 20kV. To establish optimal process condition, development for PMMA and PMGI is performed according to development time. Then, we deposit the Ni layer using e-beam evaporator and perform the lift off process. We obtain the PCs structure of Ni layer with 70nm undercut at the optimal development condition. The fabricated PCs structure has dimensional accuracy below 5nm. These values are sufficient for meeting with optical characteristics of PCs.

7605-27, Poster Session

A white-light interferometry scheme to measure wide-wavelength dispersion of thermo-optic coefficients of optical switch materials

S. Kim, S. H. Kim, K. Kim, J. H. Oh, Y. K. Kwon, E. Lee, Inha Univ. (Korea, Republic of)

In recent years thermo-optic (TO) materials are widely used in many applications such as thermo-optic switches, thermally tunable optical filters and attenuators, and thermally controllable optical sensors. Many new polymer materials are considered for such TO device applications. Thus, it is very important to know the TO coefficients of new optical materials in a wide wavelength region for applications to wavelength-division-multiplexed (WDM) signal processing and multi-wavelength sensing devices. Conventional TO coefficient measurement methods are mostly related to measurement of TO coefficient value(s) at a single wavelength or discrete wavelengths, and/or engaged in a complicated measurement setup. In addition, some of the conventional methods require a specific sample geometry for the TO coefficient measurements.

In this paper we have proposed and demonstrated a new simple white-light interferometry method for continuous dispersion curves of the TO coefficients of optical samples. Phase shifts of the interference spectra of the white-light interferometer output are measured by changing temperature of an optical sample located in of the interferometer arms. Based on the phase shift information with the temperature change we obtain a continuous dispersion curve of the TO coefficient of the sample materials over the full wavelength coverage region of the white light beam. We have tested our method with a fused silica glass material which is a well-know optical material for its optical properties. This continuous dispersion information of the TO coefficients of new optical materials will be useful for fabrication of the WDM signal processing devices or functional devices in multi-wavelengths.

7605-28, Poster Session

Development of integration technology for optical PCB and electrical PCB

D. Y. Cha, S. J. Cho, J. H. Lee, S. P. Chang, Inha Univ. (Korea, Republic of)

Traditionally, networks have been fabricated with electrical boards in which copper lines are printed. However, networks need the more broader bandwidth and high speed with low noise and interference. But the electrical networks have several problems such as increases in electrical signal attenuation, power consumption, and impedance mismatching to boost the transmission speed. To overcome these problems, optical interconnection with electrical PCB can be used to achieve high-bandwidth and high-performance information channels that do not radiate themselves and that are completely unaffected by electromagnetic noise. Therefore, many efforts have been made to develop optical interconnection with electrical PCB.

In this paper, we investigate the key technologies to integrate the Electrical PCB with Optical PCB. One of the studied technologies shows the possibility to getting very dense via interconnection line with low resistivity using pulse mode electroplating method and the other one demonstrate for obtaining the high bonding strength with low temperature process. From the forming technology of via interconnections using pulse current mode, the measured value of electrical resistivity shows with a range from 20 to 26 mΩ. The result shows that pulse current mode has lower resistivity than direct current mode. And the PCB bonding technology with low bonding temperature is demonstrated with the value of bonding strength from 7 to 8 MPa at the range of temperature from 90   to 100 . This low temperature bonding technology provides good stability to bonded PCB because of preventing the bonded PCB from warpage and crack.

7605-29, Poster Session

Measurement of optical constants of thin metal films with a   -SPR systems

D. Lee, S. Hong, C. Kong, S. Lee, S. Park, E. Lee, B. O, Inha Univ. (Korea, Republic of)

The determination of optical properties of thin metal films using   -SPR (surface plasmon resonance) technique has been considerable interest since Kretschmann's study. In this method, changing the incident angle with fixed wavelength, two sets of optical constants and thickness of thin metal film could be derived from the SPR dip in the attenuated total reflection (ATR) spectrum at a given wavelength. The unique solution can be selected with the optical constants which have the same thickness at another wavelength. In a different way, that solution can be obtained from two SPR dips by changing the media of the metal cladding. However, these techniques will result in uncertainty during the process of the measurement because of the different environment. In this study, we discuss the feasibility to determine unique optical constant and thickness of a thin metal film using a   -SPR system, changing the wavelength with fixed incident angle. In a   -SPR system, two SPR dips are obtained at bound mode and quasi-bound mode region of surface plasmon dispersion relation and we can determine the unique solution, optical constant and thickness of a thin metal film, using these dips.

7605-11, Session 4

A platform for multiplexed sensing of biomolecules using high-Q microring resonator arrays

I. Brener, J. B. Wright, K. R. Westlake, D. W. Branch, M. J. Shaw, G. A. Vawter, Sandia National Labs. (United States)

We demonstrate a robust platform for multiplexed sensors of biomolecules in solution using a combination of high performance waveguide resonators, sensitive readout, integration and packaging. Even though we use a fabrication process that is compatible with CMOS foundries and microfluidic integration, the Q factors (~2.5x105) reported here are among the highest reported in the literature using waveguide evanescent coupling. Our sensor responsivity of 5.34 nm/RIU was obtained experimentally and can be used along with the 75 fm resolution of our real-time readout to estimate a limit of detection of 1.4x10-6 RIU.

7605-12, Session 4

Integrated bio-inspired fluidic imaging system

Y. Lo, Univ. of California, San Diego (United States)

We discuss the principle and technology of integrated bio-inspired fluidic optic systems for medical imaging and other health-related applications. Applications include surgical cameras for minimally invasive surgery, retina cameras for diabetic retinopathy, and accomodating intraocular lenses.

7605-13, Session 5

Solar spectrum rectification using nano-antennas and tunneling diodes

M. Dagenais, K. Choi, F. Yesilkoy, A. N. Chryssis, M. C. Peckerar, Univ. of Maryland, College Park (United States)

A micro-antenna coupled to a tunneling diode is demonstrated and is used to directly rectify mid-infrared radiation. This is a transformational approach as this approach uses an antenna element to concentrate the electromagnetic wave energy on a nonlinear diode for rectification as compared to using a photon detector to detect quanta of radiation as it is typically done for solar cells. By adjusting the size of the antenna and minimizing the size of the tunneling diode, these devices can be made to be sensitive to either IR or visible light. It is envisioned that, during the day, panels incorporating these devices would directly convert solar energy to electricity and at night, these panels would convert to electricity the blackbody radiation centered at 10 um emitted from the earth. These will allow for around the clock scavenging of electromagnetic energy.

7605-14, Session 5

Design, development and manufacture of high-efficiency low-cost solar modules based on CIGS PVICs

L. A. Eldada, HelioVolt Corp. (United States)

We describe the design, development and manufacture of solar power panels based on photovoltaic integrated circuits (PVICs) with high-quality high-uniformity Copper Indium Gallium Selenide (CIGS) thin films obtained with rapid and robust deposition and reaction processes performed on low-cost low-energy-consumption high-uptime capital equipment.

7605-15, Session 6

Nonlinear and quantum optics in photonic nanostructures

C. W. Wong, J. F. McMillan, R. Bose, R. Chatterjee, C. J. Chen, J. Gao, T. Gu, C. A. Husko, S. Kocaman, F. Sun, Columbia Univ. (United States); Y. Xiao, BeiHang Univ. (China); X. Yang, Univ. of California, Berkeley (United States)

We examine the control of photons in engineered nanostructures. First, we demonstrate the strong control of dispersion and localization in photonic crystal structures, leading to the observations of negative refraction, zero-index superlattice band gaps, and ultrahigh-Q subwavelength nanocavities. Coherent interactions in such nanostructures lead to recent observations of an optical analogue to electromagnetically-induced-transparency. Second, we report our studies in nonlinear optics through the tight field confinement and long photon lifetimes in our photonic crystal structures. Examples include slow-light Raman scattering and femtojoule Fano-type optical bistability. Third, we describe our efforts in nonclassical optics through these nanostructures. Examples include controlling spontaneous emission through cavity quantum electrodynamics for efficient on-demand single photon sources, and realizing scalable quantum phase gates for quantum information sciences.

7605-16, Session 6

Slow light enhanced nonlinear photonic functionalities

T. F. Krauss, Univ. of St. Andrews (United Kingdom)

Nonlinear optics is at the core of many optical functionalities, such as switching, wavelength conversion and optical signal processing. By exploiting the slow light effect in photonic crystal waveguides, we are able to reduce the pump power to achieve sizeable nonlinear effects considerably. I will discuss enhanced self-phase modulation and its use in optical regeneration, third harmonic generation and its application for the monitoring of optical data signals as well as enhanced Raman scattering for optical amplification.

7605-17, Session 6

Design and integration of plasmonic and dielectric nanowires for VLSI photonic circuit application

E. Lee, Inha Univ. (Korea, Republic of)

We report on the design and integration of nano-scale surface plasmonic polariton (SPP) wires and dielectric wires as applicable for VLSI photonic integrated circuits. We analyze the propagation characteristics of the slow plasmonic lightwave and the fast lightwaves. We then design and integrate coupled structures of plasmonic nano-wires and examine the optical mismatch problem between the two wires for VLSI nano-photonic circuit applications. The plasmonic nano-wires are also integrated with other micro/nano-scale dielectric wires and devices, such as silicon sires and devices. We analyze the effective index of the silicon waveguides and the SPP waveguides and design a guided directional coupler based on the matching of the effective refractive indices between two waveguides. We calculate the mode field of the individual SPP nano-waveguide. We then calculate the coupled eigen-modes of even and odd eigen-modes directly to analyze the coupling between two nano-waveguides. We find that, for the even mode, the magnetic field has the same direction in all the position while the odd mode has opposite field direction on the two nano-waveguides. In terms of energy transfer, we find that the lightwave coming into a no-wire is transferred to the SPP wire due to the refractive index matching or the optical impedance matching. We study both the single SPP and the slot SPP wire excited by the electrical filed component normal to metal-dielectric interface. For a single SPP waveguide we find that the SPP modes are not excited by TE mode but by TM mode in the lateral guided wave coupler. In the slot SPP waveguide, we find that the SPP modes are not excited by TM mode but by TE mode in the lateral guided wave coupler. We also used surface plasmon-polaritons (SPPs) formed on a flat metal surface like silver or gold for micro/nano-photonic circuits and networks. We have designed and fabricated stripe waveguides, horizontal directional couplers, vertically integrated directional couplers, using plasmonic waveguides.

7605-18, Session 7

High performance quantum dot and quantum well infrared focal plane arrays

M. Razeghi, Northwestern Univ. (United States)

Intersubband detectors based on quantum dots (QD) and/or quantum wells (QW) are a promising technology for next generation infrared imagers. We have studied QD, QW, and QD/QW hybrid detectors on both

InP and GaAs substrates for focal plane array applications in the mid and long wave infrared windows. The QD-based technology, in particular, shows great potential for high operating temperature applications. An InAs quantum dot-based imager has been demonstrated with high temperature operation up to 200 K in the mid-wave. For future monolithic integration applications, we have also studied the growth of III-V materials on non-native substrates. Long-wave InGaAs/InP quantum well infrared detectors grown on silicon substrates have been demonstrated.

7605-19, Session 7

Selective co-doped erbium Ti:LiNbO3 waveguide amplifiers

R. Salas-Montiel, C. K. Madsen, Texas A&M Univ. (United States)

The erbium concentration profile is measured by dynamic secondary ion mass spectrometry analysis. The erbium diffusion coefficient was measured to be Dx = 0.17 ± 0.01 μm2/h at 1100°C. This corresponds to a decrease in diffusion time of 7.6 for a given depth. Small-signal net gain of 1.6 ± 0.1 dB and internal gain of 0.8 ± 0.1 dB/cm at 1531 nm was measured for the transverse magnetic mode by optical pumping at 1488 nm with a launched pump power of 94 mW.

7605-20, Session 7

On-chip integrated lasers in Al2O3:Er on silicon

M. Pollnau, J. D. B. Bradley, F. Ay, E. H. Bernhardi, R. M. de Ridder, K. Wörhoff, Univ. Twente (Netherlands)

We have developed Al2O3:Er3+ as an integrated gain material, which is deposited by reactive co-sputtering and structured by reactive ion etching. Low-loss channel waveguides with 2 dB/cm gain allow for the realization of integrated Al2O3:Er3+ ring lasers on thermally oxidized silicon substrates. With a novel design high pump coupling into- and low output signal coupling from- the ring is achieved. Output powers of up to 9.5 μW and slope efficiencies of up to 0.11 % were measured. Lasing was observed for a threshold power of only 6.4 mW for ring lasers with cavity lengths varying from 2.0 to 5.5 cm. Lasing in the wavelength range 1530 to 1557 nm was demonstrated by varying the coupler length. The potential for integration of a tunable laser source with silicon photonic devices is demonstrated, which makes this a highly promising technology. Furthermore, fabrication of distributed feedback structures to achieve single-frequency lasers is under investigation.

7605-21, Session 8

Advanced LiNbO3 devices and materials technology for optical circuit applications

R. M. Osgood, Jr., O. Gaathon, A. Ofan, Columbia Univ. (United States)

This talk will focus on the development of single-crystal LiNbO3 film technologies for advanced integrated-optical applications. Our approach uses ion-slicing with He ions to enable liftoff of single crystal sheets of LNO. These single crystal films can then be used either for elements in a hybrid circuit as a stand-alone oxide platform.

7605-22, Session 8

Dynamic photonic structures for integrated photonics

S. Fan, Z. Yu, Stanford Univ. (United States)

Based on the effects of photonic transitions, we show that a linear, broadband and nonreciprocal on-chip optical isolation can be accomplished by dynamic refractive index modulations. Such scheme allows for on-chip optical isolation using standard CMOS fabrication process. We also show how to use photonic transition to create on-chip tunable resonance with quality factor and resonant separately controllable.

This is for an invited talk for this conference.

7605-23, Session 9

Birefringent ring resonator-based optical filters

C. K. Madsen, M. Solmaz, Texas A&M Univ. (United States)

An analysis revealing a simple closed form solution for the poles of a polarization-coupled ring resonator is presented . The resonant frequencies are easily calculated as well as the pole magnitudes based on the relative phase and polarization-dependent ring coupling. Applications include WDM filters with new pole magnitude tuning capability and analysis of polarization dependence in birefringent fiber-based and integrated-optic resonator-enhanced filters.

7605-24, Session 9

Large-scale integrated silicon photonics using microdisk and microring resonators

A. W. Poon, X. Luo, S. Feng, H. Chen, H. Cai, Hong Kong Univ. of Science and Technology (Hong Kong, China)

Silicon-based microresonators are versatile device structures. In order to attain large-scale-integrated (LSI) silicon photonics using microresonators, the microresonators can be coupled in the form of a coupled-resonator optical waveguide as an optical delay line structure or coupled to a bus waveguide grid as an optical network structure.

Here, we review our progress in LSI silicon photonics using microdisk/microring resonators for wavelength-division-multiplexed (WDM) optical delay lines and N x N (N-input-N-output) cascaded matrix switches. Our delay lines comprise as many as 100 double-notch-shaped microdisk resonators, which are gaplessly coupled with each other via sub-micrometer-sized notches. We demonstrated 100-ps-scale delay in 41-element devices with an insertion loss of ~0.3 dB/disk in a footprint of ~40 micron x 1.6 mm. The passband is relatively flat-top with steep roll-off exhibiting a bandwidth of ~nm due to inhomogeneously linewidth broadening.

Our N x N cascaded matrix switch designs comprise 2 x 2 matrix switches as building blocks. Each 2 x 2 matrix switch comprises 4 cascaded add-drop filter structures using single or a pair of microresonators coupled to a bus waveguide crossing. The crossing adopts a low-loss low-crosstalk multimode-interference design. We use carrier injection-type plasma dispersion effect to switch each microresonator. We demonstrated 2 x 2 matrix switches comprising 4 microring resonators routing 4 WDM channels at 10-Gbit/s channel rate, with sub-ns switching speed upon DC power consumption of few mW in footprint of ~100 micron x 100 micron.

7605-25, Session 9

Integrated microsphere resonator arrays: light focusing and propagation effects

V. N. Astratov, A. Darafsheh, M. D. Kerr, K. W. Allen, The Univ. of North Carolina at Charlotte (United States)

Unique feature of technology of microsphere resonator arrays is connected with a possibility to pre-select size-matched cavities with the standard deviation of spheres' diameters ~10<-4>. In such practically indistinguishable classical "photonic atoms" the individual whispering gallery modes (WGMs) can be strongly coupled leading to applications in slow-light devices, filters, array-resonator LEDs, and sensors. Along with the WGM-based coupling effects such arrays have very interesting nonresonant properties of periodical focusing of light. The focused beams with subwavelength dimensions termed "photonic nanojets" and corresponding quasi-periodic "nanojet-induced modes" (NIMs) can be obtained in such structures.

In this work we integrated chains of microspheres with the flexible optical delivery systems (hollow waveguides and microcapillaries) of biomedical microprobes. Using high resolution imaging and spectroscopy we study the optical transport and focusing properties of such structures for spheres from 10 to 300 µm with the refractive index from 1.45 to 1.9. We show that the NIMs scattering losses can be dramatically reduced below the level of 0.1 dB per sphere for certain parameters of spheres. We also show that in hollow waveguide structures the tight focusing of the beams can be achieved with higher optical throughput compared to microcapillaries due to recycling of scattered photons. Due to compactness and mechanical robustness, subwavelength focusing of the beam, high optical throughput and broad spectral transmission properties such structures can be used as local microprobes in biomedical optical spectroscopy and minimally invasive laser surgery.

Return to Contents

Conference 7606: Silicon Photonics V

Sunday-Wednesday 24-27 January 2010 • Part of Proceedings of SPIE Vol. 7606

Silicon Photonics V

7606-01, Session 1

InP overgrowth on SiO2 for active photonic devices on silicon

C. Junesand, Z. Wang, L. Wosinski, S. Lourdudoss, Royal Institute of Technology (Sweden)

Integration of III-V materials on silicon wafer for active photonic devices have previously been achieved by growing thick III-V layers on top of silicon or by bonding the III-V stack layers onto a silicon wafer. Another way is the epitaxial lateral overgrowth (ELOG) of a thin III-V material from a seed layer directly on the silicon wafer, which can be used as a platform for the growth of active devices. We have investigated lateral overgrowth of InP by Hydride Vapor Phase Epitaxy (HVPE) over SiO2 masks of different thickness on InP substrates from openings in the mask. Openings which varied in direction, width and pitch were made with E-beam lithography allowing a good dimension control even for nano-sized openings (down to 100 nm wide). Overgrowth of InP on top of SiO2/Si waveguides has also been achieved. By optimizing the growth conditions in terms of growth temperature and partial pressure of the source gases with respect to the opening direction, pitch, height and width, we show that a thin (~200 nm) layer of InP with good morphology and crystalline quality can be grown laterally on top of SiO2/Si waveguides. Due to the thin grown InP layer, amplification structures on top of it can be well coupled with the underlying silicon waveguides. The proposed ELOG technology provides a promising integration platform for hybrid silicon evanescent active devices.

7606-02, Session 1

Stranski-Krastanov mode grown multilayer InAs/GaAs quantum dot heterostructures on Germanium: a step toward integrating III-V photonics on silicon

S. Banerjee, N. Halder, S. Chakrabarti, Indian Institute of Technology, Bombay (India)

The growth of III-V semiconductors on Ge substrates, which will ultimately lead to the integration of III-V/Si technology, is one of the major challenges of present day research. Here we have addressed the Molecular Beam Epitaxial (MBE) growth of S-K grown multilayer InAs/GaAs QDs on 6° offcut Ge substrate towards the (110) plane, by depositing a migration enhanced epitaxy (MEE) grown GaAs layer in between the GaAs/Ge interface. The low temperature (350°C) MEE grown layer which involves migration of metal surface adatoms along the surface, is used to complement the GaAs/Ge heterointerface which typically suffers from anti-phase domain disorder due to the polar/nonpolar epitaxy and interdiffusion across the interface. High quality of GaAs growth front on Ge substrate for the subsequent growth of InAs QDs is further ensured by overgrowing the MEE GaAs layer with a thin GaAs layer grown at very slow growth rate (0.1μm/hr) at 500°C followed by thick GaAs at a fast rate (1μm/hr) at 590°C. AFM and PL measurements were done on the MBE grown samples to investigate the morphological and optical properties of the grown QDs. The AFM shows growth of QDs of nearly uniform density of ~6.56 x 10-10 cm-2. The 8K PL emission peak at 1051 nm, shows a FWHM of ~55 meV, which is comparable to the control InAs/GaAs QD samples grown on GaAs substrates. Structural characterization of the samples by XRD and XTEM is underway. DST India, SPM facility at IIT-Bombay and University of Glasgow UK is being acknowledged.

7606-03, Session 1

Efficient photoluminescence from GaSb/AlGaSb multiple quantum wells grown on Si substrate

D. H. Nguyen, J. Park, Y. K. Noh, M. D. Kim, D. Lee, Chungnam National Univ. (Korea, Republic of); J. E. Oh, Hanyang Univ. (Korea, Republic of)

The development of efficient light sources on silicon substrate is very important for future silicon integrated circuits, but it is still far from practical deployments. Here we present strong photoluminescence (PL) at room temperature from a high quality GaSb/AlGaSb multiple quantum well (MQW) on silicon substrate, with the help of dislocation blocking InSb quantum dot layers. The PL peak is at 1530 nm at room temperature and strong enough to show a clean PL spectrum even at an excitation power density of 0.6 W/cm2. This indicates the greatly reduced defects due to the quantum dot layers that terminate dislocations from a silicon hetero-interface. The power dependence of integrated PL intensity at room temperature also indicates the low defect density in the MQW.

PL spectrum from the MQW showed only one well-defined peak at low temperature. However, another peak at the high-energy side appeared at intermediate temperatures, which became dominant at room temperature. Polarization resolved PL spectrum shows the dominance of electron-light hole transition at low temperature due to the wide well width, 17 nm, but that of electron-heavy hole transition at room temperature due to its larger density of states. The time resolved PL decay curve shows a single exponential decay of 1.4 ns at low temperature and does not change with excitation power, indicating that the non-radiative contribution is not significant for the MQW. This result shows that the present MQW is a good candidate for a light source on silicon.

7606-04, Session 1

Correlation of optical and electrical characterization of point defects introduced via ion implantation

J. K. Doylend, A. P. Knights, McMaster Univ. (Canada)

One of the requirements for silicon optical interconnects operating at standard C-band wavelengths is a means of detection using silicon. SiGe photodetectors have emerged as one possibility, while defect-engineered silicon photodetectors provide an alternative approach. For the latter, defects introduced by ion implantation allow free carrier generation by incident light at optical frequencies to which silicon is ordinarily transparent. Data concerning the exact mechanism of this process is scarce, thus limiting efforts to optimize such detectors via processing parameters such as implantation dose, energy, and anneal recipe.

In this paper we correlate DLTS characterization with optical loss, free carrier injection efficiency, and photocurrent in order to gain insight into the optical properties of defect states introduced via self-ion implantation and annealing. This combination of electrical and optical characterization provides a means to begin modeling the mechanism of defect engineered photodetector response.

7606-05, Session 2

Single photon Si detectors

R. Pagano, Univ. di Catania (Italy) and Consiglio Nazionale delle Ricerche (Italy); S. Libertino, S. A. Lombardo, Istituto per la Microelettronica e Microsistemi (Italy); G. G. Valvo, G. Condorelli, D. D. Sanfilippo, G. G. Fallica, STMicroelectronics (Italy)

Silicon-based photodetectors are very appealing for many applications thanks to their reduced dimensions, weight and costs. In particular, Si avalanche photodetectors (SPAD) and Si photomultipliers (SiPM) are considered interesting devices for biomedical and sensoristic applications.

We electrically and optically tested both SPAD, with active area of 40µm×40µm, and SiPM arrays, from 5x5 to 64x64, fabricated by STMicroelectronics in Catania. The operation of single cell devices, having a quenching resistor of 220 kΩ integrated, were studied as a function of the sample temperature from -25°C to 85°C, voltage over breakdown (from 5% up to 20%) and illumination conditions using lasers at 488nm and 659nm. We determined, using both the dark count signal (charge) and the current under laser illumination, the device gain and demonstrated it is a function of the conditions chosen for operation. Typical gain values above 1×105 were obtained for operation times of 10 ns, while higher gains are obtained for longer integration times. The electrical behaviour as a function of temperature was correctly modelled in the full range studied, considering both thermal emission and diffusion physical mechanisms. Applications in biomedical (Positron Emission tomography) and environmental fields (water quality control) will also be discussed.

7606-06, Session 3

Handheld microfluidic-based detection platform for on-the-flow analyte characterization

P. Kiesel, M. Beck, N. M. Johnson, Palo Alto Research Center, Inc. (United States)

The strategic landscape for biological and biomedical testing is undergoing a truly disruptive transformation. Today the majority of tests are performed at major, centralized clinical laboratories since compact, robust, and inexpensive instruments for point of care (POC) testing are not available. The principal drivers for POC testing are reducing costs, obtaining timely test results, lowering mortality rates, and reducing morbidity.

We have demonstrated a new optical detection technique that delivers high signal-to-noise discrimination without precision optics to enable a flow cytometer that can combine high performance, robustness, compactness, low cost, and ease of use. The enabling technique is termed “spatially modulated fluorescence detection.” Relative movement between analyte and a predefined patterned environment generates a time-dependent signal, and correlating the detected signal with the known pattern achieves high discrimination of the particle signal from background noise. The basic optical detection technique is broadly applicable and compatible with many silicon photonic systems. The detection technique has been extensive evaluated with measurements of absolute CD4+ and percentage CD4 counts in human blood, which are required for screening, initiation of treatment, and monitoring of HIV-infected patients. To benchmark our technique we performed a direct one-to-one comparison of measurements on the same samples with a commercial instrument (BD FACSCount) and obtained excellent agreement for both absolute CD4 and percentage CD4. We have also assembled a first-generation, compact, handheld, single-parameter instrument based on the spatial modulation technique. The performance of this prototype provides clearly evidence that a multi-parameter, high-performance, compact instrument is fully realizable.

7606-07, Session 3

Optofluidic biosensing for the study of disease at the molecular level

I. M. White, Univ. of Maryland, College Park (United States)

Despite decades of gains in biotechnology, currently much remains unknown about the molecular mechanisms of a number of deadly diseases. New tools are needed to speed discovery at the molecular level and to mitigate the complexity of studying the systems biology of disease. In the last decade, a number of advancements have been made in photonic biosensing aimed at developing a new generation of technologies for the study and early detection of disease. Label-free photonic biosensing techniques such as surface plasmon resonance imaging (SPRI), nanoporous silicon waveguides, interferometry, and optical resonators have achieved detection limits on par with conventional techniques while decreasing the size of the biosensing element and reducing the number of steps involved in the biosensing procedure. In addition, surface enhanced Raman spectroscopy (SERS) has been shown to detect molecules in extremely low numbers, even single molecules.

In parallel to the development of a new generation of photonic biosensing techniques, advanced microfluidic technologies have emerged. The last decade has seen the development of automated micro-valves and micro-pumps, particle sorting, concentration gradient generation, and sample mixing. Also, photonic components, including waveguides and lenses, have been fabricated from soft-lithography materials. Synthesizing advanced microfluidic techniques with the new generation of photonic biosensing is likely to be the key to increasing throughput by increasing automation, decreasing equipment costs, and enabling multiplexing. This presentation will review examples of recent work in optofluidic biosensors and will discuss the opportunities for advancing research related to disease at the molecular level utilizing optofluidic biosensing technologies.

7606-08, Session 3

Waveguide-based optofluidics

G. Testa, Consiglio Nazionale delle Ricerche (Italy); Y. Huang, Technische Univ. Delft (Netherlands); L. Zeni, Seconda Univ. degli Studi di Napoli (Italy); P. M. Sarro, Technische Univ. Delft (Netherlands); R. Bernini, Consiglio Nazionale delle Ricerche (Italy)

Optofluidics is a very promising field that has seen a significant improvement over the last few years. Optofluidics is essentially the integration of optics and microfluidics. This permits to realize innovative optical system in which the fluids can be used to efficiently change the optical properties of a device.

In this work we show that integrated silicon liquid core Antiresonant Reflecting Optical Waveguide (ARROW) can be used as a basic tool for the realization of complex optofluidic devices. ARROW waveguides, with hollow core, permit to confine the light in a low refractive index liquid core, by means of two high refractive index cladding layers designed to form a high reflectivity Fabry-Perot antiresonant cavity. This arrangement allows to realize liquid core waveguides that can be very useful in optofluidic applications. We report the fabrication and the characterization different optofluidic devices based on hollow core ARROW waveguide like Mach-Zhender interferometers, tunable couplers and filters. The proposed devices have been realized by silicon technology. The channels have been realized by etching the silicon wafer, while the two claddings have been deposited on both wafers by PECVD or ALD deposition

7606-09, Session 4

Planar FRET detection from biomolecules on an optofluidic chip

A. Chen, P. Measor, Univ. of California, Santa Cruz (United States); E. J. Lunt, B. S. Phillips, A. R. Hawkins, Brigham Young Univ. (United States); H. Schmidt, Univ. of California, Santa Cruz (United States)

Fluorescence resonance energy transfer (FRET) is one of the powerful tools used to study the dynamics of biomolecules. By monitoring the energy transferred from a donor fluorophore to an acceptor fluorophore, one can determine the spatial proximity between the fluorophores on the nanometer scale and thus extract information regarding interactions between biomolecules. Here we demonstrate a novel way of measuring FRET from oligonucleotides using an integrated optofluidic chip containing a planar liquid core waveguide that can guide liquid and light simultaneously. FRET experiments were carried out using fluorescein and Cy3 labeled oligonucleotides FRET pairs. An excitation laser (488 nm) was fiber-coupled to a solid-core waveguide perpendicular to the chip's liquid-core channel. A FRET efficiency of 50% was measured in good agreement with bulk microscopy experiments. By photobleaching the acceptors and manipulating the fluidic flow, we also demonstrated controllable FRET events: an increase in donor signal, a decrease in acceptor signal and the recovery of FRET due to new FRET pair flow. The flexibility of our chip design also allows for improvements such as separate donor and acceptor detection at either chip end using integrated filters.

7606-10, Session 4

Arrays of SOI photonic wire biosensors for label-free molecular detection

A. Densmore, D. Xu, M. Vachon, S. Janz, R. Ma, Y. Li, G. Lopinski, C. Luebbert, J. H. Schmid, A. Delâge, P. Cheben, National Research Council Canada (Canada)

We present new SOI photonic wire waveguide biosensor arrays for the simultaneous detection of multiple molecular targets. We have developed both Mach-Zehnder interferometer and ring resonator arrays that are compatible with microarray spotting in two dimensions. Both optical power splitting and wavelength division multiplexing schemes are used to address several sensors on a chip through a single input waveguide. For controllable and low volume analyte delivery a microfluidic channel was monolithically integrated on the sensor platform, which eliminates alignment challenges with hybrid fluidic approaches. Using an infrared camera to simultaneously monitor the sensor outputs, we have successfully demonstrated the specific and real-time detection of various protein and antibody systems.

The individual sensors exploit the high-index-contrast of the SOI material platform to produce large evanescent field strength at the waveguide surface for strong interaction with surface bound molecules. The sensor arrays employ a new double spiral waveguide design in both the Mach-Zehnder interferometer and ring resonator sensors to obtain several millimeters of waveguide length in a compact 150 micrometer diameter circular area. This provides the sensitivity advantages of a long waveguide, while maintaining a compatible geometry for the two-dimensional arraying of sensors. We show that individual sensor elements are capable of detecting sub-femtogram levels of molecules with near temperature independent response.

7606-11, Session 4

A photonic biosensor system on a CMOS chip

K. L. Lear, R. Yan, Colorado State Univ. (United States)

Silicon photonics allows the integration of optoelectronic systems on a chip for a variety of applications including biosensing. Researchers have investigated a variety of systems for sensing the presence of molecules in the evanescent field of a surface waveguide using approaches or components such as surface plasmon resonance, ring resonators, and Mach-Zehnder interferometers. However, they require high performance optical sources or off-chip spectroscopy.

We report biosensors using SiNx/SiO2 waveguides fabricated in a commercial CMOS process read out on-chip with an integrated polysilicon photodetector array buried under the waveguide. Increased surface refractive index locally decreases evanescent coupling to the detector array resulting in reduced photocurrent from elements under the higher index region. The operating principle of this local evanescent array coupled (LEAC) sensor differs from those of other waveguide sensors and has been explored using numerical simulations. The presence or absence of target biomolecules bound to various probe molecules attached at different locations along the waveguide can be detected by the array to provide multi-analyte biosensing on a single waveguide. Experimental studies have been performed using adsorbed BSA nanofilms as well as antigen-antibody pairs. The projected limit of detection is approximately 10 pm of protein.

The anticipated low cost of smart chips with LEAC biosensors enabled by commercial CMOS fabrication supports their potential as a point-of-care diagnostic platform for personalized medicine and non-traditional healthcare environments. The approach offers multi-analyte capability without the need for labeled reagents or external instruments and has minimal demands on the spectral properties of the light source.

7606-12, Session 4

A porous silicon based microarray for label-free optical detection of DNA hybridization

I. Rea, G. Coppola, M. Gioffrè, E. De Tommasi, I. Rendina, Istituto per la Microelettronica e Microsistemi (Italy); A. Lamberti, Univ. degli Studi di Napoli Federico II (Italy); L. De Stefano III, Istituto per la Microelettronica e Microsistemi (Italy)

The microarray technology has demonstrated a great potential in drug discovery, proteomics research, and medical diagnostics. The key issue is the high throughput of these devices due to the large number of samples that can be simultaneously analyzed in a single parallel experiment. In this work, we propose an optical microarray constituted by hundreds of Porous Silicon (PSi) Bragg mirrors, characterized by a diameter of 200 micron, as functional platform for the detection of biological events. The PSi has emerged as an interesting support due to its morphology characterized by a high specific surface area, which makes it efficient for biomolecules immobilization. The integration of PSi single sensing elements in a microarray was not straightforward; to this aim a proper process, based on different technological steps, was designed. Then, the PSi elements were functionalized with different sequences of DNA probes and the whole chip was placed in a buffer solution containing the complementary DNA single-strands so to induce hybridization. The bio-recognition event was monitored studying the variation in the optical spectra of the Bragg mirrors.

7606-13, Session 5

Applications of subwavelength grating structures in silicon-on-insulator waveguides

J. H. Schmid, P. Cheben, National Research Council Canada (Canada); P. J. Bock, Univ. of Ottawa (Canada); S. Janz, W. Sinclair, National Research Council Canada (Canada); J. Garcia, Univ. Politécnica de Valencia (Spain); J. Lapointe, D. Poitras, Y. Li, G. Lopinski, A. Delâge, A. S. Densmore, B. Lamontagne, R. Ma, M. Shiu, D. Xu, National Research Council Canada (Canada)

Periodic dielectric structures with a periodicity shorter than the wavelength of light, commonly referred to as subwavelength gratings (SWGs), are used to create new effective dielectric media with useful optical properties. SWGs can be non-resonant, with a periodicity small enough to suppress all diffraction effects, or resonant, with a periodicity that couples the first diffraction order of an incident beam to a guided waveguide mode. Silicon-on-insulator (SOI) waveguides consist of just two materials with a fixed high refractive index contrast, namely silicon and silicon dioxide. Non-resonant SWGs allow designs of effective dielectric materials with a continuous range of intermediate refractive indices, and can be fabricated by standard nanofabrication techniques. We will review several applications of non-resonant SWGs in SOI waveguides, namely the modification of facet reflectivity, highly efficient fiber-chip couplers for photonic wire waveguides, low-loss photonic wire waveguide crossings and mode transformers. As an example of the application of a resonant subwavelength grating in SOI, we will present a guided mode resonance grating filter used for molecular sensing. This grating sensor makes use of the strong overlap of the TM mode evanescent electric field in a thin silicon waveguide with the waveguide surface to achieve high sensitivity to molecular binding events. Compared to photonic wire molecular sensor chips, the resonant grating sensor has simplified fabrication and eased packaging requirements and can be used with an optical readout that is almost identical to established surface plasmon resonance sensor technology.

7606-14, Session 5

Germanium implanted Bragg gratings in silicon on insulator waveguides

R. Loiacono, G. T. Reed, R. M. Gwilliam, G. Z. Mashanovich, Univ. of Surrey (United Kingdom); L. O'Faolain, T. Krauss, Univ. of St. Andrews (United Kingdom); G. Lulli, Istituto per la Microelettronica e Microsistemi (Italy); C. Jeynes, Univ. of Surrey (United Kingdom); R. Jones, Intel Corp. (United States)

Integrated Bragg gratings are an interesting candidate for waveguide coupling, optical filters, and for the fabrication of integrated photonic sensors. These devices have a high potential for optical integration and are compatible with CMOS processing techniques if compared to their fibre counterparts.

In this work we present design, fabrication, and testing of Germanium ion implanted Bragg gratings in silicon on insulator (SOI). A periodic refractive index modulation is produced in a 1µm wide SOI rib waveguide by implanting Germanium ions through a SiO2 hardmask.

The implantation conditions have been analysed by 3D ion implantation modelling and the induced lattice disorder and refractive index change has been investigated on implanted samples by Rutherford Backscattering spectroscopy (RBS) and ellipsometry analysis respectively.

An extinction ratio up to 30dB in transmission around 1.55µm wavelength has been demonstrated for Germanium implanted gratings on SOI waveguides.

7606-15, Session 5

Effects of annealing silicon ion irradiated rib waveguides with respect to free carrier lifetime

N. M. Wright, A. J. Smith, K. Litvinenko, R. Gwilliam, G. Mashanovich, G. Reed, Univ. of Surrey (United Kingdom)

Previously we have reported the effects of silicon ion irradiation on free carrier lifetime and propagation loss in silicon rib waveguides, and simulated net Raman gain based on experimental results. We further extend this work by reporting the effects of thermally treating a silicon irradiated sample with a higher dose and energy than previously reported, which produced a poor trade-off between free carrier lifetime and excess optical absorption prior to thermal treatment. Excess losses greater than 80dB/cm were recorded prior to annealing. After thermal treatment, the sample demonstrated characteristics of excess loss and free carrier lifetime recorded previously in much lower energy and dose silicon ion irradiated samples, suggesting that thermally treating samples could enhance the trade-off between free carrier lifetime and excess loss introduced to the rib waveguides. Raman gain simulations based on the new experimental data are reported and show an increase in net gain over previously reported data, suggesting that higher dose, shallow silicon ion implantation is the most efficient way of optimising the trade-off between lifetime reduction and excess optical absorption in silicon rib waveguides, a proposal in our earlier work. The effects of thermally treating low temperature oxide clad waveguides with respect to free carrier lifetime are also reported. Results show that thermally treating a low temperature oxide clad waveguide can vary the intrinsic lifetime. The results of this investigation as well as a discussion into the possible origin of the lifetime change are given.

7606-16, Session 5

Early stage growth of silicon nanocrystals formed in SiO2 by Si+ implantation and rapid thermal annealing

A. P. Knights, O. Hul'ko, McMaster Univ. (Canada); I. Crowe, N. Hylton, M. Halsall, The Univ. of Manchester (United Kingdom); R. M. Gwilliam, Univ. of Surrey (United Kingdom)

Low dimensional silicon structures remain of significant interest for applications in a number of important technologies such as solid state optoelectronics, photovoltaics and non-volatile memories. Of these, the most prominent is their potential use for light emission and amplification. The formation of silicon nano-crystals (Si-ncs) embedded in a dielectric such as SiO2 or Si3N4 is of particular interest since in the form of a thin film they tend to be well passivated allowing for relatively intense red and near infrared luminescence. Further, when containing both Si-ncs and rare-earth ions dielectric thin films allow for strong emission from the rare-earth dopant through an efficient, short range sensitization mechanism. It may be argued that the well-controlled introduction of excess silicon and the subsequent formation of Si-ncs can be best achieved through ion implantation and subsequent annealing. In this case it is necessary to perform post-implantation annealing at a temperature >900 C in order to induce phase separation and crystallization. Debate still remains regarding the exact atomistic nature of the formation of Si-ncs in SiO2 following ion implantation and annealing. Direct observation and quantitative determination of the distribution of Si-nc size and concentration, necessary to provide the data required to elucidate the formation process, remains somewhat sparse. In the current work we will present a quantitative description of the evolution of the mean radius and concentration of an ensemble of Si-ncs in SiO2, with particular attention to the rapid growth regime which takes place in the first few seconds of high temperature annealing. We will relate the physical properties of the Si-ncs to their luminescence and their ability to sensitize rare-earth dopants.

7606-17, Session 6

Cantilever couplers for fiber coupling to silicon photonic integrated circuits

R. M. Reano, P. Sun, Ohio State Univ. (United States)

Highly confined optical modes of silicon waveguides produce challenges when attempting to couple light between silicon strip waveguides and optical fibers. Coupling schemes that include width tapers and inverse width tapers have been proposed to bridge the mode size mismatch. To couple light out-of-plane, alternative schemes may be employed such as grating couplers or evanescent couplers. In this work, we demonstrate fiber-to-chip cantilever couplers that consist of silicon inverse width tapers embedded in stress-engineered silicon dioxide cantilevers which enable out-of plane intra-chip coupling to tapered fibers. The cantilever couplers enable access to photonic devices on a chip surface without dicing or cleaving. The silicon dioxide cantilevers are comprised of a bilayer of buried oxide (BOX) and plasma-enhanced chemical vapor deposition (PECVD) silicon dioxide. The stress in the BOX-PECVD silicon dioxide bilayer deflects the cantilevers out-of plane. In our design, the cantilevers are 40 microns long so that the released ends are deflected enough above the chip surface to allow for out-of-plane coupling to tapered optical fibers. The fiber-to-waveguide coupling loss extracted from linear regression is 1.6 dB per connection for TE polarization and 2 dB per connection for TM polarization.

7606-18, Session 6

Fabrication of porous silicon channel waveguides with multilayer Bragg cladding

A. A. Bettiol, E. J. Teo, National Univ. of Singapore (Singapore); S. Prashant, Sri Sathya Sai Univ. (India); B. Xiong, M. B. H. Breese, National Univ. of Singapore (Singapore)

Waveguides fabricated in porous silicon have several unique features that make them potentially useful for various niche applications. One advantage is that they can be produced in bulk silicon using a relatively low cost fabrication procedure. The porous nature of the material makes it highly sensitive to small changes in refractive index hence it can be utilized for example, in biosensing applications.

In this work, porous silicon waveguides with a multilayer Bragg cladding have been fabricated using an electrochemical anodization process. Using this process, porous silicon layers with various porosities (refractive index) and thickness can be fabricated with a high degree of precision by controlling the etching current and time. Lateral confinement in these multilayer waveguides is obtained by two different methods. The first involves the use of proton irradiation prior to electrochemical etching, and the second involves the localized oxidization of the porous silicon using a femto-second Titanium Sapphire laser. The two alternative fabrication techniques will be compared. We have characterized the waveguides at 1550 nm using the scattering technique and show that a propagation loss between 1-2 dB/cm is achievable for both TE and TM polarization. Simulations using finite element methods are carried out in order to optimize the design of the waveguides for low loss and large core single mode operation. This is important for reducing the modal mismatch between the waveguide and single mode optical fiber.

7606-19, Session 6

Self-alignment and instability of waveguides induced by forces of guided and radiated fields

A. Mizrahi, K. Ikeda, F. Bonomelli, V. Lomakin, Y. Fainman, Univ. of California, San Diego (United States)

Recently, there has been a growing interest in optical forces exerted by guided waves on the guiding structures themselves. Here, we introduce a new fundamental property of waveguides, namely the ability of a waveguide to self-align by light forces when it is perturbed by a small offset misalignment. We employ a mode matching technique for the analysis of the scattering of an incident guided mode into the reflected and transmitted guided modes and the radiation modes. Closed form expressions of the optical forces show that they result from the interaction of the guided mode with the radiation modes. The two offset parts of the waveguide either tend to self-align to form a continuous waveguide, or deflect away from each other, being unstable, depending on the size of the waveguide and the eigenmode polarization. A strong self-alignment force is created for a transverse magnetic mode due to polarization surface charges that dominate the optical force with a near field interaction.

We further investigate the exerted forces when a gap is introduced between the two parts of the waveguide. Finite element method simulations show that the effects are present over a significant range of the offset and gap, and a strong longitudinal force may exist as well. The discussed forces can thus be used to control the relative motion of two waveguide cantilevers. The effects presented here suggest a new way for holding a cantilever in a stable equilibrium as well as vibrating it, with applications in light-driven machines and sensing.

7606-20, Session 6

Low-loss silicon-on-insulator waveguides fabricated using proton beam irradiation

E. J. Teo, A. Bettiol, M. B. H. Breese, National Univ. of Singapore (Singapore); P. Yang, Univ. of Surrey (United Kingdom); B. Xiong, National Univ. of Singapore (Singapore); G. Z. Mashanovich, G. T. Reed, Univ. of Surrey (United Kingdom)

Most of the conventional photonic devices are built on a silicon-on-insulator substrate whereby vertical confinement is provided by the buried oxide layer produced by the SIMOX (Separation by Implantation of Oxygen) process. Subsequently, a lithographic and etching process is performed to define the waveguide and providing lateral confinement. In this paper, we use proton beam irradiation and electrochemical etching as an alternative technique for SOI waveguide fabrication. The technique gives us three-dimensional control of the optical confinement in a single irradiation-etch step.

Waveguide patterns created by 250 keV protons consist of localized regions of increased resistivity that are prevented from etching during subsequent anodization. The resultant structure becomes completely isolated in porous silicon. Smooth surface quality of 3.1 nm rms is achieved after post-oxidation treatment. Optical characterization at 1550nm wavelength shows a loss of 1.1 dB/cm in both TE and TM polarizations. This opens up new opportunities for all silicon-based optoelectronics applications since expensive SOI substrates are not needed and fewer processing steps are required.

7606-21, Session 7

Slow light photonic crystal switches and modulators

T. F. Krauss, Univ. of St. Andrews (United Kingdom)

One of the key problems of realising high speed, low power optical modulators in silicon is the size and resulting capacitance of the devices. I will discuss the benefit of the slow light effect for this purpose, which allows us to make modulators that are 10-20 times shorter than conventional devices while accomodating a sizeable bandwidth (5-10 nm). A particular challenge is the integration with CMOS Electronics. The same effect can also be used to make ultrashort switches, where we have already demonstrated switching times of order 3 ps.

7606-22, Session 7

High-speed silicon optical modulator

D. Marris-Morini, G. Rasigade, Institut d'Électronique Fondamentale (France); L. Vivien, P. Crozat, E. Cassan, Institut d'Electronique Fondamentale (France); P. Lyan, P. Rivallin, J. Fédéli, Commissariat à l'Énergie Atomique (France)

Silicon optical modulators have generated an increasing interest in the recent years, as their performances are crucial to achieve high performance optical links. Their evolution will be recalled, from the first demonstrations to the latest developments on high performance devices integrated in optical waveguides. Among possibilities to achieve optical modulation in silicon-based materials, the carrier depletion effect has demonstrated good capacities. Carrier depletion in Si and SiGe/Si structures has been theoretically and experimentally investigated. Recent results on high speed and low loss silicon optical modulator will be presented. It uses free carrier-concentration-variation, as free holes have been inserted inside a lateral pin diode and are depleted when the diode is reverse biased, leading to refractive index variations. This device presents a rather low capacitance which allows the reduction of RC time constant and power consumption. A Mach-Zehnder interferometer, with 4-mm long phase shifter, is used to convert the effective index variation into intensity modulation. Modulation contrast up to 15 dB, with insertion loss around 5 dB have been measured at 1.55µm. A -3dB optical bandwidth of 15 GHz has been experimentally demonstrated. These experimental results will be compared with simulations and expected performances will be discussed.

The research leading to these results has received funding from the European Community's Seventh Framework Programme (FP7/2007-2013) under grant agreement n° 224312 HELIOS.

7606-23, Session 7

Power and speed analysis of miniaturized SOI Y-branch Mach-Zehnder thermo-optic switches

K. P. Yap, National Research Council Canada (Canada) and Carleton Univ. (Canada); T. J. Smy, Carleton Univ. (Canada); J. H. Schmid, P. Waldron, A. S. Densmore, National Research Council Canada (Canada); B. A. Syrett, Carleton Univ. (Canada); S. Janz, National Research Council Canada (Canada)

Using 1×1 y-branch Mach-Zehnder Interferometers (MZIs) as our simulation models, we calculate the π-phase shift power and rise time of numerous silicon-on-insulator (SOI) thermo-optic switches as a function of miniaturization. These thermo-optic switches consist of different waveguide core layer thickness, ranging from 10, 3, 1.5, 0.7, 0.3 to 0.22 um. By scaling the waveguide from the largest 10 um ridge to the smallest 0.22 um channel, we show that the variation in π-power and speed of these switches follows a parabolic response, in which an optimum core layer thickness exists for the best power and speed performance. This optimum thickness is at 0.7 um, while further miniaturization results in an increased power and reduced speed. The descent in performance from further miniaturization is attributed to several factors: (i) the delocalization and expansion of mode from the waveguide core into the cladding layers, (ii) the thickening of cladding layers in an effort to minimize absorption loss from the metal heater, and (iii) the change in heat flow pattern as the waveguide shrinks in size. We quantitatively determine the contribution of each factor and propose several design options to improve the performance of miniaturized thermo-optic switches. These options include optimizing the MZI arm separation and heater width, as well as using silicon nitride as the cladding layer. The results from this study will provide useful guidelines to optical switch designers.

7606-24, Session 7

Strain engineering of Ge/SiGe quantum confined Stark effect modulators for communications wavelengths

L. J. Lever, Z. Ikonic, R. W. Kelsall, Univ. of Leeds (United Kingdom)

Conventional Si-based Mach-Zehnder modulators are generally large (several millimetres in length) and dissipate considerable amounts of power. The quantum-confined Stark effect (QCSE) is a strong electro-optic effect which can be exploited to create compact modulators, with low drive currents. Ge/SiGe multiple quantum well (MQW) structures have been demonstrated on Si substrates, and show a strong shift of the absorption edge under an applied field.

So far, however, modulation of 1310-nm light has not been achieved, and modulation of 1550-nm light has only been achieved by heating MQW structures to shrink the bandgap. We show simulation results, using a combined 6×6 k.p and effect mass modelling tool, of designs for of Ge/SiGe QCSE electro-absorption modulators at 1310 nm. This is achieved by employing strain engineering to shift the band edge of the Ge quantum wells to shorter wavelengths. Additionally, we demonstrate the feasibility of electro-refractive Mach-Zehnder based QCSE modulators operating at 1550 nm, and at room temperature.

We show designs for waveguide-integrated electro-absorption modulators operating at 1300 nm. The simulated data for our MQW structures shows that we can expect a contrast in the absorption coefficient greater than 4, and this leads to devices less than 100 µm in length, with an extinction ratio of 10 dB, and with an insertion loss due to the zero-field absorption in the MQW structure of 3 dB.

7606-25, Session 7

Charge injection using conformal junctions for low-energy optical switching

S. P. Anderson, P. M. Fauchet, Univ. of Rochester (United States)

Although switching techniques based on charge injection in silicon have progressed greatly in recent years, switching energies are still above 10 fJ/bit, which is considered the threshold for practical implementation in optical interconnects [Miller, Proc. IEEE 97, 2009]. This is due principally to silicon's relatively weak electro-optic response, as well as the large physical extent of existing switching geometries, both of which increase the number of charges that must be injected to effect switching. By using a resonant approach in which the optical mode is tightly confined, however, the volume of active material is reduced, resulting in decreased switching energy. In this work we report on the use of a thin MOS capacitor to inject charge into a resonator based on a photonic crystal microcavity. By injecting charge only into the volume in which the optical mode is localized, switching energy is theoretically reduced below 0.1 fJ/bit. The available index shift is large enough to allow use of a relatively low-Q resonator (Q < 2500), enabling high bandwidth and a device size of only 30 µm2.

7606-26, Session 7

Modulators and photodetectors developed in the framework of the European HELIOS project

L. Vivien, Institut d'Électronique Fondamentale (France); J. M. Fédéli, Lab. d'Electronique de Technologie de l'Information (France); D. Thomson, Univ. of Surrey (United Kingdom); J. Brouckaert, Univ. Gent (Belgium); J. Osmond, G. Rasigade, D. Marris-Morini, Institut d'Électronique Fondamentale (France); F. Y. Gardes, Univ. of Surrey (United Kingdom); P. Crozat, Institut d'Électronique Fondamentale (France); D. Van Thourhout, Univ. Gent (Belgium); E. Cassan, Institut d'Électronique Fondamentale (France); J. F. Damlencourt, Lab. d'Electronique de Technologie de l'Information (France); G. T. Reed, Univ. of Surrey (United Kingdom)

Silicon-based photonics have generated a growing interest with impressive results on active devices such as optical modulators and photodetectors in the last few years. The main reason of such an evolution is due to the possibility firstly to use optics to overcome the bottlenecks of metallic interconnects and secondly to reduce the cost and foot-prints of circuits for optical telecommunication applications. In the framework of the HELIOS project*, several research groups and industrial partners associate their efforts on the main building blocks to make high-speed optical links based on either silicon-based materials or III-V components bonded on silicon. Here, we present an overview of the main achievements first on PN and PIPIN optical modulators based on carrier depletion and then on germanium and III-V photodetectors integrated with silicon waveguides obtained at a wavelength of 1.55 µm. Optical modulators with -3dB bandwidths higher than 10 GHz and high modulation efficiencies have been obtained, as well as high speed (fC > 40 GHz) and high responsivity (R > 1 A/W at = 1.55 µm) photodetectors.

*Funding from the European Community's Seventh Framework Programme (FP7/2007-2013) under grant agreement n° 224312 HELIOS.

7606-27, Session 8

Integrated photonic platform based on silicon photonic wire waveguides

K. Yamada, T. Tsuchizawa, T. Watanabe, H. Shinojima, H. Fukuda, H. Nishi, S. Park, Nippon Telegraph and Telephone Corp. (Japan); Y. Ishikawa, K. Wada, The Univ. of Tokyo (Japan); S. Itabashi, Nippon Telegraph and Telephone Corp. (Japan)

Silicon photonics based on photonic wire waveguides is an emerging and attractive technology for high-density integrations of optoelectronic systems. A silicon photonic wire waveguide is a sub-microemeter-scale silicon-based waveguide. Its strong optical confinement makes photonic devices ultra-compact. Moreover, silicon-based photonic devices can be converged with electronics. The propagation loss of the waveguide has been reduced to around 1 dB/cm, and the coupling loss to an external fiber has been reduced to be around 0.5 dB. Various passive devices, such as wavelength filters, have been developed. Polarization dependence, which has been a serious problem, can be eliminated by using a recently developed on-chip polarization diversity circuit. Various dynamic and active devices have also been developed. In compact silicon-based thermo-optic switches, operation power has been reduced to be a few milliwatts. A more sophisticated carrier-injection-type variable optical attenuator (VOA) and germanium photodetectors have recently been developed and monolithically integrated. The VOA offers a nanoseconds response and the detectors show a 0.8-A/W responsivity and 50-nA dark current at -1V bias. The germanium detectors accurately detect light powers attenuated by the VOA. In silicon photonic wire waveguides with ultrasmall cores, optical power density is remarkably increased and various nonlinear effects are enhanced. For example, wavelength conversion based on the four-wave-mixing effect shows a practical conversion efficiency and bandwidth. These characteristics would be further improved by using a p-i-n carrier extraction structure and dispersion control. Some silicon-based photonic devices have already reached practical standards; therefore, the next step is their integration for practical applications.

7606-29, Session 8

Semiconductor nanomembranes for stacked and flexible photonics

W. Zhou, The Univ. of Texas at Arlington (United States); Z. Ma, Univ. of Wisconsin-Madison (United States)

Crystalline semiconductor nanomembranes (NMs), which are transferable, stackable, bondable and manufacturable, offer unprecedented opportunities for unique electronic and photonic devices for vertically stacked high density photonic/electronic integration, high performance flexible electronics, and flexible photonics. High quality single crystalline silicon NMs (SiNM) have been transferred onto various foreign substrates, such as glass, flexible PET (polyethylene terephthalate) plastics, etc., based on low temperature transfer and stacking processes. Very high performance electronics based on transferable Si/SiGe NMs were already reported. Flexible Ge photodetectors were also reported recently. We have also reported various photonic devices based on photonic crystal Fano resonances on Si, glass and flexible PET substrates. In addition to Group IV materials (Si, Ge, etc), NMs based on III-V (GaAs, InP, etc.) and other material systems are also being developed for heterogeneous integration (membrane stacking) on Si and other foreign substrates, with desired electronic and photonic functions.

We will report the design, fabrication and characterization of these unique photonic devices, with focus on the spectral, angular, and polarization properties, based on the dispersion engineering. Large area flexible photodetectors and solar cells have also been developed recently, based on the NM stacking processes, with very promising performances. The potentials and prospects of this low temperature NM stacking process will finally be discussed, on silicon photonic integration and inorganic flexible photonics.

Work is supported by US AFOSR MURI program (FA9550-08-1-0337), AFRL/CONTACT program (FA8650-07-2-5061), and US NSF Nano-manufacturing program (DMI-0625728)

7606-30, Session 8

Nanomembrane enabled nanophotonic devices

A. S. Sharkawy, O. Ebil, EM Photonics, Inc. (United States); M. J. Zablocki, D. W. Prather, Univ. Of Delaware (United States)

The proposed technology will enable the possibilities to develop adaptive intelligent photonics and electronics devices and systems that are flexible, deformable, and conformable. Thus all manner of Si & III-V devices can be fabricated, and high-volume manufacturing is feasible. Of particular interest are innovative approaches for the development of 1) flexible intelligent photonics (FIP): adaptive frequency selective photonic components, modulators, mechano-activated adaptive optics, 3D photonic crystals and membrane waveguides; 2) strain engineered ultrasensitive, high-speed SiNM/GeNM photodetectors; 3) Si-membrane-based light sources; 4) high-speed flexible, conformal, and/or 3-D electronics; 5) hybrid-orientation technology (HOT): fast flexible CMOS with integration on other hosts; 6) flexible conformal photovoltaics - integrated personal portable power sources; or 7) Si-membrane based thermoelectric materials. Adaptive intelligent photonic/electronic systems, improved detectors and imagers, light sources, conformal electronics and power sources, and very fast flexible electronics would all be of great value, with potential impacts in the areas of energy-efficient ultra-compact dynamic intelligent information collection, high-capacity data networks, and adaptive rapid-response systems.

7606-31, Session 8

Integrated recirculating optical buffers

M. J. R. Heck, G. Kurczveil, E. F. Burmeister, H. Park, J. P. Mack, D. J. Blumenthal, J. E. Bowers, Univ. of California, Santa Barbara (United States)

In this paper we first present the rationale behind photonic integration of optical buffers for packet switching using optical delay lines. Optical buffers in a recirculating, or feedback, configuration are shown to meet all requirements for 40-Gb/s operation with reasonable packet payload lengths, unlike alternative approaches based on e.g. slow light.

We review our work on integrated recirculating buffers consisting of indium phosphide-based gate matrix switches combined with either silicon or silica-on-silicon based delay lines. Successful implementation with packet recovery greater than 97% of such a hybrid integrated chip in a synchronously loaded optical packet buffer at 40 Gb/s and with 40-byte packets is shown.

We further show the possibilities of integration of an optical buffer on the silicon evanescent device platform, consisting of III-V quantum wells bonded to silicon waveguides, where an active gate matrix switch can be combined with a low-loss silicon delay line. Error free operation at 40 Gb/s with a packet delay of 1.1 ns is achieved with an integrated recirculating optical buffer in this technology. We report on our current efforts to integrate optical signal regeneration on the chip and to bring down the silicon loss for use in 40-byte packet systems, where 12.8-ns delay is required.

7606-32, Session 9

Optofluidic ring resonator dye lasers

Y. Sun, J. D. Suter, X. Fan, Univ. of Missouri, Columbia (United States)

We overview the recent progress on optofluidic ring resonator (OFRR) dye lasers developed in our research group. The fluidics and laser cavity design can be divided into three categories: capillary optofluidic ring resonator (COFRR), integrated cylindrical optofluidic ring resonator (ICOFRR), and coupled optofluidic ring resonator (CpOFRR). The COFRR dye laser is based on a micro-sized glass capillary with a wall thickness of a few micrometers. The capillary circular cross-section forms the ring resonator and supports the whispering gallery modes (WGMs) that interact evanescently with the gain medium in the core. The laser cavity structure is versatile to adapt to the gain medium of any refractive index. Owing to the high Q-factor (>109), the lasing threshold of 25 nJ/mm2 is achieved. Besides directly pump the dye molecules, lasing through fluorescence resonance energy transfer (FRET) between the donor and acceptor dye molecules is also studied in COFRR laser. The energy transfer process can be further controlled by designed DNA scaffold labeled with donor/acceptor molecules. The ICOFRR dye laser is based on a cylindrical ring resonator fused onto the inner surface of a thick walled glass capillary. The structure has robust mechanical strength to sustain rapid gain medium circulation. The CpOFRR utilizes a cylindrical ring resonator fused on the inner surface of the COFRR capillary. Since the capillary wall is thin, the individual WGMs of the cylindrical ring resonator and the COFRR couples strongly and forms Vernier effect, which provides a way to generate a single mode dye laser.

7606-33, Session 9

16-channel MUX/DeMUX Si ring filters designed and fabricated by 365nm Hg-I line photolithography

S. Park, K. Kim, G. Kim, Electronics and Telecommunications Research Institute (Korea, Republic of)

The large refractive index contrast between Si core and oxide cladding gives rise to the strong confinement of light in the typical dimension, 220nm x 500nm, of Si waveguide, which requires a very small gap width in the coupling region, typical width of 100nm. The gap width is smaller than the minimum size of 120 nm, or guaranteed size of 160 nm, of the ArF photolithography. The Si ring resonators in most published papers have been prepared by E-beam lithography. To be integrated in CMOS-process-compatible photonic interconnect circuits it is necessary to use KrF or ArF photolithography.

We designed a Si ring resonator filter to be fabricated by 365nm Hg-I line photolithography of which resolution is much worse than KrF or ArF photolithography. The mode volume of the electric field in the coupling region was magnified by reducing the size of waveguide to 190 nm x 400nm. The waveguide size in the non-coupling region is 190 nm x 1200 nm, which we confirmed by observing far-field pattern and transmitted spectra that it transmits only the fundamental mode for TM component. The gap width in the coupling region is 1.5 m for 1st order rings and 1 m and 2.5 m for 3rd order rings. We observed nice spectra of all 16 channels for 1st and 3rd order rings, which proves that lithography is not an obstacle for Si ring devices to be integrated into the photonic integrated circuits.

7606-34, Session 9

Highly dispersive one-dimensional photonic crystal embedded silicon microring cavities

J. Y. H. Lee, P. M. Fauchet, Univ. of Rochester (United States)

Microring cavities have become one of the important building blocks in photonic integrated circuits. However, their large free spectral range (FSR) limits their capacity to support multiple optical channels in wavelength-division multiplexing technology. We report a microring cavity structure consisting of a closed-loop photonic crystal waveguide that eases this limitation. It consists of a silicon waveguide embedded with one-dimensional periodic air holes. We evanescently in- and out-couple light to this photonic crystal ring cavity (PCRC) using a straight waveguide. The waveguide widths are optimized to achieve efficient coupling near the photonic band edge. We simulate the throughput transmission and reflection spectra, and the steady-state mode profiles using 2-D FDTD. Near the photonic band edge, the resonant mode indices increase and strongly dispersive. We obtain a small FSR of 1.1 nm with PCRC diameters of ~15 µm. The slow light propagation allows longer photonic lifetimes and higher quality factors of Q ~ 4,000. Compared to a control microring cavity of the same size, the FSR of the PCRC decreases by one order of magnitude, and the Q-factor increases by a factor of 5. Moreover, degenerate modes are excited assisted by the periodic photonic crystal structure. We observe beating patterns in the resonance intensity profile, which is caused by the interference of the degenerate modes. Preliminary devices are fabricated for demonstrating our approach. This highly dispersive PCRC should be useful as optical buffers and ultrasensitive optical sensors. This work is supported by AFOSR (G. Pomrenke).

7606-35, Session 9

Numerical investigation of high-Q resonances in circular grating resonators

S. Burger, Konrad-Zuse-Zentrum für Informationstechnik Berlin (Germany); F. Schmidt, L. W. Zschiedrich, JCMwave (Germany)

Circular grating resonators (CGR) are a potential candidate for future on-chip all-optical switches. In a recent experiment, high-Q resonances and switching in such a devices, fabricated with silicon-on-insulator technology, have been demonstrated [1].

Rigorous 3D Maxwell solvers are helpful in the design of such structures, however, due to the complex structure of CGRs and due to the large volume of the computational domains, accurate computation of field distributions and Q factors in CGR setups is numerically challenging [1].

We have developed finite-element method (FEM) based solvers for the

Maxwell eigenvalue and for the Maxwell scattering problems. The method is based on higher order vectorial elements, adaptive unstructured grids, and on a rigorous treatment of transparent boundaries [2].

We have simulated the experimental setups reported in the literature [1]. We present a convergence analysis of the numerical results, and we present good agreement with experimental results.

We further investigate the influence of structural parameterson the CGR Q factor.

[1] S. Schoenenberger et al., Opt. Express 17, 5953 (2009).

[2] S. Burger, L. Zschiedrich, J. Pomplun, F. Schmidt, JCMsuite - an adaptive FEM solver for precise simulations in nano-optics, in Int. Phot. and Nanophot. Res. and Appl. (OSA), ITuE4 (2008).

7606-36, Session 10

Applications of coherent anti-Stokes Raman scattering in silicon photonics

N. Vermeulen, C. Debaes, H. Thienpont, Vrije Univ. Brussel (Belgium)

An important category of nonlinear light-matter interactions are Raman scattering interactions. When a Raman scattering process takes place in a material, incident photons interact with a characteristic energy level of the material, such as a vibrational energy level, so that new photons with a different energy and wavelength are generated. Although there exist many different types of Raman scattering processes, only few attracted as much attention over the past decades as Coherent Anti-Stokes Raman Scattering or CARS. Apart from its widespread use as optical analysis tool in spectroscopy and microscopy, CARS can also be employed as light generating mechanism in photonic devices based on Raman-active media, such as Raman wavelength converters and Raman lasers.

CARS is a four-wave mixing process - an interaction involving four electromagnetic waves - that yields high efficiencies in case the phase mismatch associated with this four-wave mixing interaction is small. This condition can be fulfilled in optical waveguides, since the dispersion in these media, which is a determining factor for the phase mismatch between the waves involved in the CARS process, can be engineered in a flexible way. Especially silicon-based waveguides are very appropriate for achieving a specific phase mismatch value, since there has been tremendous progress over the past decades in their design and fabrication. Taking also into account the strong Raman susceptibility of silicon, one finds that the light generating functionality of CARS can be very effectively exploited in Raman devices based on silicon waveguides.

In this paper, we will first address the differences between the uses of CARS as optical analysis tool and as light generating mechanism. Next, with respect to the light generating functionality of CARS, we will review the latest progress on CARS-based Raman wavelength converters in silicon-on-insulator (SOI) technology and explain how these converters can be made compact, efficient, and relatively insensitive to fabrication tolerances. Finally, we will show that the CARS process can not only generate new wavelengths but is also able to extract heat from a Raman-active medium and that therefore CARS can be used for reducing the heat dissipation in SOI-based Raman devices.

7606-37, Session 10

Using reach-through techniques to improve the external power efficiency of silicon CMOS light emitting devices

M. du Plessis, P. J. Venter, Univ. of Pretoria (South Africa); A. W. Bogalecki, INSiAVA (Pty) Ltd. (South Africa)

For CMOS silicon-based light emitting devices to become practical the external power efficiency must be increased. In this paper a reach-through technique is described whereby the external power efficiency can be increased as a result of three phenomena: i) Increase in internal quantum efficiency, ii) Increase in external quantum efficiency, and iii) Lower operating voltage.

In reach-through devices the n+p junction depletion region spreads from the n+ material into the lightly doped p-type material and reaches through towards a closely placed p+ doped region. Shortening the spacing between the n+ and p+ regions will lower the avalanche breakdown voltage, and eventually field-emission breakdown will occur at very short distances. Using this technique the operating voltage of the device can be lowered.

Since the electric field within the reach-through depletion region is almost constant over a relatively long distance, impact ionization will occur over a longer distance in the silicon. The result is higher carrier concentrations of both electrons and holes, leading to more efficient and radiative carrier interaction, thus increasing the internal quantum efficiency.

In 350 nm CMOS technology the n+p impact ionization will be dominant near the LOCOS (local oxidation) periphery of the junction, but using the n+pp+ reach-through structure the radiation source will move towards the parallel plane surface of the device, increasing the external quantum efficiency.

The six times improvement in external power efficiency will be analyzed making use of the electrical current-voltage characteristics as well as experimental three-dimensional radiation patterns from the Si-based light emitting devices.

7606-38, Session 10

New interpretation of photonic yield processes (450-750nm) in two-junction Si CMOS LEDs: simulation and analyses

L. W. Snyman, Tshwane Univ. of Technology (South Africa); E. Bellotti, Boston Univ. (United States)

We have recently made new interpretations on the photonic yied processes as they occur in two junction injection-avalanche, 450-750nm, light emitting devices (InAvLEDs) (Snyman et al, Japanese Journal Applied Physics, 2007; Snyman et al, Proc SPIE, Vol 6898, OE 1- 12, 2008). Advanced device simulations were performed using SENTAURUS device modelling software follwed by subsequent physical interpretations of existing results. These simulations indicate that controlling the energies of injected carriers into avalanching light emitting junctions are crucial in enhancing the photonic transitions and yield from the device and that very special device design procedures should be implemented. Diverse examples of the advanced modelling as were peformed will be given, as well as the correlation with existing experiminental observations will be presented. Indications are that the yieds can be increased by about three orders of magnitude, as compared with single junction CMOS avalanche LEDs (Snyman et al, IEEE Photonic Technology Letters, 2005) yielding potential light emission spots of of up to 10-100 nW / µm 2 in micron dimension areas, all fabricated in 0.35 micron CMOS integrated circuitry. The emission power is about three orders higher than the dedectivity of pn CMOS based detectors. The technology has application in new generation CMOS and optoelecronic based data processing, as well as in generating new generation CMOS IC- based MOEMS (Proc.SPIE, Vol.7208, 72080C, 2009). The technology also offers new innovative applications in bio - technology and in nanotechnology. The work forms the topic of three new South Africa Provisional Patent Applications 2009/04161, 2009/04163, 2009/04164.

7606-39, Session 10

Lateral electrical injection into Si/SiO2 horizontal multislot waveguides

S. P. Anderson, H. G. Yoo, K. Ni, P. M. Fauchet, Univ. of Rochester (United States)

Development of a silicon-based on-chip light source has recently focused on the incorporation of nanocrystalline silicon (nc-Si) into a multislot waveguide structure [Yoo et al, Opt. Express 16, 2008], using erbium embedded in silicon oxide as a luminescence source. The multislot confines TM polarized light in the oxide (low-index) layers, thus reducing the loss caused by interaction with free carriers in the nc-Si layers. Here we demonstrate a lateral electrical injection scheme using a p-i-n junction embedded into the multislot, allowing much more efficient charge injection than alternative vertical injection approaches which have been limited by the highly insulating oxide layers. By exploiting the difference in the mode profiles of TE and TM light, we were able to gauge the injection of free carriers as a function of applied voltage by measuring the polarization-dependent optical loss for light transmitted through the multislot. Experimental measurements are well-predicted by numerical simulations using both FDTD and the transfer matrix method.

7606-40, Session 11

Waveguide-based optofluidics

C. Karnutsch, The Univ. of Sydney (Australia) and Hochschule Karlsruhe (Germany); S. Tomljenovic-Hanic, C. Monat, C. Grillet, P. Domachuk, R. McPhedran, B. J. Eggleton, The Univ. of Sydney (Australia); L. O'Faolain, T. F. Krauss, Univ. of St. Andrews (United Kingdom); S. Xiao, N. A. Mortensen, Technical Univ. of Denmark (Denmark)

Optofluidic devices exploit the characteristics of liquids to achieve a dynamic adaptation of their optical properties. The use of liquids allows for functionalities of optical elements to be created, reconfigured or tuned. We highlight the benefits of an optofluidic approach, making specific reference to microfluidic optical cavities created in silicon photonic crystal (PhC) waveguide platforms. PhC cavities represent a versatile building block for realizing micron-scale optical control, promoting their use in applications such as channel-drop filters or optical switches.

In this paper, we will discuss the most recent results of our work on silicon-based optofluidics. We show that PhC microcavities can be formed by infusing a liquid into a selected section of a uniform PhC waveguide and that the optical properties of these cavities can be tuned and adapted (reconfigured) by either altering the dimensions of the infiltrated region, or removing the infiltrated liquid using organic solvents.

By taking advantage of the negative thermo-optic coefficient of liquids, we describe a new method which renders PhC cavities insensitive to temperature changes in the environment. This is only one example where the fluid-control of optical elements results in a functionality that would be very hard to realize with other methods and techniques.

7606-41, Session 11

Photonic crystal microcavities in SOI waveguides produced in a CMOS environment

S. Meister, A. Al-Saadi, B. A. Franke, S. Mahdi, K. Voigt, Technische Univ. Berlin (Germany); B. Kuhlow, Fraunhofer-Institut für Nachrichtentechnik Heinrich-Hertz-Institut (Germany); B. Tillack, H. H. Richter, L. Zimmermann, IHP GmbH (Germany); V. Ksianzou, S. K. Schrader, Technische Fachhochschule Wildau (Germany); H. Eichler, Technische Univ. Berlin (Germany)

We have investigated microcavities in Silicon-on-Insolator (SOI) waveguides. The rectangular waveguides with 500 nm width are fabricated in a 220 nm silicon device layer. The microcavities are formed by one-dimensional photonic crystals in Fabry-Perot structure directly written in the waveguides.

The SOI photonic structures are produced in a CMOS environment using a 248 nm DUV lithography. The waveguides as well as the photonic crystal microcavities are created in the same step using a single mask. The results are compared to that of similar structures produced by electron-beam lithography.

The one-dimensional photonic crystals have cavity lengths of a few wavelengths and such filters allow therefore a very high degree of integration. The cavities can act as band pass filters and are also suitable for electrooptic modulation of light.

In order to achieve the desired spectral shape of the filter function for several applications, a number of different cavities were designed and investigated, for instances single cavities of first and higher order as well as multi-cavity filters.

The experimental results are compared with simulations of photonic crystal microcavities in strip waveguides. The spectral transmission function of the filters dependent on the design parameters are calculated by an analysis based on a Finite-Difference Time-Domain (FDTD) method.

Additionally, the temperature influence on the filter peak-wavelength of the microcavities were investigated.

7606-28, Session 12

Thin film III-V edge emitting lasers integrated onto silicon

N. M. Jokerst, S. Palit, Duke Univ. (United States); J. Kirch, G. Tsvid, L. J. Mawst, T. F. Kuech, Univ. of Wisconsin-Madison (United States)

The integration of compound semiconductor edge emitting lasers onto silicon enables the realization of complete optical systems on silicon for chip scale applications. One interesting application for III-V lasers on Si is portable optical sensing for medical, environmental, and security applications. For these applications, the chip scale integration of an entire optical sensing system is a design goal, including an optical source, waveguide interconnect, optical sensors, and optical detection. For system portability, low power consumption and low heat dissipation are essential, which drives high efficiency optical components, interfaces, and interconnections. Processes and tradeoffs for the integration of III-V edge emitting lasers onto Si will be discussed, including laser contact schemes and metal/metal bonding for heat dissipation. Results for contacts (n and p) on the top side of thin film lasers will be presented, as well as results for contacts on both sides of the thin film lasers. Test results for lasers integrated onto Si with other optical components will also be discussed, including waveguides, passive couplers, and photodetectors. Prospects for chip scale integrated sensing systems on Si using these components and sensors will also be presented.

7606-29, Session 12

Compact hybrid Si microring lasers

D. Liang, J. E. Bowers, Univ. of California, Santa Barbara (United States); M. Fiorentino, R. G. Beausoleil, Hewlett-Packard Labs. (United States)

Microring resonator lasers are promising components for photonic integrated circuits due to their small size, single mode lasing behavior and the fact that etched or cleaved facets are not required. In this paper we review the recent progress in developing compact microring lasers on the hybrid silicon platform. A simplified self-aligned process is used to fabricate devices as small as 15 micrometer in diameter. The optically-pumped, continuous wave (cw) devices show low threshold carrier density, comparable to the carrier density to reach material transparency. In the electrically-pumped lasers, the short cavity length leads to the minimum laser threshold less than 5 mA in cw operation. The maximum cw lasing temperature is up to 60 deg.C. Detailed studies in threshold and differential efficiency as a function of ring diameter, coupling coefficient, and bus waveguide width are presented. Surface recombination at the dry-etched exposed interface is investigated qualitatively by studying the current-voltage characteristics. Ring resonator-based figures of merits including good spectral purity and large

side-mode suppression ratio are demonstrated. Thermal impedance data is extracted from temperature-dependent spectral measurement. High-speed measured results are presented as well.

The demonstrated compact hybrid ring lasers have low power consumption, small footprint and dynamic performance. They are promising for Si-based optical interconnects and flip-flop applications.

7606-30, Session 12

Monolithic integration of the Ga(NAsP)-laser material lattice matched on (001) Si-substrate

W. Stolz, Philipps-Univ. Marburg (Germany); B. Kunert, NAsP III/V GmbH (Germany); S. Liebich, M. Zimprich, S. Zinnkann, K. Volz, Philipps-Univ. Marburg (Germany)

The novel direct band gap, dilute nitride Ga(NAsP)-material system allows for the first time the monolithic integration of a III/V laser material lattice matched to Si substrate. This lattice-matched approach allows for the first time for a high-quality, low defect density integration of a III/V-laser material potentially leading to long-term stable laser devices on Si-substrate. The broad area laser structures consist of pseudomorphically strained active Ga(NAsP)/(BGa)(AsP) multi-quantum-well heterostructures (MQWHs) embedded in thick doped (BGa)P waveguide layers, grown by a specific low-temperature metal organic vapour phase epitaxy (MOVPE) process on (001) Si-substrate. The optimization of the laser properties focus on improvements in material quality based on MOVPE growth conditions as well as the design parameters such as optimal carrier and light field confinement, doping levels and post-growth annealing treatments. This paper will present and discuss the current status to realise electrical injection laser diodes as a basis for Si-photonics based opto-electronic integrated circuits (OEICs) with novel functionalities.

7606-31, Session 12

Sb-based laser sources grown by molecular beam epitaxy on silicon substrates

J. Rodriguez, L. Cerutti, P. Grech, G. Boissier, G. Narcy, E. Tournie, Univ. Montpellier 2 (France)

The material system comprising GaSb, InAs, AlSb and their related alloys are an impressive toolbox for device designers, as they offer a very large choice of band-gaps and band offsets. Molecular beam epitaxy (MBE) and device processing have been improved quickly over recent years, allowing the fabrication of high performance devices as quantum cascade lasers, mid-infrared edge (MIR) emitting and surface emitting lasers, superlattice infrared photodetectors, but also very high speed / low consumption AlSb/InAs field effect transistors.

Efforts have been made to monolithically grow these devices onto larger and cheaper substrates like GaAs and Si, to improve the yield / decrease the cost of this technology and possibly integrate the devices with CMOS technology.

We recently fabricated a 2.3 μm edge emitting laser grown by MBE on a Si substrate, and demonstrated room-temperature pulsed operation. Lasers emitting at this wavelength are of particular interest for gas sensing. Challenges to further improve the device include the substrate preparation, optimization of the nucleation layer quality, but also the conduction band engineering in order to facilitate the electronic transport at the Si/III-Sb interface.

In this communication, we describe our efforts to address these issues, and discuss our latest results on antimonide-based lasers emitting at different wavelengths and grown on Si substrates.

7606-28, Poster Session

Silicon radiative cooler and optical amplifier by light down conversion

V. K. Malyutenko, V. V. Bogatyrenko, O. Y. Malyutenko, V. Lashkaryov Institute of Semiconductor Physics (Ukraine)

Primary challenges in Si science and technology are centered on active device engineering issues with the impact made at their photonic characteristics and applications. Low cost and mature Si technology is driving force toward making optoelectronic devices like LEDs, lasers, modulator, wavelength converter, to name a few. However, to fully exploit tremendous potential of these Si-based devices, which are not as efficient as their III-V-based counterparts, external cooling units are required. In this work, we present a first step towards experimental realizing radiative cooling in Si. The fundamentals behind this approach are in the light down-conversion process through thermal emission that releases the energy from the cooling element in the form of multiple intraband red-shifted photons when it is pumped with interband incoherent light. We demonstrate that a large-area Si wafer kept in an evacuated chamber becomes net cooled by >3.0 K starting from 470 K (in adiabatic conditions) or demonstrates power conversion efficiency of > 100% (in isothermal conditions) when pumped with 1.06-μm light. One of the other attractive attributes of the device is that it can be easy integrated with other silicon photonic components. We also discuss the way toward further improvement of the performance of these devices.

7606-42, Poster Session

Silicon photonics: ready to wafer-bonding fibre grating coupler

C. H. Kopp, T. Dupont, J. Fedeli, Commissariat à l'Énergie Atomique (France)

Silicon nanophotonic circuits can exhibit a very high level of functional integration that can be added directly into IC layers. Such an integration is typically performed by wafer to wafer bonding: the first wafer having the optical and optoelectronic layers, the second wafer having the microelectronic layers. After the substrate removing at the photonic wafer side, the optical structures appear then face down when compared with the initial fabrication. This structure flip may be detrimental to the performance of fibre grating couplers as there is no more a box and silicon substrate as with gratings on SOI.

We present an efficient fibre grating coupler with a bottom mirror that anticipates the structure flip. In this approach the mirror is first coated above the encapsulation layer of the fibre grating coupler in order to appear below it after the optical layers integration onto an IC wafer. This way the thickness between the grating and the bottom mirror, which is a very sensitive parameter, remains under control whatever the wafer to wafer bonding process tolerances. For this design we can compare the efficiency of various bottom mirror structures using metallic or amorphous silicon coatings. We show then that this wafer-bonding compatible design increases the fibre grating coupler efficiency from 50% to more than 80% with a spectral bandwidth of more than 60nm at 1dB.

7606-43, Poster Session

Light emission from Si LED controlling by a gate voltage and SOS tunneling junction

W. L. Guo, X. Li, G. H. Yang, P. J. Niu, Tianjin Polytechnic Univ. (China); C. H. Huang, Tianjin Samsung optoelectronics Co. Ltd. (China)

A novel silicon LED with three terminals has been designed and fabricated compatible completely with standard n-well CMOS technology. It is composed from a combination of two active parts: one

of them is a structure like a p-MOS field effect transistor but the drain region is replaced by an n+-region which can be taken as the n+-contact of n-well. In this structure, the injecting hole potential barrier between the p+-emitter and n-well will be lowered by the positive gate voltage. So the p+-n junction forward biased current can be controlled to increase by a positive gate voltage; Another light emitting active part is a poly-Si/ultrathin oxide/Si tunneling junction composed between poly-Si gate and n-well. The experimental results show that: (1)The optical output power measured by a optical power meter increases with both the current injected from the forward biased p+-n junction and the positive gate voltage; (2)As the injection current of p+-n junction is zero, the optical output power still increases with gate voltage, this shows that the optical output power emitted from poly-Si/ultrathin oxide/Si tunneling junction increases with positive gate voltage; (3)The spectra of the optical output power versus wavelength has been measured by a optical power meter for different wavelength. It is shown that an optical power peak raises at near 1000nm. All of the measured results can be explained by gate voltage induced barrier lowering effect for hole injection current and light emission model of MIS tunneling junction.

7606-44, Poster Session

Athermal and low loss ridge silicon waveguides

M. M. Milosevic, G. Z. Mashanovich, F. Y. Gardes, Y. Hu, Univ. of Surrey (United Kingdom); A. P. Knights, McMaster Univ. (Canada); N. G. Tarr, Carleton Univ. (Canada); G. T. Reed, Univ. of Surrey (United Kingdom)

In the last few years there has been an increased challenge to achieve temperature stability of silicon photonic devices, which is one of the key obstacles to development of viable commercial optoelectronic products. Low loss silicon waveguides have also been intensively investigated in recent years due to their importance for integrated photonic circuits. In this paper, we investigate a silicon-on-insulator (SOI) rib waveguide structures and propose design rules to achieve low propagation losses and athermal behaviour. Using the LOCal Oxidation of Silicon (LOCOS) technique, submicron waveguides with minimal roughness at the Si/SiO2 interface can be fabricated achieving low propagation loss of 0.1dB/cm for TE polarization, whilst the losses for TM polarization are usually higher. We have modelled propagation losses for the TM mode, for different dimensions of rib waveguides, achieving good agreement with experimental measurements. At certain waveguide widths, it is possible to obtain low propagation losses for both TE and TM modes. Polymers that have a negative thermo-optic coefficient are used for the top cladding, to compensate for the positive thermo-optic coefficient of the waveguide core, resulting in an athermal design. Significant reduction of temperature dependence can be achieved by using appropriate waveguide dimensions and adjusting the waveguide cross-section. Racetrack ring resonator structures based on rib waveguides have been fabricated aiming for an athermal design and therefore, for a very small temperature dependent wavelength shift (TDWS). Design guidelines for temperature insensitive and low propagation loss rib waveguides are presented in this paper together with experimental data.

7606-45, Poster Session

High-performance ring microresonator on SOI coupled to photonic wires

V. A. Melnikov, M. Lynch, J. F. Donegan, T. S. Perova, Trinity College Dublin (Ireland)

A high-performance ring microresonator with coupled photonic wires integrated on SOI has been realized. The device was fabricated on SOITEC Unibond SOI wafers with 220 nm device layer and 1 µm buried oxide by electron-beam lithography and inductively coupled plasma etching in the framework of Science Foundation Ireland National Access Programme (NAP 168) in the National Tyndall Institute, Cork, Ireland. Two photonic wires with 220x500 nm cross-section provide light coupling to the ring microresonator with diameter of 48.5 µm. Cleaved bare single-mode optical fibres attached to gratings into 10 um width tapered waveguides were used to couple light to the photonic wires. Transmission spectra were measured in a range from 1510 nm to 1630 nm with 10 pm resolution using Santec high performance tunable laser TSL-510 and InGaAs photodiode. Several resonances have been demonstrated in the range from 1510 nm to 1560 nm with free spectral range of 4 nm (500 GHz). Some resonances have quality factor exceeding 15000 and an extinction ratio over 15 dB which seems promising for sensing applications. Some other resonances preserves extinction ratio over 15 dB whilst having smaller quality factor of 5000 and corresponding bandwidth over 35 GHz, which can be exploited for compact wide-band WDM add-drop filters and on-chip interconnects with high-bit-rate data channels.

7606-46, Poster Session

Taper-integrated multimode-interference based crossings for silicon wire waveguides

C. Chiu, C. Chen, National Chiao Tung Univ. (Taiwan)

Ultracompact multimode-interference (MMI)-based waveguide crossings integrated with miniature tapers for high-index-contrast silicon wire waveguides are introduced numerically. The short tapers with large tapering angles are designed to convert some of guided input mode into radiation wave to diminish the transition loss between the input (or output) waveguide and the MMI region by expanding the field distribution and to minimize the beam width of the self-image at the center of the MMI section to suppress the diffraction in the crossing region by adjusting coupling efficiency of each mode of the MMI waveguide. In addition, we observe self-image process is performed not only in the MMI region but also in the taper section, giving rise to reductions in lengths of MMI sections and in dimensions of crossings. Performances of waveguide crossings constructed by 3-mode waveguides and various structured tapers are investigated, carried out by the three-dimensional finite difference time domain method with the fundamental TE-like mode of the input waveguide as the incident wave. Simulation shows that the waveguide crossing with quadratic tapers exhibits the MMI crossing lengths of 3800 nm, less than twice of beat length. This design displays the size of 5800x5800 nm2, the insertion loss of 0.13 dB, the crosstalk of -29 dB at the wavelength of 1550 nm and flat transmission response of less than 0.3 dB within 1500-1600 nm wavelength range.

7606-47, Poster Session

High phase-shift efficiency in a silicon optical modulator based on carrier depletion effect in a PN diode

J. W. Park, Electronics and Telecommunications Research Institute (Korea, Republic of)

Silicon photonics has recently obtained a great interest because it can offer cost-effective solutions in the areas ranging from fiber-optic telecommunications down to chip-to-chip optical interconnects. Silicon optical modulator is one of the important building-blocks needed for realization of solutions. In this paper, we present high phase-shift efficiency in a Mach-Zehnder silicon optical modulator based on the carrier-depletion effect. The effect of the high doping concentration in a PN diode with a small cross-sectional area rib waveguide has been investigated. Higher doping level can introduce more change of the carrier concentration in a PN junction interface, which contribute to more effective index modulation. The confinement of photons and the PN junction interface within a small region leads to a strong overlap between the optical filed and the active region of the carrier concentration variation, resulting in the enhancement of the effective index change, and thus enhancement of the extinction ratio. The measured phase-shift efficiency of the fabricated modulator, V L , is ~2 V cm, indicating a high phase-shift efficiency. The device with a 1.5 mm-long phase shifter shows the 3-dB bandwidth of 7 GHz. The extinction ratio of 3 dB at the bit rate of 12.5Gbps is obtained in a device with a 750 m-long phase-shifter. Also the device with a 2 mm-long phase shifter exhibits a high extinction ratio of ~7 dB at the bit rate of 4 Gbps.

7606-48, Poster Session

Experimental and numerical analysis study of 1D photonic crystal in Si photonic wire waveguides

K. Tomohiro, H. Yamada, Tohoku Univ. (Japan)

Silicon photonic-wire waveguides have achieved strong light confinement in nanometer-size small cross-section waveguides, and compared with all-silica devices, a huge reduction in size and power consumption is expected. In recent years, various optical components, such as ring resonators, Mach-Zehnder interferometers, etc., have been realized. We especially focus on the in-line filtering waveguides, including Bragg-grating structures, because these structures are key components to realize practical integrated photonic devices like OADMs and grating couplers. In-line type Bragg-gratings consist of periodical notch structures operating as a 1-dimensional photonic crystal, in which the specific wavelength corresponding to the Photonic Band Gap (PBG) is reflected. We fabricated and measured Bragg-gratings in Si-wire photonic waveguides with various geometrical parameters. The reflected wavelength was controlled between 1440 nm and 1562 nm. The narrowest PBG was 5.8 nm at 1555 nm. These results show good agreement with the numerical analysis.

7606-49, Poster Session

Analysis of all optical logic gate based on photonic crystals multimode interference

H. S. Kim, Chung-Ang Univ. (Korea, Republic of); D. Kim, Korea Photonics Technology Institute (Korea, Republic of); T. Lee, G. Oh, Y. Choi, Chung-Ang Univ. (Korea, Republic of)

Recently, many methods have been proposed to meet the demand for all optical gates in a high speed digital system. As of the optical gates multimode interference (MMI) device has many prominent features, such as fast signal processing, small size device, multifunctional performance, low loss, and large optical bandwidth. In this paper, we propose an optical MMI logic gate based on photonic crystals (PhCs). All optical logic gate with multifunctional performance has been designed theoretically in two dimensional PhCs structure using MMI principle. The PhCs consist of periodical air holes in silicon on insulator structure. The MMI using line defect waveguide is a 3×3 structure on the PhCs. By switching the optical signal to different input waveguide ports, the device can operate as NAND, NOT, NOR, and OR gates simultaneously or individually. Moreover, the proposed structure has much smaller size than previously studied optical logic gates based on ridge waveguide MMI. Our proposed structure would be very useful for construction of optical circuit, optical computer, and future Si-based optical integrated circuits.

7606-50, Poster Session

Mode properties of ALD filled silicon slot waveguides

A. Säynätjoki, T. Alasaarela, A. Khanna, A. Tervonen, S. K. Honkanen, Helsinki Univ. of Technology (Finland)

The slot waveguide facilitates light confinement into a low-index material on silicon [1]. Filled with an optimal material for a specific purpose (e.g. nonlinearities or light emission), the slot waveguide may therefore be utilized to enhance the performance of silicon photonic devices, or to add their functionality. However, complete filling of the slots, which is essential in order to avoid excessive scattering losses, has proved to be difficult [2].

Atomic layer deposition (ALD) is a CMOS compatible method to grow optical materials of excellent quality and with perfect step coverage even on high aspect ratio structures. Recently, we have shown that slot waveguide structures can be conveniently filled using ALD [3]. In this work, we present our recent progress towards ALD filled silicon slot waveguides. The effects of the slot geometry and the optical parameters of the filling material on the mode properties are studied, and latest experimental results on slot waveguide structures filled with ALD grown thin films are shown.

[1] V.R. Almeida, Q. Xu, C.A. Barrios, and M. Lipson, Opt.Lett. 29, 1209 (2004).

[2] E. Jordana, J.M. Fedeli, P. Lyan, J.P. Colonna, P.E. Gautier, N. Daldosso, L. Pavesi, Y. Lebour, P. Pellegrino, B. Garrido, J. Blasco, T. Cuesta-Soto, P. Sanchis, Group IV Photonics, 2007 4th IEEE International Conference on , paper ThC3.

[3] T. Alasaarela, A. Säynätjoki, P. Stenberg, M. Kuittinen, S. Honkanen, Integrated Photonics and Nanophotonics Research and Applications (IPNRA), Honolulu, Hawaii, USA, July 12-17, 2009, Paper JTuB4.

7606-51, Poster Session

Design and characterization of a large cross-section MZI rib waveguide on SOI substrate for biosensing application

J. M. Novak, S. Deng, G. Soliman, Z. R. Huang, Rensselaer Polytechnic Institute (United States)

This paper explores the design, fabrication, and testing of an integrated Mach-Zehnder interferometer (MZI) type of biosensor that is utilized on silicon-on-insulator (SOI) substrate for label-free bioagent detection. Sensing is achieved through the interaction of the evanescent wave in a silicon waveguide with the trapped bio-molecules at the waveguide surface. A rib waveguide structure is chosen for this work. The rib width of the Si layer is 3μm, and the thickness is 250nm. A rib height of 150nm is created using plasma etching. The large cross-section of the rib waveguide allows standard photolithography processing for ease of fabrication. The integrated biosensor consists of three segments: s-bend waveguide, Y-splitter and Y-combiner, and sensing arms. A radius of 5μm is designed in the s-bend to eliminate the light propagation of higher-order modes in order to provide single-mode operation. A mode-power extinction ratio of 8dB was demonstrated experimentally between the first-order mode and fundamental mode at the s-bend. Y-junctions are used for power splitting and combining, with a branching half-angle of 1°. A power splitting offset of <7.4% was achieved at the Y-splitter and an optical power leakage of <13dB was demonstrated along the center direction of the waveguide in comparison to the guided wave in the MZI arms. The mode profiles after each stage are examined by an infrared camera and image analyzer. Fiber-to-waveguide coupling is obtained by an integrated V-groove structure. The fabrication of the V-groove on an SOI wafer will also be discussed in this paper.

7606-53, Poster Session

Nano-circular Aperture with mirror for photonic tornado effect

S. Choi, Sun Moon Univ. (Korea, Republic of); N. Park, S. H. Han, D. Kim, Seoul National Univ. (Korea, Republic of); M. J. Park, Korea Military Academy (Korea, Republic of); V. Jha, O. K. Suwal, Sun Moon Univ. (Korea, Republic of)

In this report, the nano circular aperture with diameter ranging from 30 nm to 330 nm has been fabricated on the pyramidal probe with the micron size mirror. It is known that the two standing waves in the pyramidal probe and in the cavity area between the two walls around

the metallic probe provide the enhancements of light transmission via resonant tunneling. The gap will be the role of oscillator strength; with decreasing the gap width, the oscillator strength will be increasing due to the increased effective of refraction. The SEM images of the nano slits with the optical intensities will be presented. The transmitted intensities through the nano slits has been optically characterized using Nikon inverted microscope with princeston spectrophotometer and CCD camera. The TA value is calculated to be 0.136 for the diameter below 160 nm, and to be 0.053 for diameter greater than 160. This is agreeable with the results by Harrington, who claimed the transmission and the resonant behavior of a small aperture backed by a conducting body to be a constant and independent of size and shape.

7606-54, Poster Session

An all-silicon optical transmission system for clock and data transmission

P. J. Venter, P. Ellinghaus, M. du Plessis, Univ. of Pretoria (South Africa) and INSiAVA (Pty) Ltd. (South Africa); P. Rademeyer, INSiAVA (Pty) Ltd. (South Africa); A. W. Bogalecki, Univ. of Pretoria (South Africa) and INSiAVA (Pty) Ltd. (South Africa)

The low cost and mass integration potential of CMOS integrated circuits create an attractive opportunity for investigating CMOS as an optical platform. Although silicon, as an indirect band gap material, is known for inefficient electroluminescence, silicon-based optical transmission is still a much sought after capability. This paper shows the potential of an all silicon transmission system for both clock and data transmission.

By utilizing silicon light emitting diodes operating in avalanche, it is shown that a switching speed of well into the hundreds of megahertz is possible. The transmitter consists of an array of light sources, with metal light directors for improved external quantum efficiency. The array is pulsed across an optical fibre and received by an avalanche photodiode and amplifier module. Spectral results of the received signal confirm an optical component in excess of 100 MHz, were the off-chip driver circuitry and the photodiode receiver currently limit the bandwidth of the system.

As the requirements for wideband data transmission are more stringent than for a narrow band clock signal, the transmission system was tested as a baseband digital communication system, with transmission speeds of up to 176 kbps. We also present eye diagrams of the received signal to prove the success of the transmission system, where transmission speed is limited to detectable optical levels versus allowable in-band noise.

A refinement on these principles might lead to CMOS as a contender in high speed clock transmission as well as an alternative to III-V devices for low cost optical transmission systems.

7606-55, Poster Session

Optical spectroscopy of Er doped Si-nanocrystals on sapphire substrates fabricated by ion implantation into SiO2

N. P. Hylton, I. F. Crowe, The Univ. of Manchester (United Kingdom); O. Hul'ko, McMaster Univ. (Canada); R. Jalili-Kashtiban, U. Bangert, The Univ. of Manchester (United Kingdom); A. P. Knights, McMaster Univ. (Canada); M. P. Halsall, The Univ. of Manchester (United Kingdom); A. J. Kenyon, Univ. College London (United Kingdom); S. Ruffell, The Australian National Univ. (Australia); R. M. Gwilliam, Univ. of Surrey (United Kingdom)

One particular area of current interest in the field of silicon photonics is in the sensitisation of rare earth elements by Si-NCs; for example, it has been demonstrated that bright Er photoluminescence can be observed under non-resonant excitation when in the presence of Si-NCs. The mechanism behind this sensitisation is still a matter of debate, but it has been shown that the excitation of a single Si-NC with a high energy UV photon may actually result in the sensitisation of two nearby Er ions1. This so-called 'quantum cutting' phenomenon could therefore result in the emission of two low energy photons (0.8 eV) for the absorption of just one high energy photon.

We present the results of an optical investigation of a series of Er doped Si-NC samples which were fabricated via ion implantation into SiO2 on sapphire substrates, followed by a range of rapid thermal processing. The PL spectra reveal a variation in the Er sensitisation as a function of annealing conditions which we ascribe to the effects of differing Si-NC size distributions. We will also present the results of measurements of the rate of decay of PL intensity of the Er PL as a function of annealing conditions.

Furthermore the PL spectra from the samples have been investigated as a function of excitation energy; revealing dramatic changes in the Er PL intensity dependent upon the excitation energy. In fact the sensitisation due to Si-NCs may not be the only contributing factor to Er PL intensity, indicating that defect sensitisation is also of great importance. Detailed PL excitation measurements will be presented demonstrating the complex nature of the sensitisation of implanted Er ions.

1. D. Timmerman, I. Izeddin, P. Stallinga, I. N. Yassievich, and T. Gregorkiewicz, Nat Photon 2, 105-109 (2008).

7606-56, Poster Session

Formation of Si-nanocrystals in SiO2 on Al2O3 via ion implantation and rapid thermal processing

I. F. Crowe, N. P. Hylton, The Univ. of Manchester (United Kingdom); O. Hul'ko, McMaster Univ. (Canada); R. Jalili-Kashtiban, U. Bangert, The Univ. of Manchester (United Kingdom); A. P. Knights, McMaster Univ. (Canada); M. P. Halsall, The Univ. of Manchester (United Kingdom); R. M. Gwilliam, Univ. of Surrey (United Kingdom)

Silicon nanocrystal (Si-NC) based material systems have already been proposed as candidates for increased efficiency photo-voltaic cells after the recent observation of Multiple Exciton Generation [1]. The observation of a tunable room temperature visible luminescence band means that they are also being proposed as novel complimentary nano-phosphors in solid state display and lighting technologies [2, 3]. Reports of optical gain [4, 5] and the compatibility with CMOS processing will make them a very attractive light source for enhanced integrated chip functionality as computing makes the transition to photonics.

Using techniques such as ion implantation and rapid thermal processing (RTP), improvements in the control over Si-NC size and density can be realized.

In this contribution we describe the results of a recent study of the evolution of Si-NCs in thermally grown SiO2 from sputtered Si on Al2O3 (Sapphire) via ion implantation and RTP. Using dark field diffraction contrast cross-sectional transmission electron microscopy, we present evidence for the formation of crystalline silicon inclusions, ~1.5nm in diameter that exhibit efficient room temperature luminescence around 1.6eV (750 - 800nm) for annealing times as short as ~10s at 1100°C.

We have correlated the annealing conditions with the Si-NC PL intensity and the Raman intensity associated with the Si-Si phonon mode around 520cm-1, which is indicative of an increase in the crystalline fraction. A concurrent removal of non-radiative defects was confirmed by an increase in the observed Si-NC PL decay lifetime from ~15 to 90's with increasing annealing time from 10 to 300s at 1100°C.

The observation of a 'red-shift' in the Si-NC PL peak with increasing anneal time is in accord with a quantum confinement model for Si-NC band-edge recombination of electron-hole pairs.

References

[1] Timmerman et al, 'Space-separated quantum cutting with silicon nanocrystals for photovoltaic applications', Nature Photonics, 2, 105-109 (2008).

[2] Lee et al, 'White light emitting silicon nanocrystals as nanophosphor', phys. stat. sol. (b) 241, No. 12, 2767 - 2770 (2004).

[3] Hsieh et al, 'Nearly White-Light Emission From GaN-Based Light-Emitting Diodes Integrated With a Porous SiO2 Layer', IEEE Photonics Technology Letters, Vol. 19, No. 9 (2007).

[4] Pavesi et al, 'Optical gain in silicon nanocrystals', Nature 408, 440-444 (2000).

[5] Lee et al, 'Optical Gain at 1.5µm in Nanocrystal Si-Sensitized Er-Doped Silica Waveguide Using Top-Pumped 470nm LEDs', J. Lightwave Tech., Vol. 23, No. 1 (2005).

7606-58, Poster Session

Germanium p-i-n photodiode on silicon for integrated photonic applications

J. Mathews, R. Roucka, C. Weng, J. Tolle, J. Menendez, J. Kouvetakis, Arizona State Univ. (United States)

The application of silicon photonic technologies to optical telecommunications requires the development of near-infrared detectors monolithically integrated to the Si platform. Recently, efforts in this area have focused on developing detectors from pure-Ge grown epitaxially on Si substrates, but low temperature growth and processing compatible with complementary-metal-oxide-semiconductor (CMOS) technology has yet to be achieved. In this paper, we report on p-i-n heterostructure photodiodes fabricated from Ge films grown directly on Si substrates using a novel low-temperature chemical vapor deposition (CVD) process recently introduced by Wistey et al. [Appl. Phys. Lett. 90, 082108 (2007)].

The heterostructures were grown on arsenic-doped (n-type) Si(100) with resistivity 0.003 Ω-cm. A 350nm thick layer of intrinsic Ge was deposited as the active region, followed by 100nm of boron-doped (p-type) Ge. Ohmic contacts were formed by evaporation of Cr and Au. For a 60-µm-diameter device, the dark current densities were on the order of 10-2 A/cm2 and 103 A/cm2 at -1V and 1V, respectively, while the capacitance was measured to be 10 pF at -1V. The external quantum efficiencies measured at 1.3 and 1.55 µm were found to be 0.09 and 0.04, respectively. The spectral response of the above Ge devices is compared with that of similarly designed and fabricated diodes incorporating a Ge0.98Sn0.02 alloy. It was observed that the minor tin fraction of 2 at % extends the IR detection to 1750 nm (well beyond the 1550 nm value for elemental Ge) and significantly increases the quantum efficiency relative to Ge.

Conference 7607: Optoelectronic Interconnects and Component Integration X

Monday-Wednesday 25-27 January 2010 • Part of Proceedings of SPIE Vol. 7607

Optoelectronic Interconnects and Component Integration IX

7607-01, Session 1

"Macrochip" computer systems enabled by silicon photonic interconnects

K. Raj, A. V. Krishnamoorthy, J. E. Cunningham, X. Zheng, R. Ho, Sun Microsystems, Inc. (United States)

In this talk we present a computing microsystem that uniquely leverages the bandwidth, density, and latency advantages of silicon photonic interconnects to enable highly compact supercomputer-scale systems. We present the details of an optically enabled "macrochip" which is a set of contiguous, optically-interconnected chips enabled by wavelength-division multiplexed (WDM) based silicon photonics. We describe the system architecture and the WDM point-to-point network implementation of the "macrochip" providing bisection bandwidth of 10 TBps and discuss system and device level challenges, constraints, and the critical technologies needed to implement this system. We present a roadmap to lowering the energy-per-bit of a silicon photonic interconnect and highlight recent advances in silicon photonics under the UNIC program that facilitate implementation of "macrochip" grid made of arrayed chips.

7607-02, Session 1

Ultralow-power silicon photonic interconnect for high-performance computing systems

G. Li, X. Zheng, A. V. Krishnamoorthy, J. E. Cunningham, K. Raj, R. Ho, J. Lexau, D. Patil, F. Liu, H. Thacker, Y. Luo, J. Shi, J. Yao, I. N. Shubin, Sun Microsystems, Inc. (United States)

High-performance computer architectures are increasingly integrating multiple processing cores on a single chip for high yield, low power, low design complexity, and low cost. The performance of the multi-core chips highly depends on their on-chip interconnect networks. The Ultrascale Nanophotonic Intrachip Communication (UNIC) project aims to achieve unprecedented high-density, low-power, large-bandwidth, and low-latency optical interconnect for highly compact supercomputer systems. This project, which has started in 2008, sets extremely aggressive goals on power consumptions and footprints for optical devices and the integrated VLSI circuits. In this talk we will discuss our challenges and present some of our first-year achievements.

We will first review our options on active optical devices and present comprehensive considerations of their power consumptions and the issues to solve in order to meet the UNIC goals. For the micro-ring-based optical devices, our theoretical analysis of tuning requirement due to manufacturing variation is confirmed by the tested ring resonance distributions from different manufacturing platforms. We will present our most recent test data on the thermal tuning structures and a novel tuning scheme for reduced tuning requirement. We will describe the performance of a compact ring modulator with 15 um radius, including its DC modulation, frequency response and circuit model. We have hybrid-bonded the ring modulator with an internally designed modulator driver, and achieved very low power consumption at 5 Gb/s. Performances of Ge photodetectors will also be discussed in detail, and we have achieved very low power consumption at 5 Gb/s for the hybrid-bonded receivers as well.

7607-03, Session 1

A compact high-performance germanium photodetector integrated on 0.25µm thick silicon-on-insulator waveguide

N. Feng, S. Liao, P. Dong, D. Zheng, H. Liang, C. Kung, R. Shafiiha, D. Feng, M. Asghari, Kotura, Inc. (United States)

Silicon photonics has been an attractive research direction for the past years due to the potential capability of monolithic integration with complementary-metal-oxide-semiconductor (CMOS) microelectronic circuits. Recent increasing interest in optical interconnects has become a major driving force boosting the technology into a new era. To accommodate the extremely tight real-estate space for chip-to-chip connection, a submicron waveguide capable of making tight-bend and dense integration is ideal for such a system. The receiver, therefore, needs not only perform well but also be compact and readily integratable on submicron waveguide platform.

We report a very compact (1.6µmx10µm) and low dark current (20nA) Germanium p-i-n photodetector integrated on 0.25µm thick silicon-on-insulator (SOI) waveguide. A thin layer of Germanium was selective-epitaxially grown on top of SOI waveguides. Light is evanescently coupled into Germanium layer from the bottom SOI waveguide.

The device demonstrates superior performance with demonstrated responsivity larger than 0.65A/W at wavelength of 1530nm and dark current less than 20nA at -0.5V bias. The 3dB bandwidth of the reported device can be as high as 17GHz at -0.5V bias. The responsivity can be further improved by careful design of the metal contact which is believed to be a major source of light absorption. A theoretical analysis indicates that with the new design the device responsivity can approach the ideal value of 1.2A/W. The combination of low driving voltage and dark current makes it possible to integrate this device with a trans-impedance amplifier (TIA) to form a high-speed, high performance receiver.

7607-04, Session 1

Coupled vertical gratings on silicon for applications in wavelength division multiplexing

D. Tan, Univ. of California, San Diego (United States); K. Ikeda, Nara Institute of Science and Technology (Japan); Y. Fainman, Univ. of California, San Diego (United States)

An add/drop filter based on coupled vertical gratings is presented on silicon. We analyze the device theoretically and experimentally and show that the concept is easily extended to multi-channel add/drop filters. We demonstrate tunability of the device bandwidth and operation wavelength. The free spectral range of the device exceeds the bandwidth used in wavelength division multiplexing systems, which makes it ideally suited for use in such systems.

7607-05, Session 1

High-performance Ge quantum well modulators

S. A. Claussen, Stanford Univ. (United States)

No abstract available

7607-06, Session 2

Photonic buses for computer applications

M. R. Tan, Hewlett-Packard Labs. (United States)

For board-to-board and intra-board interconnections, photonics can enable system topologies no longer feasible with copper. One interesting application of photonics is to realize a high speed multidrop bus. Historically, computer system architectures were dominated by multidrop bus designs. However, signal integrity constraints on high speed electronic buses have forced system designers to abandon conventional bus architectures replacing them with networked point-to-point connections. In this paper, we present results of a 30cm long, 4 channel optical multidrop bus capable of interconnecting up to 8 receiver modules at 10Gbps per channel using off-the-shelf optoelectronics and a novel "light pipe" optical waveguide system.

7607-07, Session 2

Photonic-electronic integration technologies for high density and energy-efficient interconnects

I. Ogura, H. Kouta, S. Yanagimachi, Y. Hashimoto, R. Kuribayashi, K. Kurata, NEC Corp. (Japan)

Optical interconnection is one of the promising technologies to meet the growing demands for high speed interconnects while reducing power consumption in high performance computing systems, servers and routers. In this presentation, we describe our resent results of photonic-electronic integration technologies for high density and energy-efficient interconnects categorized in two integration levels: package level integration of LSI and optical modules, and system level integration such as inter- and intra-shelf optical wiring system. As for the package level integration, we focus on LSI package with optical I/Os to solve I/O bottlenecks in high throughput switch, graphics chips and CPU I/Os (CPU-memory). The optical I/Os for LSIs are realized by the technologies of dense and small E/O and O/E packaging with efficient optical coupling and IC(VCSEL driver/resceiver) design for low power consumption. We have demonstrated 20Gbps/ch x 12ch Transmitter/ receiver modules of minimum footprint of 5mmx5mm. The power consumption is around 15mW/Gbps/ch and further reduction is expected by the CMOS technologies. As for system level integration, we show resent progress of intra-shelf optical wiring systems to solve bandwidth limitation of electrical backplane and inter-shelf connection in total. Wide range of collaboration from waveguide materials to system management is in progress.

7607-08, Session 2

200Gb/s miniature optical interconnect transmitter module for high-performance computing

E. M. Mohammed, H. Au, Intel Corp. (United States)

The bandwidth density and the communication distance targets of high performance computing (HPC) systems are expected to increase to accommodate petaflops of data transmission between computing nodes. As the bandwidth*distance product increases, electrical interconnects such as infiniband (IB) cables currently used for HPC will be bandwidth limited, expensive and they will have complex cable management issues. High bandwidth small form factor (SFF) electro-optic (E/O) or optoelectronic (O/E) conversion modules with fiber arrays deployed in close proximity to HPC switch fabrics or routers could provide much higher bandwidth with less complexity.

In this paper we describe the development of a novel 10-channel miniature (7mmx3mmx1.8mm) optical interconnect transmitter module. The module consists of a high precision molded optical alignment unit with integrated microlens arrays, high-speed coplanar waveguide (CPW) electrical interfaces and a VCSEL array chip which is flip chip mounted. The module is designed to uniquely interface vertically with high-speed electrical I/O lines on a microprocessor package or a motherboard to convert electrical signals to optical for transmission to other similar units using a standard MT style optical connector.

We will report on optical coupling efficiency, misalignment tolerance and high-speed electrical and optical measurements of the module. In our initial result we have measured 40Gb/s electrical eye for the CPW interfaces on the optical module. We also measured 20Gb/s clear optical eye for VCSEL assembled module from a single channel indicating an aggregate bandwidth of 200Gb/s for the 10 channels.

7607-09, Session 2

Semiconductor IC packaging using modular optical components

D. R. Rolston, R. B. Coenen, Reflex Photonics, Inc. (Canada)

A low-cost, modular optical assembly will be described that augments standard IC packages with up to 200 optical ports each operating at greater than 10-Gbps for an aggregate optical i/o bandwidth of up to 2-Tbps. The manufacturing philosophy does not disrupt either the microchip fabrication, the IC package fabrication or assembly or the hostboard and uses parallel optical fiber ribbon cables to connect to the perimeters of the optically enabled IC package. In addition to the optical i/o bandwidth, all the typical electrical bandwidth is still supported by the solder-ball BGA array on the back of the IC package. By integrating the optics with the IC package, not only are tremendous speed advantages possible, but large power consumption savings, greater transmission distances and low-cost system integration can be obtained. Typical applications for optical i/o directly from the chip allow bus extensions for PCI Express, RapidIO and others, also high-speed data switching systems as well as graphics rendering architectures using extended memories. Also possible are a variety of multi-package / multi-chip interconnect architectures.

7607-10, Session 3

True bidirectional optical interconnects over multimode fiber

R. Michalzik, A. Kern, M. Stach, F. Rinaldi, D. Wahl, Univ. Ulm (Germany)

We report on the fabrication and properties of 850 nm wavelength AlGaAs/GaAs-based transceiver chips, in which vertical-cavity surface-emitting lasers (VCSELs) and photodiodes are monolithically integrated. Various types of devices allow half- and full-duplex bidirectional optical interconnection at multiple Gbit/s data rate over a single butt-coupled glass or polymer-clad optical fiber with diameters in the 100 to 200 µm range. Whereas metal-semiconductor-metal (MSM) photodiodes are employed for these large-area fibers, we also investigate the integration of pin-type photodiodes which appear more promising in combination with standard 62.5 or 50 µm graded-index multimode fibers. This interconnect solution is attractive owing to obvious advantages like lower volume and weight and potentially lower system cost. Applications will be found in automotive, home, industrial, or in-building networks and potentially within computer clusters or central offices.

7607-11, Session 3

Thermally tunable SOI CMOS photonics circuits

I. N. Shubin, X. Zheng, H. Thacker, J. Yao, J. Costa, G. Li, A. Krishnamoorthy, J. Cunningham, Sun Microsystems, Inc. (United States); T. Pinguet, Luxtera (United States)

High-Q ring waveguide resonating structures are the key components in the silicon photonics portfolio boosting up its functionality and circuit performance. Due several manufacturing reasons their peak wavelengths are prone to deviate from the design values. To keep the ring resonator operating as specified, its peak wavelength needs to be corrected in a reliable and power efficient manner. We report the results of thermal tuning of the four channel multiplexer-demultiplexer circuits fabricated in a commercial 130nm SOI CMOS line. Different diameter mux-demux rings are tuned to cover the entire free spectral range and fully compensate for the resonators' initial wavelength offsets. The experimental results are substantiated with simulations and verified on the CMOS post-processed devices modified with FIB.

7607-13, Session 3

Converging technologies and demands toward high-bandwidth optical interconnects

T. Tekin, TU Berlin Microperipheric Technologies (Germany)

In last decades various approaches have been investigated within frame of photonics research activities. From hybrid assembly to monolithically integration including III-V and CMOS technologies, the main challenges remained: cost effective, high bandwidth, high-density devices, components and subsystems. This paper will review basic photonics packaging approaches/concepts which have been developed over years in different research projects and platforms, such as Acts-Bliss, Ist-Mufins, and recently ePIXnet (NoE). Furthermore, targeting the converging technologies the demands on future heterogeneous integration perspective will be discussed with respect to high bandwidth interconnects.

7607-48, Session 3

Ultra-compact silicon nanophotonic modulator based on electro-optic polymer infiltrated slot photonic crystal waveguide

C. Lin, B. Lee, The Univ. of Texas at Austin (United States); A. X. Wang, Omega Optics, Inc. (United States); R. T. Chen, The Univ. of Texas at Austin (United States); J. Luo, A. K. Jen, Univ. of Washington (United States)

We report an ultra-compact silicon nanophotonic modulator using electro-optic (EO) polymer infiltrated photonic crystal slot waveguide. The modulation mechanism is based on modulating the input optical signal between the defect mode and the forbidden band by changing the refractive index of infiltrated EO polymer. Coupling efficiency near the band edge is also enhanced by innovative design. Mode-matching sections are added at both input and output to convert the channel waveguide mode to photonic crystal waveguide mode. Following the mode conversion region is the tapered photonic crystal waveguide. The W1.25 to W1.1 taper gradually increase the group index of optical signal before enter the active slow light region, which improves the coupling efficiency near the band edge. Simulation shows this modulator design requires very small footprint of 5µm by 20µm and a low power operation of 25fJ/bit. Experiment demonstration of this device is carried out on a silicon-on-insulator (SOI) structure with 1µm of buried oxide (BOX) as bottom cladding layer, 240nm of silicon slab as the active layer, and 1µm of UFC-170A as top cladding layer. The photonics crystal slot waveguide pattern is patterned by JEOL JBX6000FS electron beam system using ultra-thin e-beam resist ZEP520A of 78nm to define the narrow slot waveguide and high aspect-ratio sharp tips in the mode-matching sections. The narrow slot waveguide with 80µm width is filled with a guest-host EO polymer of AJY-CKL1 (25%wt) in amorphous polycarbonate (APC) to create electro-optic effect in the photonics crystal slot waveguide. Device characterization will be performed in the near future and results will be reported in the conference.

7607-14, Session 4

New options for chip-to-chip photonic packaging by using thin glass-based waveguide substrates on board and module level

H. Schröder, L. Brusberg, N. Arndt-Staufenbiel, Fraunhofer-Institut für Zuverlässigkeit und Mikrointegration (Germany)

Electrical-optical integration is a rapidly growing field with a strong potential for applications in a wide spectrum covering optical sensors, data & telecom, respectively. The driving forces are bandwidth demand, power efficiency and increased channel density. For higher degrees of integration thin glass substrates provide very suitable properties. The technology of the "glassPack" concept relies on the realization of the passive single mode and multi mode optical waveguides within the thin glass substrates and benefits of the excellent optical, chemical, and thermal properties of glass. Suitable technologies like ion-exchange and direct optical butt coupling using laser fusion are used. The resulting single- or multi-mode waveguide are characterized by a graded refractive index profile and determination of attenuation as well as deflection and coupling losses. Novel innovative features are added to this packaging technique to leverage its generic usage. For electrical wiring thin film technologies can be applied and through glass vias have been demonstrated to address high frequency and high bandwidth applications. Furthermore planar waveguide array coupling elements of very flexible design can be applied for optical coupling and 90 degree light deflection for electrical-optical PCB, optical backplane, and to interconnect silicon photonic wires by high-index contrast vertical gratings to the micro optical periphery. First results using thin glass substrates with integrated optical interconnects as well as electrical wiring for SiP will be presented.

7607-15, Session 4

Packaging of opto-electronic devices for flexible applications

E. Bosman, G. Van Steenberge, J. Missine, B. Van Hoe, P. Van Daele, Univ. Gent (Belgium)

This paper presents the latest results on the development of a thin flexible package of commercially available opto-electronics with polymer multimode waveguides. The GaAs VCSELs and Photodiodes are thinned down to 20 µm thickness, resulting in packages which can be bended to a bending radius of 2 mm with high reliability. Optical characterization has been done to prove that thinning, embedding and bending of VCSELs does not influence their optical behavior. With these actives, also waveguides and out-of-plane coupling structures are embedded inside the foil. Flexible Polyimide micro-mirrors were fabricated, characterized and embedded inside the foil. An embedded VCSEL to Photodiode optical waveguide link was demonstrated at a speed of 1.2 Gbs with open eye diagram. Temperature (-40 to 125 degrees Celsius) and humidity (85 rh/85 °C for 1000 hours) reliability was tested with good results. The total thickness of the completed foil containing actives, waveguides and coupling elements is only 145 µm.

7607-16, Session 4

Modulation-enabled tapered remote coupler: all-optical communication on and off-chip

T. Gu, R. Nair, M. W. Haney, Univ. of Delaware (United States)

The “modulation-enabled tapered remote coupler” (METRoC) is introduced that targets the seamless integration of on-chip and off-chip optical interconnects. With the rigorous scaling of CMOS critical dimensions in accordance to Moore’s law, the computing power of modern microprocessors has grown rapidly. However, on-chip global interconnections and off-chip communications do not scale commensurately with the device sizes, resulting in challenges to meet the growing bandwidth requirements without expending excess power.

Optics is a potential solution that can outperform electrical interconnects. Recent advancements in optoelectronics may enable implementation of optical interconnects in chip-scale after global long haul communication has been completely dominated by fiber optics over the past decades. However, many of the proposed solutions in the on-chip and off-chip domains are likely to be incompatible, with separate optical interconnect schemes. This results in optoelectronic transceivers inside as well as neighboring the microprocessor, connected by electrical interconnects.

The METRoC is proposed as a compact optical coupling mechanism that may negate the need for opto-electronic and electro-optic conversions when signals propagate between the on-chip and off-chip domains. Multiple quantum well (MQW) devices are chosen as the optoelectronic transceivers. Prismatic coupling structures embedded in waveguides are implemented to enable intra-chip optical interconnects. Tapered waveguides are employed to provide interconnections between chips. Both coupling structures can potentially achieve high coupling efficiencies with small footprint areas and hence high densities and are compatible with silicon CMOS processes. The coupling fabrics can also be used to optically interconnect two silicon die in a multichip module.

7607-17, Session 4

Heterogeneous integration of thin film compound semiconductor lasers and Su-8 waveguides on SiO2/Si

S. Palit, Duke Univ. (United States); J. Kirch, L. Mawst, T. F. Kuech, Univ. of Wisconsin-Madison (United States); N. M. Jokerst, Duke Univ. (United States)

The heterogeneous integration of thin film compound semiconductor lasers with optical waveguides all on silicon is a critical step towards the realization of chip-scale portable photonic systems. We present the design and implementation of a thin film InGaAs/GaAs laser metal bonded to SiO2/Si endfire coupled with a tapered Su-8 waveguide on the same substrate. Rsoft simulations are performed to determine the performance implications of the effect of the gap between the laser and waveguide, waveguide dimensions and material properties. Fabrication of the index guided ridge lasers involves p-side ridge processing and metallization under growth substrate (GaAs) support, followed by substrate removal using selective etches. The 3.8 um thick thin film lasers are cleaved on a thin flexible diaphragm and metal-metal bonded p-side down on metallized SiO2/Si.The n-side is subsequently metallized and annealed under host substrate (SiO2/Si) support. A 2.8 um thick tapered waveguide of Su 8-2002, a negative photoresist, is photolithographically patterned next to one facet of the laser. The 4 um thick SiO2 layer of the substrate forms the bottom and air formed the top cladding of the waveguide. Experimental results of the system, obtained by a pulsed drive current to the laser and measuring the output from the waveguide with a multimode fiber, indicate a lasing wavelength of ~ 997nm and a threshold current density of 250 A/cm2. IR images of the coupled light at the output waveguide are presented. A proposed fabrication process for integration of such a system on a Si substrate is also discussed.

7607-18, Session 5

Design and implementation of an electro-optical backplane with pluggable in-plane connectors

R. C. A. Pitwon, K. M. Hopkins, Xyratex Technology Ltd. (United Kingdom); K. Wang, D. R. Selviah, H. Baghsiahi, Univ. College London (United Kingdom); B. Offrein, R. Dangel, F. Horst, IBM Zürich Research Lab. (Switzerland); M. Halter, M. Gmür, Varioprint AG (Switzerland)

The design, implementation and characterisation of an electro-optical backplane and an active pluggable in-plane optical connector technology is presented. The connection architecture adopted allows line cards to be mated to and unmated from a passive electro-optical backplane with embedded polymeric waveguides. The active connectors incorporate a photonics interface operating at 850 nm and a mechanism to passively align the interface to the optical waveguides embedded in the backplane. A demonstration platform has been constructed to assess the viability of embedded electro-optical backplane technology in dense data storage systems. The demonstration platform includes four switch cards, which connect both optically and electronically to the electro-optical backplane in a chassis. These switch cards are controlled by a single board computer across a Compact PCI bus on the backplane. The electro-optical backplane is comprised of copper layers for power and low speed bus communication and one polymeric optical layer, wherein waveguides have been patterned by a direct laser writing scheme. The optical waveguide design includes densely arrayed multimode waveguides with a centre to centre pitch of 250µm between adjacent channels, multiple cascaded waveguide bends, non-orthogonal crossovers and in-plane connector interfaces. In addition, a novel passive alignment method has been employed to simplify high precision assembly of the optical receptacles on the backplane. The in-plane connector interface is based on a two lens free space coupling solution, which reduces susceptibility to contamination. Successful transfer of 10.3 Gb/s data along multiple waveguides in the electro-optical backplane has been demonstrated and characterised.

7607-19, Session 5

Polymer waveguide-based multilayer optical connector

D. Jubin, R. Dangel, N. Meier, F. Horst, T. Lamprecht, J. Weiss, R. Beyeler, B. Offrein, IBM Zürich Research Lab. (Switzerland); M. Halter, R. Stieger, F. Betschon, Varioprint AG (Switzerland)

The increasing intra-system I/O bandwidth requirements for supercomputing and server applications make it indispensable to integrate optical interconnects in future systems. Both the data rate per channel as well as the number of channels will continue to increase. To overcome routing and assembly issues of a large number of fibers, we are developing flexible polymer waveguide sheets. Polymer waveguide based optical technology offers the advantages of integrated processing and simplified electro-optical packaging.

We report on a polymer waveguide based optical backplane link for computing applications consisting of 192 channels. At each end the optical link is equipped with four MT connectors. We present a novel method to passively align multiple layers of polymer waveguides in a single MT ferrule. Optical waveguide connectors with 48 channels were realized by stacking four waveguide layers with 12 channels each. The horizontal and vertical waveguide pitch was chosen to be 250micrometer, compatible with MT fiber connectors. The positioning accuracy demonstrated in such connectors is better then ±5micrometer. The connection losses between a 48 channel MT fiber connector and the waveguide connector were found to be about 2 dB. The connector assembly concept we developed uses only few assembly steps and can easily be automated using a pick-and-place tool.

The realized 192 channel optical link demonstrates the feasibility of the

polymer waveguide technology for complex and high channel count optical interconnect solutions.in future computing systems.

7607-20, Session 5

Compact electro-optical module with polymer waveguides on a flexible substrate for high-density board-level communication

J. Weiss, T. Lamprecht, N. Meier, R. Dangel, F. Horst, D. Jubin, R. Beyeler, B. J. Offrein, IBM Zürich Research Lab. (Switzerland)

Optical link technology has been identified as THE solution to cope with the continuously increasing I/O bandwidth requirements of emerging high-performance processors, expected to reach multiple Terabits per second. To fully exploit the density advantage of optics, the electro-optical conversion must be performed very close to the processor chip, e.g., on the package laminate.

We report on the co-packaging of electrical driver-, receiver-, VCSEL- and photodetector-chip arrays on a flexible electrical substrate with optical polymer wave¬guides. The electro-optical components are attached to the substrate edge and butt-coupled to the waveguides. Electrically conductive silver-ink connects them to the substrate, at an angle of 90°. The final assembly connects to the surface of a package-laminate with an integrated compressible connector. It can be folded to save space, requires a small footprint on the package-laminate, and provides short electrical high-speed signal paths.

With our approach, the electro-optical package becomes a compact electro-optical module with integrated polymer waveguides. The latter are terminated with either optical connectors (e.g., at the card edge) or with an identical assembly for a second processor on the board. Consequently, no costly subassemblies and connectors are needed, and a very high integration density and scalability to virtually arbitrary channel counts and towards very high data-rates (20+ Gbps) become possible. Future cost targets of much less than US$1 per Gbps will be reached by employing standard PCB materials and technologies that are well established in the industry. We thus present a technology platform with both electrical and optical connectivity and functionality.

7607-21, Session 5

Mass production of planar polymer waveguides and their applications

F. Betschon, Varioprint AG (Switzerland); M. Michler, Interstaatliche Hochschule für Technik Buchs NTB (Switzerland); M. Halter, Varioprint AG (Switzerland); J. Kremmel, K. Dietrich, Interstaatliche Hochschule für Technik Buchs NTB (Switzerland); M. Gmür, S. Paredes, Varioprint AG (Switzerland); D. Craiovan, Friedrich-Alexander-Univ. Erlangen-Nürnberg (Germany)

The increasing demand for planar polymer optical waveguides on board level requests for appropriate materials, systems, assembly concepts and production technologies which guarantee a high reproducibility and quality of the waveguides. The manufacturing and assembly costs have to be kept on a low level, while the integration of the highly sensible waveguides into the rough environment of PCB's with their cheap and non-ideal substrates is a particular challenge.

The present paper describes an assembly and manufacturing technology for electro-optical circuit boards which meets these requirements.

In the first part the manufacturing and characterization of multimode polymer waveguides is presented. Different processes for layer deposition and structuring are described. Specific attention is given to the reproducibility of these processes and the warranty of high optical quality of the waveguides.

In the second part different light coupling concepts are presented. In particular, a novel mirror element based on parabolic reflectors is described. The optical design was carried out analytically and was optimized using simulations. The manufacturing of the mirror element is based on injection molding and can be manufactured reproducible in high quantities at lowest costs. Due to wider tolerances for the subsequent assembly steps this novel concept allows the use of conventional SMD- placement machines for mounting the electro-optical transceivers which makes the process very cost effective.

In the third part the practical use of this building set is illustrated with different successfully realized applications in the field of ICT and optical sensor technology.

7607-22, Session 6

Chip-level optical I/O for FPGA on optical PCB

S. Nakagawa, IBM Japan, Ltd. (Japan)

Power-efficient multicore systems, widely exploited to increase performance under power-constrained environment, require high-bandwidth, low-power off-chip or off-module I/Os. Optical interconnects have demonstrated integration of large number of high-speed I/O channels, and employment of advanced CMOS technology for high-speed driver ICs reduces the I/O power dissipation, which is lower compared to electrical counterparts even for shorter-distance transmission. Waveguide integrated, optical printed circuit board (PCB) enables direct chip mounting of optical and electrical chips, which include CPUs or other logic ICs, on the board, and provides high-density integration of high-speed optical I/O channels.

12channel 850nm VCSEL, GaAs PD, and their driver array chips were flip-chip mounted on an OPCB with 2 x 12 35um square waveguides, and provide optical I/Os, operating at 6.5 Gbps and higher, for FPGA, which was also mounted on the board. The FPGA and optical I/Os are connected with 10~14mm-long electrical link, which can be shorter if I/O layout of FPGA are designed for parallel optical I/Os. Optical signals between the VCSEL or PD and the waveguides are coupled through a 45-degree mirror formed on the waveguides. The alignment accuracy of the flip-chip mounting of the optical chips was within 4 um. The measured insertion loss of the optical I/O was 2.8 dB for Tx and 3.0 dB for Rx. The optical I/O performance, including bit error rate test, as well as the packaging technologies will be presented.

7607-23, Session 6

Simplex optical transceiver integrated on PCB using novel connectors compatible with pick-and-place assembly technology

N. Bamiedakis, J. Beals IV, A. H. Hashim, R. V. Penty, I. H. White, Univ. of Cambridge (United Kingdom)

On-board optical waveguides are increasingly being recognised as a key component in a wide range of potential applications such as high-speed board-level optical interconnects and lab-on-chip sensors. However, the cost-effective integration of optics and electronics on a single board requires manufacturing and assembly methods which can be implemented by the electronics industry. Towards this goal, a transceiver composed of integrated electronic and photonic components on the same PCB is demonstrated for the first time using siloxane polymer materials and novel through-board connectors. This approach to realising the reported optoelectronic board satisfies the industry requirement that the fabrication, alignment and packaging of both the optical and electronic components are compatible with conventional PCB technology. The polymer material employed possesses the mechanical and thermal properties necessary for withstanding PCB soldering and lamination and allows patterning by a range of techniques suitable for large-scale manufacturing such as stamping and printing. The novel connectors presented accommodate the active optoelectronic components and provide the interface between the optical and electrical layers formed on opposite board surfaces. When used with multimode waveguides, these connectors permit relaxed alignment tolerances and can be mounted in a straightforward manner suitable for pick-and-place PCB assembly technology. The reported simplex transceiver comprises the electronic circuitry, mounted laser and photodiode chips and a polymer Y-splitter. Initial demonstration of 2.5 Gbps data transmission via the Y-splitter with error-free operation has been achieved.

7607-24, Session 6

Point-to-point waveguide array with buried mirrors for board-level optical interconnect

X. Dou, The Univ. of Texas at Austin (United States); A. X. Wang, Omega Optics, Inc. (United States); H. Huang, R. T. Chen, The Univ. of Texas at Austin (United States)

In this paper, point to point waveguide array with buried 45º facet mirrors was fabricated by the Ni metal hard mold imprint technique. The Ni metal hard mold which also has 45º facet at the ends was prepared through metal electroplating process on a hard metal substrate. The waveguide array pre-mold was successfully fabricated using negative photoresist SU8 through inclined exposure in Di-water. In this process, the waveguide array as well as the 45º facet at the waveguide end were simultaneously fabricated. We fabricated the point to point waveguide array with fully buried 45ºfacet mirrors and its optical properties were also measured.

7607-25, Session 6

Optical link between FPGA microprocessors using a fiber-embedded rigid PCB

D. Kim, T. Lee, M. H. Cho, M. Lee, D. Im, Korea Advanced Institute of Science and Technology (Korea, Republic of); J. Choi, K. Chun, LG Micron Ltd. (Korea, Republic of); H. Park, Korea Advanced Institute of Science and Technology (Korea, Republic of)

Optical link between FPGA microprocessors has been demonstrated using a fiber-embedded rigid optical printed-circuit board (OPCB). To fabricate a stable OPCB, a fiber component is prepared, which is mounted with L-shape connectors at both ends of a silica fiber ribbon. In the L-shape connector, fiber strands are bent by 90 and installed in a MT ferrule where guide-holes are formed to assemble optical transmitter/receiver (Tx/Rx) modules. Whole body of the connector-mounted fiber ribbon is laminated in FR4 board, exposing only the guide holes on the board. This structure can guarantee a high stability and a low optical loss, since the fibers are seamlessly buried in the board. Optical Tx/Rx modules operating up to 2.5 Gb/s/ch are prepared as a compact size of 9mm x 10.5mm x 0.7mm. In the module, 1x4 VCSEL/PD array chips and Tx/Rx IC chips are integrated. The modules are assembled using guide holes/pins on the OPCB. It records a low total loss below -3dB in the link between Tx and Rx modules through the OPCB. Using these components, a platform for optical link of video data between two FPGA microprocessors is prepared. The platform composes of five main compartments; video signal input/output stages, signal control, power supply, O/E conversion, and optical transmission parts. The platform board consists of 1 optical layer with 4 channels and 4 electrical layers with 8-bit channels. The system successfully demonstrated a clear image transmission through the OPCB. It proves a possibility of the application of our OPCB structure for computer systems. Especially, embedding whole body of the optical fiber layer with connectors in the board can simplify the OPCB fabrication process and guarantee high stability and performances.

7607-26, Session 6

Flexible polymer optical layer for board-level optical interconnects by highly durable metal imprinting method

X. Wang, Omega Optics, Inc. (United States); X. Dou, R. T. Chen, The Univ. of Texas at Austin (United States)

Low cost optical waveguides are essential for the deployment of board level optical interconnects. Polymer optical waveguides by molding method are considered as an attractive approach. We have demonstrated the fabrication methods by PDMS soft mold and silicon hard mold, however, the durability is not good enough for industrial production. In this paper, we implement nickel hard mold through electroplating, which can achieve smooth surface profile and high durability. The experimental results will be given in the final manuscipt.

7607-27, Session 7

Optical and electrical hybrid flexible printed circuit boards with unique photo-defined polymer waveguide layers

K. Choki, SUMITOMO BAKELITE Co., Ltd (Japan); T. Mori, K. Takahama, M. Fujiwara, K. Watanabe, H. Owari, Y. Shirato, S. Terada, M. Sakamoto, SUMITOMO BAKELITE Co., Ltd. (Japan)

Optical and electrical hybrid flexible printed circuit boards (O/E-FPCs) with unique photo defined polymer waveguide layers have been investigated for short-to-middle range data-com applications. The newly developed photo defined polymer waveguides are made by very simple pattering process, so-called “Photo-addressing”. In the process, only UV irradiation through a photo mask over photosensitive dry film is carried out to form entire waveguide patterns, and any additional steps like etching or developing are not required.

Lithography is one of major process for making polymer waveguides. In litho process, developing step must be necessary to create core structure (light path). After developing step, the surface around core line is easy to be rough, and some cracks or pits might be observed. These defects cause light scattering, then lead to poor optical property.

In our new Photo-addressing process, no developing step is required. The Core structure with far less light scattering defects have to show lower optical loss. Also we selected addition type of cyclic olefin homo-polymer (Polynorbornene) as its matrix polymer, which has excellent optical, mechanical and thermal properties by nature. Then we have successfully got high-performance polymer waveguide, which has extremely low optical loss of 0.03dB/cm at 830nm and very high glass transition temperature of 270 degree-C.

We are now giving high priority to further process development how to integrate them with conventional flexible printed circuit boards (O/E-FPCs), and gathering data of basic characteristics, properties and reliabilities of those kinds of hybrid product. Several experimental results will be discussed.

7607-28, Session 7

Optical interface devices applying UV curable resin for flexible optical interconnection

O. Mikami, M. Kanda, Tokai Univ. (Japan)

The success of optical interconnection for practical use is apparently dependent on the development of sophisticated packaging and coupling technologies capable of achieving both high coupling efficiency and easy alignment

We have developed several fabrication technologies applying UV curable resin so far. The basic technology is the mask transfer method. This

technology enables fabrication of arrayed M x N optical patterns at one shot of UV light. It is also possible to fabricate very precise patterns, as an example, optical rod with diameters of 50 m to 500 m, by using a conventional photomask. The length/thickness of the fabricated patterns can be controlled by the thickness of the resin and/or the spacing gap between the photomask and the substrate. The maximum length reaches over 1000 m.

Several optical interface devices fabricated by this method will be reviewed. One is a new VCSEL device which consists of VCSELs, optical output ports as the core, and a surrounding clad layer. The optical output port can be accurately fabricated on the emitting spot of the VCSEL. This VCSEL device enables flexible packaging on opto-electronic PCBs.

Another is a 90-degree light path conversion device for coupling to an optical wiring on opto-electronic PCBs. It features in hybrid comb-clad consisting of air and polymer parts. This device has a large refractive index difference between the core and the hybrid comb-clad, and enables the small curvature radius of bending.

7607-29, Session 7

Correlation of organic cross-linking behavior and optical properties of inorganic-organic hybrid polymers

A. Bock, R. Houbertz-Krauss, Fraunhofer-Institut für Silicatforschung (Germany); G. Sextl, Fraunhofer-Institut für Silicatforschung (Germany) and Julius-Maximilians-Universitaet Wuerzburg (Germany)

For the fabrication of highly sophisticated optical devices, optical elements with adaptable properties are needed. It is advantageous, if these elements consist of low-cost nanomaterials, enabling an rms roughness down to the Å range after processing and integration on a larger scale. Furthermore, the optical elements should be producible by various low-cost technologies with a high process throughput. A property that is particularly important for the production of optical elements such as waveguides is the refractive index difference of core and cladding.

A material class which is often used to produce such optical elements is the class of inorganic-organic hybrid polymers (ORMOCER®s1). These materials consist of interpenetrating networks, based on inorganic Si-O-units and on an organic network. The materials' properties can be adjusted by chemical modifications on the molecular level and, to some extent, by varying the processing conditions of the organic cross-linking. The photo-induced radical polymerization of several inorganic-organic hybrid materials comprising different kinds and amounts of organic cross-linkable moieties was investigated by Photo-DSC measurements. The polymerization was carried out gradually by repeatedly exposing the materials to UV light for 2s at a time which demonstrates the possibility to well-defined interrupt the organic cross-linking. The materials' organic cross-linking, which was investigated by spectroscopic measurements, was correlated to the materials` refractive index.

Registered by the Fraunhofer-Gesellschaft für Angewandte Forschung e.V.

7607-30, Session 7

Thermally stable and lowloss optical waveguide using optical-fiber-embedded epoxy matrix for optical printed-circuit board applications

D. Im, J. Kim, D. Kim, M. H. Cho, H. Park, Korea Advanced Institute of Science and Technology (Korea, Republic of)

We propose a thermally stable and low-loss optical waveguide and its simple and cost-effective fabrication method for optical printed circuit board applications. The optical waveguide is fabricated with fiber-embedded epoxy matrix and has good property about adhesion and thermal expansion coefficient with FR-4 printed circuit board material. The new waveguide is composed of epoxy resin matrix, conventional ferrules and 90°-bent fiber arrays. The epoxy matrix defines the waveguide dimension and holds ferrules and 90°-bent fiber arrays. The conventional ferrules enable passive alignment. The measured total propagation loss is about 0.375dB when total propagation length is 83mm, and is lowered by amount of 0.0825dB when it experience thermal stress at 180   for an hour. This measured result shows that the waveguide is thermally stable and low-loss, and can be used for optical printed circuit board applications.

7607-31, Session 8

Cost-effective DWDM optical interconnects enabled by quantum dot comb laser

A. R. Kovsh, G. L. Wojcik, D. Yin, Innolume Inc. (United States); A. E. Gubenko, I. L. Krestnikov, S. S. Mikhrin, D. A. Livshits, Innolume GmbH (Germany)

Owing to fundamental differences in the gain properties of Quantum Dot compared to conventional Quantum Well structures, the former offers a unique opportunity to build single cavity lasers with multiple lasing wavelengths (10, 16, 32, 64+) and low modal intensity noise. In combination with silicon photonics solutions under active development today, such a laser enables migration of DWDM optical transmission principles into board-to-board, chip-to-chip and on-chip communication. The paper will cover operational details of comb-lasers based on InAs/GaAs quantum dots in the 1.3 micrometer wavelength range. An overview of complementary silicon photonics devices will focus on micro-ring resonators.

7607-32, Session 8

Bias-free Y-branch waveguide modulator based on domain-inverted modulation of electro-optic polymer

B. Lee, C. Lin, The Univ. of Texas at Austin (United States); A. X. Wang, Omega Optics, Inc. (United States); R. T. Chen, The Univ. of Texas at Austin (United States)

A bias-free Y-branch directional coupler modulator (YDCM) based on electro-optic (EO) polymer is fabricated and tested. 25wt% AJLS102/APC (amorphous polycarbonate) is used as an active core layer with an experimentally confirmed device r33 value of 56pm/V and an extinction voltage of 4V at 1.59   wavelength. The directional coupler consists of two 5 -wide waveguides separated center-to-center by 10 . The vertical structure of device comprises of 3.5   bottom-cladding (UV-15LV), 1.5   of active core (AJLS102/APC), and 3   of top-cladding (UFC-170A). The rib waveguide is etched 0.5   deep into the bottom-cladding to support TM single-mode condition. A lumped electrode with two sections is designed to simplify the poling process while achieving the inverted modulation that can improve the linearity and the distortion suppression. The electrode has two sections and the length of both sections is 3.55mm which is 2.86   the normalized coupling length of directional coupler. Two-tone numerical procedure is used to find the optimum electrode design that can achieve the highest distortion suppression ratio which is defined as the ratio of fundamental signal to distorted signal. A two-tone test is performed using two fundamental signals of 50kHz and 55kHz at 25% modulation depth. The fundamental signals and the third order intermodulation distortions (IMD3's) are measured to be -27.80dBm and -92.13dBm, respectively. The achieved IMD3 suppression of 64dB is 22dB higher than that of the conventional Mach-Zehnder modulator.

Return to Contents

7607-33, Session 8

Surface-normal asymmetric Fabry-Perot quantum-confined Stark effect electro-absorption modulator on silicon

R. M. Audet, S. A. Claussen, E. H. Edwards, S. Ren, R. K. Schaevitz, E. Tasyurek, Stanford Univ. (United States); O. I. Dosunmu, M. S. Ünlü, Boston Univ. (United States); D. A. B. Miller, Stanford Univ. (United States)

One of the major challenges in the design of future integrated circuits is accommodating the increasing power usage and density of inter- and intra-chip communication links. Replacing wires with optical data links is one possible solution, as long as device size and performance criteria are met. To achieve practical optical interconnects, high-performance CMOS-compatible modulators are desired.

Strong electroabsorption modulation can be obtained in Ge/SiGe quantum wells (QWs) using the quantum-confined Stark effect (QCSE). This has recently enabled a working mechanism for a new generation of CMOS-compatible optical modulators. We present results from a surface-normal asymmetric Fabry-Perot QCSE modulator grown on a silicon substrate. The asymmetric Fabry-Perot cavity is formed by Si-SiO2 Bragg mirrors surrounding Ge QWs with SiGe barriers epitaxially grown on a SiGe buffer.

The device has a compact footprint suitable for solder bonding to Si integrated circuits, and the double-SOI substrate potentially enables monolithic integration. At wavelengths near 1450nm and a reverse bias of 0.5V, we have experimentally measured modulation contrast of 3 dB over a 1.5V swing.

7607-34, Session 8

Improved silicon light emission for reach- and punch-through devices in standard CMOS

P. J. Venter, M. du Plessis, Univ. of Pretoria (South Africa) and INSiAVA (Pty) Ltd (South Africa)

A key requirement for the success of future microphotonic devices will be the ability to integrate such devices into current mainstream semiconductor technologies. The ability to create silicon-based light sources in a standard CMOS process is therefore very appealing. This paper reveals a technique for improving the operational performance of a silicon light source by increasing the external quantum efficiency and relaxing the separation requirements for the light source operating under reach- or punch-through mechanisms.

When operating a silicon light source in avalanche, it is possible to enhance light emission by utilizing reach- and punch-through conditions. However, it is extremely difficult to obtain the exact optimum separation distance between the n+pp+ regions for the reach-through and n+pn+ for the punch-through devices using a standard CMOS LOCOS process. Limitations on a typical foundry's fixed manufacturing grid further limit the continuity of region spacing.

A design technique is explained in this paper, which not only reduces the strong dependency of reach-and punch-through devices on small incremental separation steps for maximum performance, but also increases the external quantum efficiency of the light sources by allowing more light to leave the surface at an orthogonal angle. This results in better coupling into external waveguiding structures.

Devices manufactured in a 0.35 μm standard CMOS technology are tested over a range of separation distances. Operation of reach- and punch-through mechanisms are verified through V-I characteristics, while the external quantum efficiency improvements are shown through the relative radiation patterns of the test and control devices.

7607-35, Session 8

Design of a 7GHz SiGe HBT EO modulator

S. Deng, T. Guha Neogi, J. F. McDonald, J. M. Novak, Z. Huang, Rensselaer Polytechnic Institute (United States)

Silicon-based electro-optic (EO) modulator is an indispensable building block for integrated lightwave circuits. In this paper, we report an EO modulator that incorporates a heterojunction bipolar transistor (HBT) with Ge composition graded base. The emitter is n-type doped silicon with a doping concentration of 1021/cm3. The width of the emitter strip is ~ 0.2μm and the thickness of the emitter layer is 0.2μm. The base has a thickness of 30nm with varying Ge composition from zero at the emitter/base side to 20% at the base/collector side. Raised extrinsic base structure is used to construct device model. The width of the intrinsic base is ~ 1μm and the thickness is 30nm. The base is p-type doped with a concentration of 4×1019/cm3. The HBT is biased at VCE = 0.5 V whereas VBE is switched between -1.2V and 1.2V. The carrier distribution at "ON" state of the EO modulator and the transient analysis are performed by MEDCI simulation. The changes of the refractive indices of the HBT are computed from the carrier density in all three regions, and then the refractive index map is imported into an optical mode solver (3D-BPM of RSoft). The HBT EO modulator that supports only one optical mode is ideal, but a trade-off between modal integrity and device speed is observed. For current design, we achieved a π-phase modulation length of 200μm, and a switching speed of 7GHz.

7607-36, Session 9

Laser-formed bumps on glass for precision alignment of planar optical components

J. S. Sutherland, A. M. Streltsov, R. R. Grzybowski, B. R. Hemenway, Corning Inc. (United States)

Techniques are presented for precision alignment of active and passive planar waveguide components using laser-formed glass bumps. Recently a process was developed for forming raised bumps on IR-absorbing glass substrates using a focused laser beam. Glass bumps with heights exceeding 90 um have been formed with an accuracy of ~100 nm using multiple laser shots. Proper selection of materials permits the bump height to be raised or lowered via subsequent laser shots by adjusting laser power. This paper describes hybrid assembly of a wavelength selective switch using this laser bump alignment technique. The wavelength selective switch consists of an InP arrayed Semiconductor Optical Amplifier (SOA) device aligned to two passive Si PLC (Planar Lightwave Circuit) AWG (Arrayed Waveguide Grating) multiplexer and demultiplexer devices. Three glass laser bumps are formed under each Si AWG component that serve as a pedestals. The heights of the bumps are changed in situ using a laser to perform the precision out-of-plane align of the AWG waveguide arrays to the InP SOA waveguide array. Using this approach arrays of waveguides on the substrates are aligned to each other with a positional accuracy of ≥0.3 um. In-plane alignment of substrates is provided by an overhead vision system and a precision X-Y stage. After alignment an adhesive is applied between each AWG and the glass substrate to hold the AWGs in position.

7607-37, Session 9

Life-stress relationship for thin film transistor gate line interconnects on flexible substrates

T. Martin, L-3 Display Systems (United States); A. Christou, Univ. of Maryland, College Park (United States)

Change in resistance of interconnect traces on flexible substrates is dependent on material properties and mechanical stress imposed by tensile strain. When a film is bent to a set radius of curvature, it leads to a well defined deformation profile whereby the outerlayer is in tension and the inner layer is in compression. The ANSYS shell-91 element was used

in the modeling of strain and stress in each of the layers.

A test system was designed and fabricated for the specific purpose of mechanically flexing the test structures while simultaneously monitoring changes in resistance of the interconnect lines. The approach was having a PC based Labview program controlling and synchronizing the two activities.

A unique gate level wafer mask was designed and fabricated for the purpose of this research. The mask allowed for the etching of interconnect lines with three different widths.

Time to failure data was used to determine model parameters for an inverse power law as the accelerated life model as well as a Weibull life distribution. This model can then be used as a basis for modeling the source lines or even higher level modeling of the entire display. The approach taken in this research can also be applied as a standard for qualifying future changes in materials, fabrication process, device geometry, or even parallel interconnect architectures.

7607-38, Session 9

Silicon-integrated photonic circuit for a single-stage large-angle beam steering optical phased array

D. N. Kwong, A. Hosseini, C. Lin, B. Lee, Y. Liu, R. T. Chen, The Univ. of Texas at Austin (United States)

In this paper, we present the results of the design and fabrication of a 12 channel nano-membrane-based optical phased array (OPA) that allows for large angle beam steering operating at wavelength=1.55μm. By implementing unequally-spaced waveguide array elements, we can relax the half-wavelength spacing requirement for large angle beam steering, thereby avoiding the optical coupling between adjacent waveguides and reducing the side-lobe-level of the array radiation pattern. Here, an integrated approach using standard CMOS processes on silicon on insulator is taken. One-dimensional beam steering of transverse-magnetic polarized single mode light is achieved thermo-optically through the use of thin film metal phase shifters. Using deeply etched air trenches, we ensure that heat dissipation from the heater is directed to the targeted silicon waveguide. Thus, the structure of the heater has been designed to provide efficient heat transfer and therefore, it allows us to achieve both fast response time and low power consumption. The voltage applied to each heater is controlled independently to achieve large beam steering angles of ±45 degrees using a one-stage OPA. An array of S-bend waveguides connects the outputs of a 1-to-12 multimode interference (MMI) coupler to the unequally-spaced radiating array elements. The S-bend waveguides have been designed to equalize the phase at the output to compensate for the MMI output phase profile. The use of silicon/silicon dioxide MMI coupler with high index-contrast provides a high bandwidth of 70nm.

7607-39, Session 9

Differential photo-acoustic gas cell based on LTCC for ppm gas sensing

K. Keränen, K. Kautio, J. Ollila, M. Heikkinen, VTT Elektroniikka (Finland); I. Kauppinen, Gasera Oy (Finland); T. Kuusela, Univ. of Turku (Finland); B. Matveev, Ioffe Physico-Technical Institute (Russian Federation); P. Karioja, VTT Elektroniikka (Finland)

Silicon MEMS cantilever based photo-acoustic technology allows for the sensing of ultra low gas concentrations with very wide dynamic range. The sensitivity enhancement is achieved with a cantilever microphone system in which the cantilever displacement is probed with an optical interferometer providing a pico-meter resolution. In the gas sensor, the silicon cantilever microphone is placed in a two-chamber differential gas cell. By monitoring differential pressure changes between the two chambers, the differential cell operates as a differential Infra-Red detector for optical absorption signals through a measurement and reference path. The differential pressure signal is relative to gas concentration in the optical measurement path. We have designed, implemented and tested a differential photo-acoustic gas cell based on Low Temperature Co-fired Ceramic (LTCC) multilayer substrate technology. LTCC is a multi-layer glass-ceramic material, which is co-fired in around 980 C temperature during the manufacturing process to remove organic binders from the substrate so that the final substrate consists of in-organic glass-ceramic material. Standard LTCC technology enables implementation of 2.5D structures including holes, cavities and channels into the electronic substrate. The implemented differential photo-acoustic gas cell structure includes circular cells, diameter of 2.4 mm and length 10 mm each. Reflectance measurements of processed gas measurement cell showed that reflectivity of the substrate material can be improved by a factor 15 ... 90 at a 3 ... 8 μm spectral region using gold and silver paste coatings. A transparent window is required in the differential gas cell structure in order to probe the displacement of the silicon cantilever. The transparent sapphire window was sealed to the LTCC substrate using two methods: screen printed Au80/Sn20 solder paste and pre-attached glass solder paste (Diemat DM2700P/H848). Both methods showed to provide hermetic sealing of sapphire windows to LTCC substrate. The measured He-leak rate for the sealed 10 test samples implemented using glass paste were under < 2.0 10-9 atm cm3/s, which meets the requirement for the leak rate according to MIL-STD 883. The achieved hermeticity level suggests that the proof-of-principle packaging demonstrator paves the way for implementing a novel differential photo-acoustic gas cell for a future miniature ultra sensitive gas sensor module. The future module together with sample gas cell and immersion lens IR LEDs is expected to be capable to measure ultra low concentrations of wide range of gases, which fundamental absorption bands at 3 ... 7 μm wavelength band, such as CO, CO_2 and CH_4.

7607-40, Session 9

Micro-optics packaging and integration for structured laser beam shaping

Y. G. Soskind, David H. Pollock Consultants, Inc. (United States)

Micro-optics packaging provides a practical approach for controlling the spatial field distribution of structured beams. Micro-optics packaging is commonly employed for structured beam shaping in a variety of photonics applications, including ultrahigh resolution microscopy, biophotonics, optical micromanipulation and trapping, laser pumping, materials processing and microfabrication, quantum information, and optical communications.

It is shown that the limited aperture sizes, as well as the distortions introduced by micro-optics components during the integration phase influence field formation of the structured laser beam, and may alter their spatial characteristics. Micro-optics design optimization for packaging and integration reduces the structured beam field distortions caused by the base beam shape imperfections, the wavefront distortions and lens-induced aberrations, the finite operating spectral range, as well as the diffraction effects caused by field truncation. Compensation techniques can be applied to improve the structured beam quality during the packaging process.

7607-01, Session 10

Active and tunable waveguide devices based on silicon and silica for use in optical communication systems

E. Brinkmeyer, Technische Univ. Hamburg-Harburg (Germany)

A variety of waveguide devices are in use or could be used for improving or enabling optical communication systems, including on the one hand fiber optical components such as fiber Bragg gratings (FBGs), and on the other hand planar waveguide devices - in particular silica-on-silicon structures - such as arrayed waveguide gratings (AWGs). Some of the devices under consideration are quite mature while others could be called up-and-coming and may be useful in the future. The latter applies to waveguide devices in silicon-on-insulator (SOI) which offer tremendous prospects, in particular regarding compactness and a seamless interface to electronics. From yet another perspective the devices may be either passive or active and tunable. Active, for example, are amplifying, lasing or switchable devices based on stimulated Raman scattering in silicon, tunability can arise from free carriers, from the thermo-optic effect or the electro-optic effect in the waveguide itself or in polymers combined with it (e.g. using slotted waveguides). Aspects of design, applications and characterization of such devices will be reviewed in this paper with focus on planar waveguide components for adaptive dispersion compensation, active devices in silicon and measurement techniques.

7607-02, Session 10

Optical transceivers for short and medium reach optical networks

B. Huebner, Finisar Corp (United States)

Optical transceivers are the dominating technology for the optical front end of short and medium reach optical communication systems.

They are very diverse, ranging from extremely low cost and high volume applications to extreme performance and relatively high cost products. Very different technical solutions for the optical components are used and this paper will give an overview of these enabling technologies.

Furthermore we will discuss the challenges (Density, Power consumption, Cost) that optical transceivers face today and which technologies may be used to solve these challenges in the future.

7607-41, Session 10

Evolution of optical access network technologies

T. Pfeiffer, Alcatel-Lucent Deutschland AG (Germany)

Photonic technologies have found widespread applications in high-speed longhaul and metro transmission networks for decades. Introducing similarly advanced optical technologies into access networks must respect the strict requirements for simple deployment and operations as well as ease of system migration and network maintenance. The large number of optical ports and fiber links to be provided and operated at lowest cost make access networks special as compared to their longhaul and metro networks counterparts. The presentation will provide a view on the status and future evolution of optical access networks and the photonic technologies applied therein.

7607-42, Session 10

Optical fiber interconnects: physical design for reliability

E. Suhir, Univ. of California, Santa Cruz (United States) and Univ. of Maryland, College Park (United States) and ERS Co. (United States); A. M. Earman, Arasor (United States)

We address a number of practically important problems of the mechanical behavior and structural mechanics of bare or coated optical fiber interconnects (OFIs), experiencing thermal and/or mechanical loading. The emphasis is on analytical ("mathematical") modeling. Possible failure modes are indicated and recommendations for a rational mechanical ("physical") design and improved reliability of OFI structures are suggested. We determine the loading conditions, evaluate the stresses and strains, and provide recommendations of what should be done to ensure that the OFI response to thermal and/or mechanical loading is acceptable from the standpoint of structural integrity, elastic stability, dependability, and normal operation (both optical and mechanical) of the system. We show how methods of Engineering Mechanics and Materials Engineering can be effectively applied to obtain closed form solutions to various practical problems of the mechanical behavior, physical design and reliability of photonics materials and structures experiencing thermally induced and/or "mechanical" loading. We discuss how to choose the appropriate material(s) for a particular package design and how to change, if necessary, the geometrical characteristics of the design to create a viable and reliable FOI structure. The major topics discussed include, but might not be limited to: bending of bare and coated OFIs, OFIs under the combined action of bending and tension, role of silica material nonlinearity, stresses in coated and partially coated fibers, interaction of "global" and "local" thermally induced stresses, elastic stability and microbending of OFIs, solder materials and joints in OFI structures, dynamic response of OFI structures to shocks and vibrations.

7607-43, Poster Session

Analytical formula for output phase of symmetrically excited one-to-N multimode interference coupler

A. Hosseini, D. Kwong, R. T. Chen, The Univ. of Texas at Austin (United States)

In this paper, we present a closed form formulation for the output signals of one-to-N multimode interference coupler under symmetric excitation. Using the reciprocity law for quadratic Gauss sums, we derive the output ports phases and show that the output phase has a quadratic dependence on the output port number. Using beam propagation simulations we compare the analytical phase profile with the simulation results for different waveguiding structures. In the case of silicon/silicon dioxide structure, our formulation predicts the output phase profile with errors not more than about 1 degree. We find that the effect of the penetration of the field into the cladding layers at the side walls is more than the modal phase errors on the output phase profile. However, even in the case of low refractive index contrast of $\Delta n = 0.01$, the output phase are within the 10 degrees intervals from the predicted values. Finally, we show that non-ideal effects such as limited number of guided modes, modal phase errors and extension of the field profile into the cladding layers have minimal effects on the phase profile in comparison with the output amplitudes. These results can be used in variety of optoelectronic applications, where the knowledge of the phase profile is crucial, such as optical phased arrays.

7607-44, Poster Session

Optimum operation of single-cavity photonic switches

A. Naqavi, Z. Monem Haghdoost, M. Edalatipour, S. Khorasani, K. Mehrany, Sharif Univ. of Technology (Iran, Islamic Republic of)

High speed operation and low power consumption are two main goals to be achieved through all-optical switching [1]; however, both of them cannot be satisfied simultaneously because of the power-bandwidth trade-off. Near the linear resonant frequency of the switch, low power consumption is achieved at the expense of slow operation whereas at off-resonance, higher speed is obtained at higher power levels. Furthermore, switching very close to the linear resonance or quite off-resonance results in low contrast between the transmission of ON and OFF states.

In this work, an optimum point is found for the operation of single cavity photonic switches. At this optimum point, the transmission contrast of ON and OFF states takes its highest value while keeping the device power threshold relatively low and the device speed acceptably high. Then, the dynamic behavior of a typical single cavity all optical switch is investigated in the optimum operation point through temporal coupled mode theory. Switching speed and power are discussed and the device is shown to be applicable for telecommunication and data processing applications. The analysis is quite general and can be used for resonant structures such as photonic crystals and microring resonators in both side coupled and direct coupled configurations.

[1] A. Naqavi, H. Abediasl, K. Mehrany, S. Khorasani, M. R. Chamanzar, A. Adibi, "On the power-bandwidth trade-off in bistable photonic switches," Proceedings of SPIE, Vol. 7223, Photonic and Phononic Crystal Materials and Devices IX, A. Adibi; S.-Y. Lin; A. Scherer, Eds., 722308 (2009).

7607-45, Poster Session

Electro-optic co-site interference mitigation

J. R. Bruno, U.S. Army CERDEC Intelligence and Information Warfare Directorate (United States)

Co-site interference is roughly defined as the unintentional degradation of receiver functionality as a result of close proximity to a powerful in-band transmission source; for instance receivers located on modern cellular communication towers often suffer as a result of co-site interference introduced through space limitations and overcrowding. The Electro-Optic Co-site Interference Mitigation system (EOCIM) was designed as a novel approach to control the problem of co-site interference. The EOCIM accomplishes interference cancellation through the integration of traditional EO telecommunications devices into an otherwise wholly RF communications system. This paper will discuss the integration of EO components into an RF communications system as well as the non-traditional integration of EO components to perform co-site interference mitigation.

To date the EOCIM has performed cancellation up to 80 dB reduction of a narrowband signal, 55 dB reduction of a 100 MHz bandwidth signal, ~35 dB/Hz cancellation for a 1.8 GHz bandwidth signal without affecting the receiver's signal of interest. The EOCIM is able to perform extremely wideband interference cancellation by utilizing the large instantaneous bandwidth and continuous signal conversion inherent in a fast EO modulator, largely addressing the limitations of traditional RF interference cancellation/mitigation techniques such as digital sampling and filtering. Furthermore, this approach allows the simultaneous operation of both Transmit and Receive systems without introducing significant degradation in performance or operability, ultimately removing the interfering Transmission signal without degrading the Receiver signal of interest.

7607-47, Poster Session

Design of analog-type high-speed SerDes using digital components for optical chip-to-chip link

J. Sangirov, N. Nguyen, T. Ngo, I. A. Ukaegbu, T. Lee, M. H. Cho, H. Park, Korea Advanced Institute of Science and Technology (Korea, Republic of)

An analog-type serializer/deserializer (SerDes) has been designed for utilizing the full bandwidth of the optical link in multipoint-to-multipoint data transmission architecture. The SerDes is one of key components of serial communication architecture for high-speed optical interconnect. The analog-type SerDes using digital components as a step towards a fully integrated transmitter/receiver design has such advantage as low power consumption as it occupies less area. And other advantages of digital components can be adopted to get full advantages from circuit design like reliable performance, and circuit techniques for high speed such as using dynamic circuits. The SerDes uses a system clock and its phases to multiplex data to the serial link which avoids the need for a phase-locked-loop-based high frequency clock generation used in serializing parallel data as in conventional SerDes design. The multiplexed link combined with the de-serializing clock is used as a reference signal for de-serialization. Signal latency has been evaluated for the synchronization of the de-serializing clock with data signal. The de-serializing clock has been substituted with a differential clock for resolving latency. The analog-type SerDes has been designed in a 0.13 µm Si-CMOS technology. Power dissipation is 71.4 mW at 1.2 V supply for the SerDes and the system operates up to 6.5 Gbps. The fabricated serializer has a core chip size of 360 x750 µm2. The performance of the fabricated SerDes is measured to check for consistency with simulated results and for implementation in multipoint-to-multipoint optical links. High reliability will be demonstrated with high-speed and high-capacity optical data link using the analog-type SerDes.

Conference 7608: Quantum Sensing and Nanophotonic Devices VII

Sunday-Thursday 24-28 January 2010 • Part of Proceedings of SPIE Vol. 7608

Quantum Sensing and Nanophotonic Devices VII

7608-02, Session 1

Quantum-dot mode-locked lasers with single- and dual-mode optical injection

G. Huyet, Cork Institute of Technology (Ireland) and Tyndall National Institute (Ireland); T. Habruseva, Tyndall National Institute (Ireland); S. O'Donoghue, N. Rebrova, Cork Institute of Technology (Ireland) and Tyndall National Institute (Ireland); S. P. Hegarty, Cork Institute of Technology (Ireland); D. I. Rachinskii, Univ. College Cork (Ireland)

We investigate in-band single- and dual-tone injection locking of QD-MLLs. Two-section monolithic InAs/GaAs quantum-dot lasers with repetition rate around 10 GHz emitting at 1300 nm with 23%, 17% and 12% absorber sections were used as slave QD-MLLs.

Both single- and dual-mode injection results in significant narrowing of the optical spectrum and tunability of the slave laser spectrum via the master wavelength. Remarkably, the spectral narrowing had no impact upon the second-harmonic autocorrelation width of the mode-locked pulses. Along with the large spectral narrowing with injection, this results in a large reduction in the TBP (10 times smaller compared to free running).

The slave laser modal linewidths measured via the heterodyne technique demonstrated parabolic dependence on the mode optical frequency for free-running case with the slope proportional to the radio-frequency linewidth and therefore directly related to the timing jitter. With single-mode injection the modal linewidth in the vicinity of the master wavelength is greatly reduced to that of the TLS due to phase locking. However far from this wavelength it increases to a value greater than that of the free running case. In the case of dual-mode injection all modes in the narrowed spectrum of the slave laser took on the linewidth of the master laser. The effect of phase locking of all slave laser modes to two highly coherent master tones improved greatly device jitter. The integrated timing jitter was as low as 210 fs (20 kHz-80 MHz), which is comparable to record results for the hybrid mode-locking.

7608-03, Session 1

Semiconductor quantum light emitters and sensors

S. Höfling, T. Heindel, C. Kistner, C. Schneider, M. Lermer, S. Reitzenstein, M. Kamp, A. W. B. Forchel, Julius-Maximilians-Univ. Würzburg (Germany)

Quantum light emitters have great application potential in quantum key distribution, precision metrology and quantum imaging. We present electrically driven single photon sources based on semiconductor quantum dots in GaAs/AlAs micropillar cavities with on demand single photon rates of 35 MHz while a record outcoupling efficiency up to 35 % is obtained. The high efficiency is achieved due to an optimized contact scheme which allows for the injection of electrical current into micropillar cavities which are characterized by low absorption losses and they have diameters down to 1 µm. By exploiting the established fabrication procedure, micropillar cavities exhibiting pronounced cavity quantum electrodynamic effects in both the weak and strong coupling regime have been realized. Furthermore, by applying a reverse bias to the micropillar cavities, photocurrent measurements allow for wavelength selective sensing of light at powers down to 20 nW. Routes to further reduce the detection limit are discussed whereas the envisaged devices have prospects to deliver sensitivities approaching the quantum limit.

The authors thank M. Emmerling and A. Wolf for technical assistance. Financial support by the German Ministry of Education and Research (BMBF) within the project "QPENS" and by the European Commission (EC) within the IST-project "QPhoton" is gratefully acknowledged.

7608-05, Session 1

Quantum cascade laser-based optoacoustic detection: application to nitric oxide and formaldehyde

V. Spagnolo, A. Elia, C. Di Franco, P. M. Lugarà, G. Scamarcio, Univ. degli Studi di Bari (Italy)

The detection and quantification of trace chemical species in the gas phase is of great interest in a wide range of applications such as environmental monitoring, industrial process control and medical diagnostics. In combination with quantum cascade lasers (QCLs), photoacoustic spectroscopy (PAS) offers the advantage of high sensitivity (ppbv detection limits), compact set-up, fast time-response and simple optical alignment. We will report here on the design and realization of a sensitive alignment-free optoacoustic sensor. The sensor consists of a commercial QCL and a PA detector. Different types of PA systems will be discussed, based on resonant cell and/or tuning forks. The use of a mid-ir optical fiber to couple the laser source and the PA detector eliminates any optical alignment issue. The optical fiber is directly inserted in the PA cell using a SMA hermetic feedthrough connector, so no input windows are required, or coupled with tuning forks. Two different type of sound detector have been employed: electret microphones and optical MEMS-based microphone. As possible applications, we will describe the results obtained in the detection of two different gases of great interest for industrial processes and automotive, i.e., nitric oxide and formaldehyde.

7608-95, Session 1

High power photonic crystal distributed feedback quantum cascade lasers emitting at 4.5 um

B. Gökden, S. Slivken, M. Razeghi, Northwestern Univ. (United States)

Quantum cascade lasers possess very small linewidth enhancement factor, which makes them very prominent candidates for realization of high power, nearly diffraction limited and single mode photonic crystal distributed feedback broad area lasers in the mid-infrared frequencies. In this talk , we present room temperature operation of a two dimensional photonic crystal distributed feedback quantum cascade laser emitting at 4.5 µm. peak power up to ~0.9 W per facet is obtained from a 2 mm long laser with 100 µm cavity width at room temperature. The observed spectrum is single mode with a very narrow linewidth. Far-field profile has nearly diffraction limited single lobe with full width at half maximum of 3.5 degrees normal to the facet. the, mode selection and power output relationships are experimentally established with respect to different cavity lengths for photonic crystal distributed feedback quantum cascade lasers.

7608-06, Session 2

Fiber sensor for QCL-based glucose measurement

C. Herrmann, C. Vrancic, N. Gretz, S. Hoecker, A. Pucci, W. Petrich, Ruprecht-Karls-Univ. Heidelberg (Germany)

The tight control of the concentration of glucose in blood constitutes a strong benefit for persons suffering from diabetes mellitus. Frequent testing reduces the probability of acute complications as well as long-term risks, such as retinopathy or diabetic foot. A continuous measurement would therefore offer an even stronger advantage over the medical standard of punctual measurements throughout the day.

Our approach is based on a fiber sensor for the measurement of the glucose-specific absorption in the mid-infrared range (~10µm). Based on the high specificity and sensitivity of infrared spectroscopy, it aims to determine the concentration of glucose in the interstitial fluid. Quantum cascade lasers (QCLs) in this spectral range offer a high spectral energy density to overcome the weak transmission through water which is dominant in biological materials. The properties of a pulsed Fabry-Perot QCL are studied in detail and are evaluated with respect to the demands of a quantitative glucose measurement.

We compared various design options for an absorption cavity in the fiber using non-sequential ray tracing simulations. A comparison between circular, cylindrical and rectangular shapes of the cavity will be given. We identified an optimal design with regards to the trade-off between an adequate path length for a preferably high glucose absorbance and the limit of a sufficient signal-to-noise ratio due to the high water absorption. Accompanying toxicity measurements for potential sensor materials were performed to test the potential for a future transcutaneous application.

7608-07, Session 2

Infrared laser-based sensing in medical applications

M. W. Sigrist, R. Bartlome, M. Gianella, ETH Zürich (Switzerland)

Since the advent of lasers, medical applications, e.g. in surgery, diagnosis and treatment, are steadily gaining in importance. In this talk, two examples of analytical applications will be presented, namely the laser-based analysis of human breath and of surgical smoke.

Breath analysis as a noninvasive tool for medical diagnosis has attracted much interest recently. We present a study on the temporal evolution of the D/H isotope ratio recorded in the exhaled breath following heavy water intake. With the help of a tunable mid-infrared laser source based on difference frequency generation and a heatable multipass cell we were able to detect an elevated D/H ratio up to several weeks after the intake of only 5 ml of heavy water without any further sample treatment. In addition, the total body water weight (55.2% ± 1.8%) with respect to the total body weight) could be determined.

Surgical smoke is generated in surgery with instruments like electroknives or laser-scalpels. The composition of the smoke and its potential danger to both the patient (particularly in minimally invasive laparoscopic surgery) and the operation team are of concern. We present first results on smoke samples generated in vitro and in vivo, analyzed with both laser and Fourier transform IR spectroscopy in combination with a newly developed algorithm for spectral analyses. Apart from water concentrations of some tenths of a percent we could quantitatively identify several compounds like methane, ethane and ethene at ppm concentrations.

Both examples demonstrate the power and potential of infrared laser spectroscopy for clinical applications.

7608-08, Session 2

Imaging stand-off detection of explosives using tunable MIR quantum cascade lasers

F. Fuchs, J. Kaster, B. Hinkov, Q. K. Yang, W. Bronner, K. Köhler, J. Wagner, Fraunhofer-Institut für Angewandte Festkörperphysik (Germany)

invited talk:

Fast and reliable stand-off detection of small concentrations of explosives is still an unresolved challenge. We present experimental results on imaging stand-off detection based on multi-spectral MIR backscattering (lambda>7 µm) using a tunable quantum cascade (QC) laser for spectrally selective active illumination of the scene. This technique offers several advantages: (i) Hidden observation is possible. (ii) Since low illumination power levels for spectroscopic detection are needed, the technique is eye-safe. (iii) Besides the spectrsocopic information the infrared imager needed for detection also provides the passive IR-image. The application scenario varies from the detection at a very short distance to control unattended luggage (10 - 100 cm), to a medium distance at security gates and checkpoints (1 to 10 m). Most challenging is the surveillance of larger areas, where long-range detection is desired (> 50 m).

By integrating the QC laser chip into an external cavity laser set-up, a large spectral tuning range exceeding 120 cm-1 could be demonstrated. A high performance infrared imager working in synchronisation with the active laser illumination is used for detection of the backscattered radiation. Concentration levels of TNT around 10 µg/cm2 could be detected for medium distances on real-world sample surfaces. Limitations and the needs to explore the full potential of the technique are discussed.

7608-10, Session 2

Novel broadband amplifier for mid-IR external cavity laser and applications in spectroscopy

S. Wu, California Institute of Technology (United States)

To taking advantage of the latest progresses in Quantum Cascade Mid-IR semiconductor laser growth, we built a broadband external cavity that could work over a wide IR range only limited by the gain bandwidth of the waveguide. By adding a 45 degree folded micro mirror on the buried hetero waveguide and reflect light out of the ~100 micron thick wafer, the FP cavity is converted into an amplifier, and a single layer broadband AR coating could suffice the high efficiency operation over the entire Mid-IR range. The surface emitting amplifier is validated in the external Littrow grating tuned cavity using all reflective gold coated Off-Axis Parabolic Mirror (OAPM) as the collimation lens. Smooth tuning without mode hopping is demonstrated over a wide range. The amplifier based on this design could work on almost all Mid-IR quantum cascade lasers with BH structures, and therefore provide a generic epi processing approach for all Mid-IR external cavity operation.

We then couple the above CW laser into a Whispering Gallery Mode CaF2 disc, and recorded the WGM transmission spectra. The tunable CW laser is also coupled into a hollow waveguide with low pressure sample gases, and saturated Doppler-free absorption spectroscopy is demonstrated for gas molecules at 4.4 microns. The linewidths of the above laser are measured in both cases against the Q of the WGM cavity and also the ultra-narrow linewidth of the Doppler-free absorption spectra.

References

1. Lee, H.P., et al., 1.5-Mu-M Ingaasp/Inp Vertically Coupled Semiconductor Optical Preamplifier. Applied Physics Letters, 1991. 59(10): p. 1141-1143.

2. Borri, S., et al., Lamb-dip-locked quantum cascade laser for comb-referenced IR absolute frequency measurements. Opt. Express, 2008. 16(15): p. 11637-11646.

3. Ilchenko, V.S., et al., Crystal quartz optical whispering-gallery resonators. Optics Letters, 2008. 33(14): p. 1569-1571.

7608-11, Session 3

Current status and potential of high-power mid-infrared intersubband lasers

S. Slivken, Y. Bai, B. Gokden, T. Huang, S. R. Darvish, M. Razeghi, Northwestern Univ. (United States)

Initial work by various groups has shown that the quantum cascade laser (QCL) can access a wide wavelength range (3.1-16 microns) at room temperature, with very good performance in some cases. Like other semiconductor lasers, the QCL is compact and based on mature InP and GaAs technology.

Despite many years of research, the scientific community is still learning subtleties about the quantum cascade laser (QCL) operation. Demonstrated device efficiencies, while increasing, are still below the theoretical expectations for a variety of reasons. One of our driving goals has always been to identify and address real limitations to device performance. Material quality is of primary importance and strongly influences both the differential gain and transport within the device. Though significant effort has been devoted to improving material quality, interface roughness still exists. Thermal effects also strongly influence device behavior, leading to broadening, leakage and a reduction of population inversion. We have made efforts to accommodate these types of non-idealities, leading to lasers with world record power and efficiency at room temperature and above.

This talk will discuss the state-of-the-art in QCL performance for high power applications. It will also focus on key areas that have led to performance enhancements at both longer (lambda~ 10 micron) and shorter (lambda~ 4.5 micron) wavelengths. Lastly, optimal performance expectations will be explored relative to the state-of-the-art.

7608-12, Session 3

Low-power laser-based carbon monoxide sensor for fire and post-fire detection using a compact Herriott multipass cell

D. M. Thomazy, Rice Univ. (United States); S. G. So, Princeton Univ. (United States); A. A. Kosterev, R. Lewicki, A. A. Sani, F. K. Tittel, Rice Univ. (United States)

With the anticipated retirement of Space Shuttles in the next few years, the re-supplying of short-lifetime sensors on the International Space Station (ISS) will be logistically more difficult. Currently, one such electrochemical sensor system monitors post-combustion gas products on the International Space Station. Carbon Monoxide (CO) is a well-known post-combustion product and its absence in a post-combustion environment is a reliable indicator for mission specialists that the air quality is at a safe to breathe level.

We report on the development and performance of a prototype compact CO sensor, based on the PHOTONS platform [1], developed for the ISS based on tunable diode laser absorption spectroscopy (TDLAS). A CO absorption line at ~4285 cm-1 is targeted using a distributed-feedback (DFB) laser diode operating at room temperature. A custom designed Herriott multipass cell 16cm long, with an effective path length of 3.7 m is employed. Mechanical, optical and electronics systems are integrated into a compact package of dimensions 12”x 3”x 4”. Power consumption is less than 1 W, enabling prolonged battery life. A detection limit of 5 ppm with 1 ppm sensitivity is achieved in a data acquisition time of 45 sec. A recent initial test at NASA-JSC was successful. Future improvements include the reduction of sampling volume and scan time and a further reduction of the CO detection limit.

REFERENCES:

[1] S. So, A.A. Sani, L.Zhong, F.K. Tittel, G. Wysocki, “Laser Spectroscopic Trace-Gas Sensor Networks for Atmospheric Monitoring Applications, ESSA Workshop ‘09, April 16, 2009, San Francisco, California, USA Copyright © 2009.

7608-13, Session 3

Design and performance of a sensor system for detection of multiple chemicals using an external cavity quantum cascade laser

M. C. Phillips, M. S. Taubman, B. E. Bernacki, B. D. Cannon, J. Schiffern, T. L. Myers, Pacific Northwest National Lab. (United States)

We describe the performance of a sensor system designed for simultaneous detection of multiple chemicals with both broad and narrow absorption features. The sensor system consists of a broadly tunable external cavity quantum cascade laser (ECQCL), multi-pass Herriott cell, and custom low-noise electronics. The ECQCL features a fast wavelength tuning rate of 2265 cm-1/s (15660 nm/s) over the range of 1150-1270 cm-1 (7.87-8.70 µm), which permits detection of molecules with broad absorption features and dynamic concentrations, while the 0.2 cm-1 spectral resolution of the ECQCL system allows measurement of small molecules with atmospherically broadened absorption lines. High-speed amplitude modulation and low-noise electronics are used to improve the ECQCL performance for direct absorption measurements. We demonstrate simultaneous detection of Freon-134a (1,1,1,2-tetrafluoroethane), ammonia (NH3), and nitrous oxide (N2O) at low-ppb concentrations in field measurements of atmospheric chemical releases from a point source.

7608-14, Session 3

Laser absorption spectroscopy based on a 7.74 µm quantum cascade laser source for UF6 analytical enrichment measurements

R. Lewicki, A. A. Kosterev, Rice Univ. (United States); F. Toor, Y. Yao, C. F. Gmachl, Princeton Univ. (United States); X. Wang, M. Fong, AdTech Optics, Inc. (United States); F. K. Tittel, Rice Univ. (United States)

Mid-infrared laser absorption spectroscopy (LAS) based on the state-of-the art quantum cascade laser technology offers the opportunity to detect, both in situ and remotely, different molecular species at trace gas concentration levels. High sensitivity and selectivity as well as non-contact isotopic measurements combined with real-time data processing, for sensor platforms employing the LAS technique, are of special interest to the International Atomic Energy Agency (IAEA) charged with the detection and verification of nuclear materials and activities on a global basis [1, 2]. The verification of 235U material balance at enrichment facilities by implementation of the LAS technique for an accurate uranium enrichment determination on UF6 samples [3] appears to be an attractive replacement for the IAEA currently used destructive analysis by thermo ionization mass spectrometry.

For this project the 1+ 3 combination band of UF6, with unresolved ro-vibrational spectral structure of several tens of wave numbers (cm-1) is targeted. As an advanced UF-LAS spectroscopic source a high performance cw TEC DFB QCL emitting radiation at 7.74 µm (1291 cm-1) can be employed. A comprehensive evaluation of the sensor platform to determine the lowest detectable absorbance, for both short and longtime laboratory measurements, with an appropriate UF6 analyte simulant (e.g CH4 and C2H2) will be demonstrated. Potential application of the UF6 LAS technique in LIDAR remote sensing will be also discussed. In addition, the development of mid-infrared QCLs at longer wavelengths will allow in the near future to access another UF6 combination band at 11.8 µm (1+ 4) and a less congested fundamental band at 16 µm (3).

References:

1. M. Zendel, "IAEA Safeguards: challenges in detecting and verifying nuclear materials and activities", TDLS 2007, Reims, France, July 9-13, 2007.

2. N. Peter, M. Stein, A. Nadezhdinskii, A. Mantz, "Tunable diode laser spectroscopy in international safeguards", TDLS 2007, Reims, France, July 9-13, 2007.

3. A.G Berezin et al, "UF6 enrichment measurements using TDLS techniques", Spectrochimica Acta Part A 66 (2007) 796-802.

7608-96, Session 3

Very high wall plug efficiency of quantum cascade lasers

Y. Bai, B. Gökden, N. Bandyopadhyay, A. Haddadi, S. Slivken, S. R. Darvish, M. Razeghi, Northwestern Univ. (United States)

We demonstrate very high wall plug efficiency (WPE) of mid-infrared quantum cascade lasers (QCLs) in low temperature pulsed mode operation (53%), room temperature pulsed mode operation (23%), and room temperature continuous (cw) wave operation (18%). All of these values are the highest to date for any QCLs. In room temperature cw operation, total output power of 3.7 W is obtained from uncoated devices. With high-reflectivity and anti-reflectivity coating, 3 W continuous power is obtained from a single facet. In room temperature pulsed mode operation, power scaling with broad area devices produces 120 W output power from devices with 400 um ridge width.

7608-15, Session 4

Recent developments on non-polar cubic group III-nitrides for optoelectronic applications

D. J. As, Univ. Paderborn (Germany)

Commercially available group III-nitride-based optoelectronic devices are grown along the polar c direction, which suffer from the existence of strong "built-in" piezoelectric and spontaneous polarization. This inherent polarization limits the performance of optoelectronic devices containing quantum well or quantum dot active regions. To get rid of this problem much attention has been focused on the growth of non- or semi-polar (Al,Ga,In)N. However, a direct way to eliminate polarization effects is the growth of cubic (100) oriented III-nitride layers. With cubic epilayers a direct transfer of the existing GaAs technology to cubic III-Nitrides will be possible and the fabrication of diverse optoelectronic devices will be facilitated. However, since cubic GaN is metastable and no cubic GaN bulk material exists in nature, heteroepitaxy with all its drawbacks due to lattice mismatch is necessary to grow this material. Due to the low lattice mismatch to cubic GaN the substrate of choice for the growth of cubic III-nitrides is 3C-SiC.

In this talk the latest achievements in the molecular beam epitaxy of phase-pure cubic GaN, AlN and their alloys grown on 3C-SiC substrates is reviewed. A new RHEED control technique is presented to carefully adjust stoichiometry and to severely reduce the surface roughness. The structural and optical properties of cubic nitrides and AlGaN/GaN heterostructures will be shown. The absence of polarization fields in cubic nitrides is demonstrated and 1.55µm inter-subband absorption in cubic AlN/GaN superlattices is reported. The progress towards the fabrication of cubic GaN/AlGaN superlattices for terahertz applications will be discussed.

7608-16, Session 4

Growth of intersubband GaN/AlGaN heterostructures

N. Grandjean, A. Dussaigne, S. Nicolay, D. Martin, Ecole Polytechnique Fédérale de Lausanne (Switzerland)

Thanks to their wide band-gap, III-nitride semiconductors are commonly used for blue-green light emitting diodes and UV-blue laser diodes. These compounds are also of interest for intersubband transition (ISBT) based devices operating in the telecommunication wavelength range or in the THz regime. Indeed, one peculiar property of nitride heterostructures is their very large conduction band offset. In addition, they exhibit very short ISBT relaxation time, due to strong electron-phonon interaction, which is highly desirable for ultra-fast optical devices.

Until now, the development of nitride heterostructures for ISB purpose has been hindered by a rather poor material quality. In addition, the heavy electron effective mass imposes ultra-thin quantum well (QW) thickness (< 2 nm) to reach 1.3-1.55 µm ISB absorption. Consequently, QW interface quality is critical and phenomena like intermixing, diffusion and/or surface segregation must be carefully considered. On the other hand, GaN/AlGaN QWs are affected by giant built-in electric field when growth is performed on polar surfaces. This leads to another degree of freedom, which makes difficult an accurate control of the electronic properties. Interestingly, this internal electric field can be eliminated by growing on non-polar planes.

In this presentation, we report on the growth of GaN/AlGaN QWs dedicated to Telecom and THz applications on both polar and non-polar substrates. A careful optimization of the QW interface morphology allows us achieving low ISB absorption peak linewidths. Finally, the quality of the samples is exemplified by the fabrication of electro-optical modulators with high-frequency response.

7608-17, Session 4

Resonant tunneling diode opto-electronic integrated circuits

C. N. Ironside, Univ. of Glasgow (United Kingdom); J. M. L. Figueiredo, B. Romeira, Univ. do Algarve (Portugal); T. J. Slight, L. Wang, E. Wasige, Univ. of Glasgow (United Kingdom)

We present a review of Resonant Tunneling Diode OptoElectronic Integrated Circuits (OEICs), Resonant tunneling diodes (RTDs) can be relatively easily integrated on the same chip as optoelectronic components and in this paper we discuss the integration of RTDs with electroabsorption modulators, photodiodes and laser diodes. The RTD provides the OEIC with negative differential resistance over a wide bandwidth. RTDs are highly nonlinear devices and by applying nonlinear dynamics we have recently gained considerable insight into the operation of the RTD OEICS and that has allowed us to design, fabricate and characterize OEICs for wireless/photonic interfaces.

7608-18, Session 4

Optical modulators in silicon

G. T. Reed, D. J. Thomson, F. Y. Gardes, W. R. Headley, G. Z. Mashanovich, Univ. of Surrey (United Kingdom)

Silicon Photonics potentially offers the implementation of optical interconnect at increasingly reduced cost due to the mature processing technology inherent in today's electronic industry. One of the key components for successful implementation of such interconnect, is an efficient optical modulator in silicon. The state of the art in this field has been transformed recently, with data rates increasing from a few tens of MHz to tens of GHz in a few short years.

The Silicon Photonics group at Surrey has long been involved in the

design, modelling, fabrication, and characterisation of optical modulators. This paper reviews the contribution of the Surrey group, detailing designs based around the plasma dispersion effect. A variety of designs are discussed, ranging from PIN, carrier injection devices based around large waveguides of multi-micron dimensions, to much smaller depletion devices that operate in the multi GHz regime. Both modelling and experimental results are presented.

7608-19, Session 4

III-V quantum dot lasers: progress and challenges

M. Henini, The Univ. of Nottingham (United Kingdom)

One of the most important devices in optoelectronics is the semiconductor laser because of its high quantum efficiency; its capabilities and the range of applications that have grown tremendously over recent years. The capability to fabricate novel materials on an atomic scale by using sophisticated epitaxial crystal growth techniques has contributed tremendously to the success of semiconductor quantum well (QW) lasers. The QW laser performances can be improved further by implementing new structures containing quantum wires (QWi) and quantum dots (QDs).

QDs can be fabricated using several techniques including lithography-based technologies. However, the self-organisation process shows great potential for the fabrication of three-dimensional structures, which are formed by the Stranski-Krastanov heteroepitaxy growth mode using lattice-mismatched systems. The advantages of this fabrication technique where the QDs are grown in-situ include a homogeneous surface morphology and prevention of defects. In addition, there are no further processes required such as advanced lithography and chemical etching.

The low cost, high performance and high reliability of the QW laser contributed to its mass production within very few years of its invention. However, theoretical calculations expect that the QD lasers to have superior properties compared to those of conventional QW lasers. These include higher characteristic temperature T0, lower threshold (Ith) currents and narrower linewidth. In the last few years tremendous progress has been made in improving T0 and Tth of QD lasers. Recently, they have overcome the performance of the best QW lasers in terms for example of threshold current, which is one of the figures of merit of this key device. This implies that the QD lasers could potentially revolutionise the optical electronics industry and make them considerably energy efficient and therefore much more attractive from a commercial perspective.

In this talk, I will describe the structural and optical properties of self-assembled QDs and review the progress in the development of QD lasers.

7608-20, Session 4

Coupled plasmonic quantum bits

A. Eftekharian, M. Sodagar, M. Khoshnegar, S. Khorasani, Sharif Univ. of Technology (Iran, Islamic Republic of)

In this paper we will introduce a coupled system of two quantum bits residing at the interface of a heterostructure device. The structure encompasses a reference quantum bit, a photonic/plasmonic crystal waveguide and an obedient quantum bit. Each quantum bit is an electronic device which is designed based on an anti-dot lattice of two-dimensional electron gas in heterostructures. By applying a potential gate in the aforementioned structure it will be possible to control electronic tunneling rate and hence quantum bits' swapping frequency. Coupling through the plasmonic waveguide may be employed to entangle quantum bits. The waveguide has been designed by exploiting conducting islands of two-dimensional electron gas in a host of layered semiconductor heterostructure, behaving effectively as a patterned metallic thin film. Plasmonic characteristics is here modeled by Drude dispersion which obviates the required frequency dependency of our case. Employment of a plasmonic crystal waveguide benefited from plasmonic nature instead of regular dielectrics will decrease the dimensions up to ten times, which helps the structure's size to be in the range of practical fabrication technologies.

In order to estimate the evolution of the entangled state of the pair of quantumn bits, it is necessary to estimate the coupling coefficient between electronic and optical subsystems. This parameter can be regarded as a design goal of matched electronic and optical structures, and has been discussed in detail for the optimization purposes.

In the present work, both plasmonic and electronic properties have been investigated. For simulating different sections revised guided mode expansion (RGME) [1] and finite difference time domain (FDTD) methods have been used.

[1] A. Eftekharian, M. Sodagar, M. Khoshnegar, S. Khorasani, M. Chamanzar, and A. Adibi, "Revised Guided Mode Expansion on Dispersive Photonic Media," Proceedings of SPIE, vol. 7223, 72230U (2009).

7608-92, Session 4

Single quantum dot optical coherent control in a planar microcavity

G. S. Solomon, Joint Quantum Institute (United States)

No abstract available

7608-21, Session 5

Intersubband device applications of nitride quantum structures

R. Paiella, K. Driscoll, Y. Li, Y. Liao, A. Bhattacharyya, C. Thomidis, Boston Univ. (United States); L. Zhou, D. J. Smith, Arizona State Univ. (United States); E. Bellotti, T. D. Moustakas, Boston Univ. (United States)

GaN/AlGaN quantum structures feature some unique properties for intersubband device development, including a record large conduction-band offset that allows extending the operating wavelength to the near-infrared spectral region. This talk will review our recent work aimed at the demonstration of novel device functionalities utilizing intersubband transitions in MBE-grown nitride quantum wells. In particular, we will first describe a family of quantum-well waveguides that we have developed for all-optical switching via intersubband cross-absorption saturation. These devices operate at fiber-optic communication wavelengths and feature sub-picosecond response times due to the ultrafast nature of intersubband relaxation processes. Strong self-phase modulation of ultrafast optical pulses has also been measured in these waveguides, revealing a large refractive-index nonlinearity which is related to the same intersubband carrier dynamics and which is also promising for all-optical switching applications. Furthermore, we have demonstrated optically pumped intersubband light emission from GaN/AlN quantum wells resonantly excited with a pulsed OPO. The measured room-temperature output spectra are peaked near 2 microns, which represents a new record for the shortest intersubband emission wavelength from any quantum-well materials system. Finally, the potential of GaN/AlGaN quantum wells in the area of THz quantum-cascade sources, related to the characteristically large LO-phonon energies of nitride semiconductors, will also be discussed.

7608-22, Session 5

Probe of coherent and quantum states in narrow-gap semiconductors in the presence of strong spin-orbit coupling

G. A. Khodaparast, M. Frazier, M. Bhowmick, R. N. Kini, K. Nontapot, Virginia Tech (United States); M. R. Santos, Univ. of Oklahoma (United States); B. W. Wessels, Northwestern Univ. (United States)

In light of the growing interest in spin-related phenomena and devices, there is now a renewed interest in the science and engineering of narrow gap semiconductors (NGS) such as InSb. NGSs offer several scientifically unique electronic features such as a small effective mass, a large g-factor, a high intrinsic mobility, and large spin-orbit coupling effects. In semiconductors with large spin-orbit interaction the coupling of electron spin polarization with electric fields can provide new opportunities for spin manipulation in both electronic and optoelectronic devices. Recent observations of the Curie temperature above 300 K in InMnAs and InMnSb, have opened new opportunities for developing infrared spin photonics.

As switching rates in electronic devices are pushed to even higher frequencies, it is important to understand the carrier and spin dynamics in these material systems on femtosecond time-scales. Optical spectroscopy with femtoscecond time resolution allows us to generate and monitor coherent optical polarization and carrier distribution in real time.

Our studies have been focused on probing and controlling the coherent and quantum states in several NGSs. Our observations are providing new information regarding the optical control of carriers and spins in these material systems.

Supported by: NSF-DMR-0507866, NSF-DMR-0520550, NSF-DMR-0804479, AFOSR Young Investigator Program 06NE231

7608-23, Session 5

Entanglement enhanced quantum sensing

H. Weinfurter, Ludwig-Maximilians-Univ. München (Germany)

Entanglement between quantum objects can be used to enhance the resolution of measurements. We demonstrate this effect by using entangled photons to obtain image resolution beyond the diffraction limit. Utilizing polarization entangled multi-photon states we are able to go beyond the standard quantum limit when observing polarization rotations.

7608-24, Session 5

A numerical tool for analyzing light propagation in photonic-crystal waveguides in the presence of fabrication imperfections

P. Lalanne, Institut d'Optique (France)

Slow light in photonic-crystal (PhC) integrated circuits is a promising solution for on-chip buffering and time-domain processing of optical signals. However, the slow-light transport is strongly impacted by random fabrication fluctuations, such as variations in hole sizes, shapes or locations, and since disorder is regarded as critical in practice, there has been significant effort to determine how does light actually propagate in real photonic-crystal waveguides (PhCWs). From early studies based on perturbation theories, our current understanding has rapidly developed over the past few years with a series of experimental and theoretical results showing that localization and multiple scattering are key ingredients of the photon transport in such waveguides.

Apart from the experimental work performed in [Engenelen PRL 2008] where an indirect frequency-space averaging procedure was elaborated, the results reported so far all concern measurements performed for a single waveguide. In principle, this precludes observing averaged transport characteristics or studying the rate of convergence toward the ensemble average characteristics. In this Letter, we collect information on a series of PhCWs that are supposedly identical and that only differ because of statistical structural imperfections. Having access to a number of samples, we infer averaged characteristics of the transport and we analyse the impact of the group velocity on the statistical fluctuations of the transmission. In particular, we evidence that, due to backscattering, the probability density function of the transmission rapidly broadens in the slow light regime even for relatively large group velocities (<c/20) and even for practically relevant situations offering tolerable losses.

7608-25, Session 6

Catalyst-free and position-controlled formation of III-V semiconductor nanowires for optical device applications

S. Hara, J. Motohisa, K. Tomioka, K. Hiruma, T. Fukui, Hokkaido Univ. (Japan)

Recent research activities for semiconductor nanowires have gained much attention in the potential applications to future nanostructured electronic and photonic devices. Realization of the single crystal nanowires with a high degree of quality, uniformity and reproducibility, however, is still a challenging task. The significance of the controlled nanowire growth would increase multifold if it could be realized without any use of the catalyst-assisted methods. The authors have realized many varieties of the nanowires, e.g. GaAs/AlGaAs and GaAs/GaAsP core-shell, and InP/InAs/InP and AlGaAs/GaAs/AlGaAs core-multishell ones, by catalyst-free selective-area metal-organic vapor phase epitaxy on partially SiO2-masked GaAs(111)B, InP(111)A or Si(111) wafers. The length, diameter, shape and position of the nanowires are precisely manipulated by optimizing growth conditions and mask designs. The nanowire growth, in addition, is controlled in either the axial or the radial directions. We report the photoluminescence characterizations for the InP/InAs/InP core-multishell nanowires. The results show the successful formation of InAs quantum well tubes with the thicknesses of a few mono-layers on the InP nanowire sidewalls. Next, we demonstrate Fabry-Perot microcavity lasers using the single GaAs and InP nanowires by optical pumping at 4.2K. The Q value at the wavelength of 845nm is estimated to be 220 for the GaAs nanowires. The lasers have also been realized using the GaAs/GaAsP core-shell nanowires. Finally, we observe the significant enhancements in the photoluminescence intensities of the GaAs/AlGaAs core-shell nanowires at 4.2K compared to those of the GaAs ones and the electroluminescence at room temperature from the AlGaAs/GaAs/AlGaAs core-multishell nanowires on Si(111) wafers.

7608-26, Session 6

Cavity polaritons for new photonic devices

J. I. Bloch, Ctr. National de la Recherche Scientifique (France); D. Bajoni, Univ degli Studi di Pavia (Italy); E. Wertz, L. Ferrier, P. Senellart, A. Miard, A. Lemaitre, I. Sagnes, S. Bouchoule, Ctr. National de la Recherche Scientifique (France)

Semiconductor microcavities in the strong coupling regime have been the subject of intensive research efforts these last years. In this system, the eigenstates are exciton-photon entangled states (named cavity polaritons). Polaritons present strong non-linearities due to their excitonic part and obey to bosonic statistics, thus being able to massively occupy a single quantum state (quantum degeneracy).

The potentiality of cavity polaritons for new photonic devices will be discussed. We will address how they can provide a low threshold source of coherent light [1], an integrated OPO [2-3] for the generation of correlated photons or a bistable device with low switching power [4-5].

[1] D. Bajoni et al., Phys. Rev. Lett. 100, 047401 (2008).

[2] C Diederichs, et al., Nature 13, 04602 (2006).

[3] D. Bajoni et al., Applied Phys. Lett. 90, 051107 (2007).

[4] D. Bajoni, et al., Phys. Rev. Lett. 101, 266402 (2008).

[5] News and Views, Nature Photonics 3, 135 (2009).

7608-27, Session 6

Quantum optics with single nanowires and quantum dots

N. Akopian, Technische Univ. Delft (Netherlands)

We present our recent developments in control and manipulation of individual spins and photons in a nanowire quantum dot. Specific examples include demonstration of optical excitation of single spin states, charge tunable quantum devices and triggered single photon sources. We will also discuss our recent discovery of a new type of charge confinement - crystal phase quantum dots. They are formed from the same material with different crystal structure, and today can only be realized in nanowires.

7608-28, Session 6

Nanoparticle for active plasmonic device

J. Delahaye, S. Grésillon, E. Fort, Ecole Supérieure de Physique et de Chimie Industrielles (France)

Active plasmonic devices are good candidates for optical devices and circuits at the nanoscale. Since the term ‘active plasmonic’ was coined in 2004, a number of modulation techniques associated to plasmonic geometries have been designed to achieve light control. However, in such geometries, modulation is achieved on wave guiding geometries resulting in lateral microscopic dimensions, not suitable for highly integrated photonic devices.

We show that single nanoparticles coupled to metallic surfaces are good candidates for integrated components with nanometric dimensions. The localized plasmon of the nanoparticle launches propagating surface plasmons in the metallic thin film. Direct particle observation using leaky wave microscope geometry permits easy homodyne detection through the interference of the direct transmitted excitation light and the surface plasmon leaky mode. Interference phase control can be tuned easily by adjusting the focus plan. Investigations of the optical response of a nanoparticle deposited on metallic thin metal films reveals surprising phenomena, including unexpectedly high transmission of light associated to contrast inversion in the images. A simple model allows us to give a clear physical interpretation of the experimental observations. We show that this simple geometry is of practical interest in the context of nano-optical switch with size smaller than the optical diffraction limit.

7608-29, Session 7

Near-field analysis of surface waves generated by nanostructures

L. Aigouy, L. Lalouat, LPEM / CNRS / ESPCI (France)

When a nanostructure is illuminated by an incident optical wave, it diffracts the light in all space. When the structure is situated on a metal like gold, part of this light is transformed into a surface wave called surface plasmon polariton (SPP). Such waves have numerous potential applications since they could be used in nano or microscale optical devices to transport information or to initiate photochemical reactions. By scanning near-field optical microscopy, we have directly observed the propagation of SPPs generated by nanostructures deposited on a thin gold film. We will first show that isolated nanoslit apertures generate two kinds of waves: a rapidly decaying electromagnetic field and a SPP that propagates on several tens of micrometers. If two nanostructures are illuminated, the generated surface waves encounter each other and create interference patterns. By analyzing the near-field distribution on such structures, we have been able to determine important parameters like the relative importance of these waves and the SPP generation rates. Finally, by comparing the electromagnetic field distribution around a nanoridge deposited on a metallic and on a dielectric substrate, we have been able to fully isolate the non plasmonic component from the SPP. The experiments, which will be compared to numerical simulations, provide a good general idea of the nature of the surface waves generated by nanostructures.

7608-30, Session 7

Enhancement of light-matter interaction using surface states in photonic crystal structures

M. Liscidini, Univ. of Pavia (Italy)

Bloch Surface Waves (BSWs) are propagation modes that exist at the interface between an homogeneous medium and a photonic crystal (PhC). The confinement mechanism relies on total internal reflection in the homogeneous medium and on the photonic band gap in the PhC. The dispersion relation of BSWs can be easily tailored through the design of the PhC. This makes BSW extremely flexible and suitable for applications in the field of optical sensors, light emitters, and photovoltaic devices, where the capability of confining and amplifying the electromagnetic field in micro- and nano-structures allows for the enhancement of the light-matter interaction.

7608-31, Session 7

Microwave technology applied to terahertz quantum cascade lasers

S. Barbieri, W. Maineult, L. Ding, P. Gellie, P. Filloux, C. Sirtori, Univ. Paris Diderot (France); J. Lampin, T. Akalin, Univ. des Sciences et Technologies de Lille (France); I. Sagne, Ctr. National de la Recherche Scientifique (France); H. E. Beere, D. Ritchie, Cavendish Lab. (United Kingdom)

At Terahertz (THz) frequencies metals are still excellent materials to guide and confine electromagnetic radiation with relatively low losses. Therefore the concepts developed in the microwave range to design efficient waveguides and resonators can be successfully transferred up to this frequency region. A successful example of such “technology transfer” is the so-called metal-metal resonator, successfully used as a waveguide for THz Quantum Cascade Lasers (QCLs). This type of resonator is essentially a downscaled version of a microstrip waveguide, widely used at microwave frequencies. In the first part of this talk we shall show that metal-metal waveguides can still support the propagation of microwaves without significant attenuation up to at least 50 GHz. We have exploited this property to demonstrate the amplitude modulation of a 2.8THz QCL up to 24GHz, the highest ever reported to date for this family of devices.

In the second part of the talk we will present how the so called horn-antenna, designed by microwave engineers to efficiently match waves from a waveguide to free-space, can be used to perform the same task in combination with metal-metal waveguide THz QCLs, yielding a striking improvement to the beam directionality.

7608-32, Session 7

Single-spin microscope with sub-nanoscale resoultion based on optically detected magnetic resonance

G. P. Berman, B. M. Chernobrod, Los Alamos National Lab. (United States)

Recently we proposed a new approach which potentially has single spin sensitivity, sub-nanometer spatial resolution, and ability to operate at room temperature (J. Appl.Phys. 97, 014903 (2005); J. Phys., Conference Series 38, 167 (2005); U.S. Patent No. 7,305,869, (2007)). In our approach a nanoscale photoluminescent center exhibits optically detected magnetic resonance (ODMR) in the vicinity of magnetic moment in the sample related with unpaired individual electron or nuclear spins, or ensemble of spins. We consider sensor materials that exhibit ODMR properties 1) nitrogen-vacancy (N-V) centers in diamond and 2) CdSe nanoparticles. Although each type of materials is optically active, has reasonable sharp photoluminescence peaks, N-V centers in diamond have serious advantage having extraordinary chemical and photostability, very long spin lifetimes, and ability of single-spin detection at room temperature. The variety of possible scanning schemes has been considered. The potential application to 3D imaging of biological structures has been analyzed.

7608-33, Session 8

Raman scattering in submicron- and nanoscale structures

N. Vermeulen, C. Debaes, H. Thienpont, Vrije Univ. Brussel (Belgium)

Raman scattering refers to a category of scattering processes during which incident photons are converted to higher- or lower-energy photons through an interaction with e.g. a vibrational energy level of a Raman-active medium. The most important, non-spontaneous Raman interaction is stimulated Stokes Raman scattering (SSRS); a process that converts pump photons to lower-energy Stokes photons and phonons. Using this process, one can establish active light generating functionalities such as lasing and optical amplification in any Raman-active material.

Due to the nonlinear nature of SSRS, however, one can only obtain a high scattering efficiency when the optical fields are strongly confined and interact intensively with the Raman material. For this purpose, the use of submicron- and nanoscale structures, such as nanowires, photonic bandgap-based waveguides, and slow light structures, is most appropriate. Employing such light confining submicron- and nanoscale structures for enhancing SSRS has, however, an important drawback, namely that the SSRS-induced phonons are created in a small volume as well. To deal with the associated heat generation, we developed an intrinsic heat mitigation technique for Raman lasers and Raman amplifiers, that suppresses the SSRS-induced phonon creation in the medium by evoking another Raman process, namely Coherent Anti-Stokes Raman Scattering (CARS).

In this paper, we will first review the submicron- and nanoscale structures that have been introduced over the past few years for enhancing the Raman scattering efficiency. We hereby focus our attention on two important Raman materials, namely silicon and hydrogen gas. Next, we will explain how the heat dissipation in silicon- and hydrogen-based Raman lasers and amplifiers can be intrinsically reduced by the use of CARS. We will conclude by numerically demonstrating that with this CARS-based heat mitigation technique the heat generation in these Raman devices could be suppressed with at least 30%.

7608-34, Session 8

Compound semiconductor micro and nanotubes: from formation to photonic applications

X. Li, I. S. Chun, K. Bassett, Univ. of Illinois at Chicago (United States)

Compound semiconductor micro- or nanotube is a new nanotechnology building block that possesses the potential to provide a wide range of functionalities. It is formed by a combination of top-down and bottom-up approach through the self-rolling of strained thin films using standard optical lithography. This allows feasible large area assembly and integration with existing semiconductor technology, while maintaining the control of tube size and heterojunction formation in the tube wall. The tubular geometry dramatically enhances the photoluminescence (PL) intensity, and the PL peak position shifts as a result of the tube curvature. In this paper, we report on the formation process, geometry dependence, optical properties and sensing applications of InxGa1-xAs/GaAs based microtubes with wall thickness as thin as 30 nm and embedded internal light emitters such as quantum dots, quantum wires, and quantum wells.

7608-35, Session 8

Carrier-induced optical index variations in InP waveguide diodes: the thermal effects contribution

N. Saadsaoud, M. Zegaoui, D. J. Decoster, E. Dogheche, X. Wallart, Univ. des Sciences et Technologies de Lille (France); J. Chazelas, Univ. des Sciences et Technologies de Lille (France) and Thales Airborne Systems (France)

When nanosecond response times are required, carrier-induced optical index variations in IIIV waveguide PIN diodes are basic effects for many active photonic or nanophotonic integrated circuits. An example of photonic integrated circuit is the optical switching matrix constituted of digital optical switches which is a Y junction with an electrode on each output branch. An example of a nanophotonic function is the electronic control of the optical delay in a slow light photonic crystal. In both cases, the engine is the optical index decrease obtained with a current flow, mainly governed by plasma effects, when carriers are injected in a PIN waveguide diode. Experiments carried out on InP PIN heterostructures, show maximum achievable index variations around 10-2. In this paper we will analyse the main factors limiting the optical index variation. Two effects are taken into account: the reduction of carrier lifetime when increasing the density of carriers, and thermal effects. To study thermal effects, active InP optical waveguides with Schottky contacts were fabricated and index variations under current injection were measured. Only thermal-induced index variations are experimentally observed with Schottky diodes; they are opposite to the carrier induced ones, with an increase of optical index as high as 0.1, and a 1µs response time. It turns out that the thermal effect can be an important limiting factor to the optical index change. In the conference we will evaluate each phenomenon separately (lifetime and thermal effects) and the influence of the thermal effects on the carrier induced index variations, and we will also discuss on how to reduce drastically the thermal effects, and how to use thermal effects with an improve response time to take advantage of high optical index variations.

7608-36, Session 8

Subwavelength antireflection structures and their device applications

J. S. Yu, Kyung Hee Univ. (Korea, Republic of); Y. M. Song, Gwangju Institute of Science and Technology (Korea, Republic of); J. W. Leem, Kyung Hee Univ. (Korea, Republic of); Y. T. Lee, Gwangju Institute of Science and Technology (Korea, Republic of)

Recently, the antireflection structures, which reduce the undesirable reflection between different optical media, have attracts growing interest in many applications of photovoltaic cells, light-emitting diodes (LEDs), photodiodes and transparent glasses. Subwavelength structures with the period smaller than the light wavelength, acting as a homogeneous medium with an effective refractive index determined by the fill factor, have a promising potential for high-efficiency optical devices due to their broadband antireflection properties. Various fabrication methods of nanostructures have been developed using e-beam lithography followed by dry etching, nanoimprint lithography followed by liftoff process, and dynamic etching. However, these methods may require complex processes and take a long time, i.e., expensive and time-consuming processes. In contrast, holographic lithography is relatively simple, fast, inexpensive, and particularly applicable for large areas.

In this study, we report the subwavelength antireflection structures in various semiconductor materials such as ZnO:Al, GaAs and Si and their LED applications in visible and near-infrared wavelengths, together with the rigorous coupled wave analysis simulation. Subwavelength structures were fabricated by holographic lithography and dry etching, effectively suppressing the surface reflection. The improvement in light output power was achieved for the fabricated the LEDs with a subwavelength structure compared to the conventional LEDs due to a strongly reduced internal reflection at the air/semiconductor interface.

7608-37, Session 8

Nanophotonic and near field optics

F. A. de Fornel, B. Cluzel, L. Lalouat, D. Brissinger, K. Foubert, L. Salomon, Institut Carnot de Bourgogne (France)

First by using the optical near-field microscopy technique coupled to microphotoluminescence or transmittance experiments, we investigate the optical near-field properties of photonic crystal nanocavities and evidence the near-field probe ability to manipulate their resonances. First, we break trough the diffraction limit to directly visualize the electromagnetic field distribution inside the cavities and locally probe their spectral properties. The recorded near-field pictures and spectra are then analysed in light of the 3D numerical predictions of the cavity properties. Next, we use the near-field probes to directly manipulate the optical properties of the cavities and evidence that the near-field interactions existing between the cavities and the probes allow us to tune their resonance wavelengths. Finally, we develop a novel interaction scanning mode allowing to directly map the previous near-field interaction and we analyze its fundamentals theoretically as well as numerically.

7608-38, Session 8

Near-field optical imaging of polarization-dependent plasmonic resonance in metal nanoparticle pairs

H. Lin, C. Huang, C. Chang, Y. Lan, H. Chui, National Cheng Kung Univ. (Taiwan)

The near-field distribution of plasmonic coupling effect in gold nanoparticle pairs was directly investigated by a near-field scanning optical microscope (NSOM) in the fiber-collection mode. It is shown that the strongest electromagnetic (EM) field is generated in the gap of two nanoparticles when the pair axis is parallel with the incident photonic polarization and the interparticle space is restricted within the diameter of a nanoparticle. NOSM images show that the localized plasmonic coupling and the EM field distribution of nanoparticle pairs are systematically influenced by the interparticle space and axial direction of incident polarization. This observation can facilitate the understanding of localized hot spots in surface-enhanced Raman spectroscopy in the near field and can be used as a guideline for fabricating specific nanostructures in controlling the spatial distribution of surface plasmon (SP) modes for ultrasensitive sensors or photonic devices.

7608-40, Session 9

Advances in III-V based photonic crystals for integrated optical processing

S. Combrié, Thales Research & Technology (France); Q. Tran, Unité Mixte de Physique CNRS/Thales (France) and Nayang Technological Univ. (Singapore); C. A. Husko, Columbia Univ. (United States) and Thales Research &Technology (France); P. Colman, Unité Mixte de Physique CNRS/Thales (France); A. De Rossi, Thales Research & Technology (France)

Compactness, massive integration of multiple functions on a single chip and power consumption are crucial for emerging applications such as the transmission of large aggregated bit rates at short distance. Efficient implementation of data processing, particularly logical operations, sampling, wavelength conversion, signal regeneration, routing at the optical level are very attractive in this prospect.

Here we present a technology for implementing ultra-fast switching with record-low energy*recovery time product. We developed high-quality photonic crystal micro-resonators based on III-V semiconductors. The very short carrier lifetime of nanopattened Gallium Arsenide enabled us to achieve ~ 6 ps recovery time, thus enabling operations beyond the 100Gb/s rate.

Moreover, owing to the extremely reduced footprint of our devices (~5 micrometers), the optical power required for switching is in the 100 fJ range. Very importantly, only 8% of the switching energy is absorbed, therefore reducing the heat generation to 1 mW approximately when operating the switch at 100Gb/s.

We will show further developments of this technology, including high repetition rate characterization and discuss thermal and switching efficiency issues.

7608-41, Session 9

Efficient terahertz mixer from plasma wave downconversion in InGaAs HEMT

L. Chusseau, J. Torres, P. Nouvel, H. Marinchio, L. Varani, Univ. Montpellier 2 (France); J. Lampin, S. Bollaert, Y. Roellens, Institut d'Electronique, de Microélectronique, et de Nanotechnologie (France); D. Dolfi, Thales Research & Technology (France)

Two-dimensional (2D) plasma waves in field effect transistors are well known since the pioneer work of Dyakonov and Shur. Their applications in THz detection was proven recently both at cryogenic and room temperatures. Aside from these experiments, we used the interband photoexcitation brought by the difference-frequency component of a photomixed laser beam to excite very efficiently plasma waves in HEMT channel at room temperature. Owing to a specific experimental setup avoiding unwanted high-frequency electrical oscillations of the HEMTs, we obtained the spectral profiles of THz 2D plasma waves resonances of InGaAs HEMTs for many experimental conditions. The effect of geometrical HEMTs parameters (lengths of the gate and surrounding regions) as well as biasing conditions (drain and gate voltages) was evaluated on both plasma oscillations frequencies and amplitudes.

Simultaneously, a numerical approach, based on hydrodynamic equations coupled to a pseudo-2D Poisson solver, was developed that compares well with experiments. Using this unique combination of experiments and numerical simulations, a comprehensive spectroscopy of plasma waves in HEMTs is thus obtained. It provides a deeper insight into the physical processes involved in plasma wave excitation and allows predicting for mixer operation at THz frequency only using the plasma wave nonlinearity. Mixing experiments are under progress.

7608-42, Session 9

Interference effects in a photonic crystal cavity

D. A. Cardimona, P. Alsing, H. Mozer, C. Rhodes, Air Force Research Lab. (United States)

We investigate quantum interference and classical interference effects when a three-level system interacts with both a cavity field mode and an external driving field mode, within the confines of a photonic crystal material. In free-space, we found that under certain circumstances the cavity field evolves to be equal in magnitude to, but 180° out-of-phase with the external pump field when the pump field frequency equals the cavity frequency. The better the cavity, the quicker this build-up occurs. When the cavity field reaches this out-of-phase condition, the resonance fluorescence from the atom in the cavity goes to zero. This is a purely classical interference effect between the two out-of-phase fields, with the resonance fluorescence going to zero at the same time as the two excited state populations go to zero. This is quite different from the quantum interference that occurs under the right circumstances, when the state populations are coherently driven into a linear combination that is decoupled from any applied field - and population is trapped in the excited states, thus allowing for a population inversion and an amplification of incoming optical signals. In this paper, we investigate the additional effects due to the presence of the altered photon density of states in a photonic crystal.

7608-43, Session 9

Iteratively optimized nonperiodic plasmon resonant nanostructures

P. Pavaskar, S. Cronin, The Univ. of Southern California (United States)

Finite difference time domain (FDTD) simulations are performed on two-dimensional clusters of plasmonic metal nanoparticles in response to incident planewave irradiation. Using an iterative optimization algorithm, we determine the configuration of the nanoparticles that gives the maximum electric field intensity at the center of the cluster. The optimum configurations of these clusters have mirror symmetry about the axis of planewave propagation, but are otherwise non-symmetric and non-intuitive. The optimized electric field intensity is found to increase monotonically with the number of nanoparticles in the cluster, producing intensities that are five times larger than linear chains of nanoparticles and 2500 times larger than the incident electromagnetic field. This enhancement is significantly higher than a linear chain of nanoparticles or the centermost dimer alone. If these optimized nanoparticle configurations can be achieved experimentally, this method could enable new devices based on near-field and non-linear effects.

7608-91, Session 9

Semiconductor nanowire optical antenna: controlling light absorption, scattering, and emission

L. Cao, M. L. Brongersma, Stanford Univ. (United States)

We demonstrate that a high refractive index semiconductor nanowire can serve as a cylindrical cavity-antenna that resonantly confines light by multiple total internal reflections from the periphery when the electromagnetic wavelength matches one of the leaky optical modes supported by the nanowire. The strong leaky mode resonances (LMRs) can be tuned in wavelength by changing the nanowire diameter. Such strong, tunable optical antenna effects present an efficient way to enhance and spectrally tune light absorption, scattering and emission from the nanowire. To illustrate this notion, we fabricated a germanium photodetector with detection efficiency for 1550 nm light significantly enhanced (by 30 folds) and demonstrated a design for high-efficiency cost-effective solar cells with the photovoltaic efficiency expected to be improved by more than 150%. Along with shape-controlled synthetic techniques for semiconductor nanowires, these results manifest tremendous opportunities for the realization of a wide range of high-performance, nanowire-based optoelectronic devices.

Reference:

Linyou Cao, Justin S. White, JoonShik Park, Jon A. Schuller, Bruce M. Clemens, Mark L. Brongersma, Engineering Light Absorption in Semiconductor Nanowire Devices, Nature Materials 8 (2009) 643.

Linyou Cao, JoonShik Park, Pengyu Fan, Bruce M. Clemens, Mark L. Brongersma, Resonant Germanium Nano-Antenna Photodetector, Submitted.

Linyou Cao, Pengyu Fan, Alok Vasudev, Justin S. White, Zongfu Yu, Wenshan Cai, Jon A. Schuller, Shanhui Fan, Mark L. Brongersma, Semiconductor Nanowire Antenna Solar Cells, Submitted.

7608-39, Session 10

Near-field characterization of the optical properties in higher order plasmonic resonances

C. Huang, H. Lin, Y. Lan, C. Chang, H. Chui, National Cheng Kung Univ. (Taiwan)

The dipole and quadrupole localized surface plasmon polariton (LSPP) resonances of gold nanoparticle array were directly investigated by a near-field scanning optical microscope (NSOM) in the fiber-collection mode. The separated gold nanoparticles (75 nm in diameter estimated form the image of scanning electron microscope) on the quartz substrate were fabricated by nanosphere lithography through the high temperature annealing technique. It is shown that carefully controlling the incident polarization and the angle of oblique incidence enables to excite dipolar and quadrupolar LSPP at 633- and 488-nm excitations. The dipole and quadrupole plasmon resonance were observed when the incident frequency and polarization simultaneously induce the redistribution of localized surface charges in the nanoparticle. The redistributed surface charges oppositely align on the pair sides of a nanoparticle, and only can be presented in the near-field when there is an incident angle of polarized photon excitations. The oblique incident absorption spectra of the fabricated Au nanoparticle array shows two absorption peaks and the emerged peak at the short wavelength is due to the higher order plasmonic resonance mode. Results manifest the correlation of the oblique incident polarizations and the responded dipolar and quadrupolar LSPP resonances at 633- and 488-nm excitations in the vicinity of gold nanoparticles. This observation facilitates the understanding of fine details of LSPP and their interactions with nanostructures in the near field and can be used as a guideline for fabricating specific nanostructures in controlling the spatial distribution of LSPP modes for novel applications for ultra sensitive bio-/chemo-detectors or plasmonic metamaterials.

7608-44, Session 10

Advances in 3D photonic crystal nanocavity with quantum dots

Y. Arakawa, A. Tandaechanurat, S. Iwamoto, M. Nomura, D. Guimard, The Univ. of Tokyo (Japan)

We discuss recent advances in light-matter coupling in quantum dots with a point-defect nanocavity in woodpile 3D photonic crystal with the highest Q factor among those for 3D photonic crystal cavities. The Q factor over 10,000 has been so far demonstarted by optimizing the size of the square-shaped defect cavity to tune the cavity mode near the midgap frequency of the complete photonic bandgap.

7608-45, Session 10

QD laser on InP substrate for 1.55 um emission and beyond

N. Bertru, Institut National des Sciences Appliquées de Rennes (France)

The basic researches on InAs/GaAs quantum dots started in the 90s have in the last decade found their way into applications. However, InAs/GaAs quantum dots only emit in the range of 0.9 to 1.3µm. For longer wavelength operation such as 1.55µm and beyond, InAs/InP QDs has been developed. Devices working at 1.55 µm based on InAs /InP nanostructures such as ultrawide semiconductor optical amplifiers with high dynamical properties or narrow mode-locked lasers required for stable clock recovery have already been reported. However the device performances are still limited by elaboration issues. Indeed the formation of high quality InAs/InP quantum dots is still an important issue.

In this talk a review on the InAs/InP QD device elaboration will be presented. The talk will focus mainly on devices elaborated on (311)B substrates but recent developments on nanostructures formed on the more conventional InP (100) substrates will be also presented. For longer wavelength operation, InAsSb nanostructures have been proposed. The incorporation of antimony induces large changes on the growth process and on the nanostructure band line up. This issue will be also discussed.

7608-46, Session 10

Growth of heterostructured III-V nanowires by molecular beam epitaxy for photonic applications

H. Weman, Norwegian Univ. of Science and Technology (Norway)

Heterostructured semiconductor nanowires have attracted considerable attention in recent years because of their potential in future nano-electronic and nano-photonic device applications. Due to that nanowires have been found to form with different crystal phases nonexistent in bulk or thin film, this now allows for heterocrystalline band-structure engineering. This includes crystal phase-modulated as well as combined crystal phase- and crystal material-modulated heterostructures.

We have found that GaAs nanowires grown by Au-assisted molecular beam epitaxy (MBE) exhibit hexagonal wurtzite (WZ) crystal structure in contrast to its normal cubic zinc blende (ZB) form. The WZ phase of the nanowire material raises questions about fundamental physical parameters such as the band gap energy, band offsets, exciton binding energy, carrier effective masses or phonon energies.

Here we will report recent results on the growth, structure and optical characterization of single WZ GaAs nanowires, ZB GaAsSb nanowires, WZ GaAs nanowires with ZB GaAsSb inserts as well as WZ GaAs/AlGaAs core-shell nanowires with ZB GaAsSb inserts. We find that the band gap energy for WZ GaAs is ~ 30 meV larger than that of ZB GaAs. For the lattice mismatched GaAs/GaAsSb heterojunction both the crystal phase of the GaAs barrier as well as the strain plays a critical role in the exact band alignment. We will show that both type I and type II band alignment can be achieved, and that this has large effects on the optical properties of the nanowires.

7608-47, Session 10

Characterization and physics of top-down silicon nanowire phototransistors

A. Zhang, J. Cheng, H. Kim, Univ. of California, San Diego (United States); Y. Liu, Agiltron, Inc. (United States); Y. Lo, Univ. of California, San Diego (United States)

Nanowire photodetectors of a variety of materials have been attracting increased attention due to their potential for very high sensitivity detection. Silicon photodetectors are of particular interest for detection in the visible spectrum, having many benefits including cost of substrate, ease of processing, and ability for integration with conventional fabrication techniques. Using top down fabrication techniques results in additional benefits of precise control of number, geometry, and placement of these wires. To demonstrate the potential of these devices, top down, vertical silicon nanowire phototransistor arrays have been fabricated using ebeam lithography and deep reactive ion and inductively coupled plasma etching. These devices show a much higher phototransistive gain over nanowire photodiodes with similar geometry under illumination from a 635nm laser. Low temperature measurements also show the dependence of dark current and sensitivity on temperature. The mechanism responsible for this gain is shown to be dominated by the large surface-to-volume ratio of nanowires where charge capture and recombination at the surface creates a radial gate bias which is modulated with light intensity. 3D numerical simulations validate this mechanism and further show the dependence of device behavior on nanowire doping, geometry, and surface state concentration. This will allow for the precise engineering of these devices to achieve the maximum sensitivity obtainable as we strive for the ultimate goal of single photon resolution.

7608-48, Session 11

Radiation damage effects on detectors from the IR to x rays

M. P. Ulmer, Northwestern Univ. (United States)

We present a review of radiation damage studies of detectors used primarily in astronomy related space missions. We cover effect on devices used for the wavelengths from the IR all the way through to X rays.

7608-50, Session 11

Polar and semipolar III-nitrides for long wavelength intersubband devices

E. Monroy, P. K. Kandaswamy, CEA-Grenoble (France); H. Machhadani, Université Paris-Sud (France); A. Wirthmüller, CEA-Grenoble (France); S. Sakr, Université Paris-Sud (France); L. Lahourcade, A. Das, CEA-Grenoble (France); M. Tchernycheva, F. H. Julien, Université Paris-Sud (France)

The interest of the far-IR spectral region for technologically-important applications, such as security screening, quality control or medical diagnostics, has driven extensive efforts to develop optoelectronics components. In this field, the large GaN LO-phonon energy (92 meV) opens prospects for intersubband (ISB) lasers and detectors at IR wavelengths inaccessible to other III-V semiconductors due to Reststrahlen absorption.

We have already proven the potential of the GaN/AlGaN material system for ISB optoelectronics by demonstrating ultrafast quantum cascade detectors, modulators and light emission in the near-IR. Furthermore, we have experimentally demonstrated that the mid-IR domain can be covered by GaN/AlGaN with proper QW design. The extension of this ISB technology towards longer wavelengths requires a reduction of the polarization-induced internal electric field, which sets new material and design challenges. In this work, we analyze the potential of polar and semipolar nitride technologies for far-IR applications. Experimental results are explained by comparison with theoretical calculations using an 8-band k.p Schrödinger-Poisson solver.

7608-51, Session 11

Optical characteristics of surface plasmon resonance based on ZnO and metallic nanograting structures

D. Kim, S. H. Kim, H. C. Ki, H. J. Kim, H. J. Ko, M. Han, S. Hann, T. U. Kim, H. Kim, Korea Photonics Technology Institute (Korea, Republic of); G. Oh, Y. Choi, Chung-Ang Univ. (Korea, Republic of)

Optical biosensors convert biological interactions to measurable quantities of optical signal. As of good example, surface plasmon resonance (SPR) sensor is preferred to other sensors which are required to take the labeling process reacting a specific biological pathogen. Though commercialized SPR sensors are readily available, these sensors are bulky and expensive to apply to the field. There are increases in development of other types of biosensors which are comparable to or better than the conventional SPR sensors in terms of sensitivity, compactness, and low cost. Here, we proposed the grating coupled SPR sensors using ZnO and metallic nano-grating structures to enhance the sensitivity of an SPR surface. The nano-grating structure can be utilized to perturb the propagation of the surface plasmon. We also have optimized the grating coupled SPR sensors using finite-difference time-domain method for the width, thickness, and period of the ZnO and metallic grating structures. Then, we have fabricated the ZnO grating on a gold layer of 50 nm, the metallic grating with gold layer, and without gold layer by using laser interference lithography with a glass substrate. The 200 nm wide grating structure with a period of 400 nm has been obtained. We have used direct and indirect coupling methods to measure the optical characteristics of the grating coupled SPR sensors. Therefore, high sensitivity is obtained due to the surface plasmon on the edge of the bandgap when the ZnO and metallic grating structures are used to excite the surface palsmon. More detailed results will be presented.

7608-52, Session 11

III-nitride nanostructures for energy generation

H. Jiang, J. Lin, Texas Tech Univ. (United States)

Nitride semiconductors have been successfully used for photonic/electronic devices including UV/blue/green/white LEDs, violet LDs, UV detectors, and high power/temperature transistors. Besides applications for energy savings as established through solid state lighting, III-nitride nanostructures hold great promises for energy generation, including applications for thermoelectrics, solar cells, and photoelectrochemical cells.

1. Thermoelectric (TE) application. The outstanding features of nitride semiconductors for TE applications include the ability for high power/temperature operation, high mechanical strength and stability, radiation hardness and band gap engineering. The results of the TE properties of InxGa1-xN epilayers grown by MOCVD will be presented. It was found that as In content increases, the thermal conductivity decreases and power factor increases, which leads to an increase in the TE figure of merit (ZT). ZT was found to be 0.08 at 300 K and reached 0.23 at 450 K for In0.36Ga0.64N, which is comparable to those of SiGe alloys. ZT could be further enhanced via alloying, bandgap engineering and nano-structure incorporation. Our initial results indicate that InxGa1-xN alloys could be potentially important TE materials and may be an alternative to SiGe alloys for the development of TE generators that are able to directly convert heat to electricity or cooling modules for micro-/nano-scale sensor networks, new generation automobiles, and radioisotope TE generators in spacecrafts with enhanced efficiency and lifetime.

2. High efficiency solar cell. The bandgap of InGaN expands from about 0.7 to 3.4 eV, which covers the entire solar spectrum. In principle, a multi-junction solar cell based on multi-layers of InGaN with different In-contents is capable of capturing whole spectrum of the sunlight and can thus be highly efficient. We report on the fabrication and photovoltaic characteristics of InGaN solar cells by exploiting InGaN/GaN multiple quantum wells (MQWs) with In-contents exceeding 0.3, attempting to alleviate to a certain degree the phase separation issue and demonstrate solar cell operation at wavelengths longer than previous attainments (> 420 nm). The fabricated solar cells based on In0.3Ga0.7N/GaN MQWs exhibit an open circuit voltage of about 2 V, fill factor of about 60%, and an unprecedented external efficiency of 40% (10%) at 420 nm (450 nm).

3. Novel photoelectrochemical (PEC) cells. In additional to its bandgap match to the solar spectrum, the bandgap of InGaN alloys can also be engineered to optimally match with conditions for direct hydrogen generation by water splitting using sunlight. The smaller lattice constants or stronger bonding between III-N over with other semiconductors (e.g., GaP) also provides higher corrosion-resistance. Most recently, we have obtained preliminary results by employing InGaN as PEC cells. Under white light illumination, a drastic dependence of photocurrent density on the In-content was observed. Direct hydrogen gas generation by splitting water was accomplished using both n-type and p-type InxGa1-xN epilayers. This demonstration of hydrogen generation by water splitting accomplished using InGaN based PEC cells is highly encouraging.

7608-53, Session 11

One-dimensional characters of excitons in carbon nanotubes

S. Uryu, Iwate Univ. (Japan); T. Ando, Tokyo Institute of Technology (Japan)

No abstract available

7608-54, Session 11

Nanoscale metallic annular structures designed and simulation for surface-enhanced Raman scattering

S. Lee, C. Wu, National Taiwan Ocean Univ. (Taiwan); D. Lin, J. Chu, Industrial Technology Research Institute (Taiwan)

Inducing a large electric field enhancement is very important to have good signals in surface-enhanced Raman scattering (SERS) experiments. In this study, the nano-scale sliver annular structures have been introduced to design the substrate for SERS experiment because of its localized surface plasmon (LSP) resonances phenomena. The excited electric field has been simulated by FDTD (finite-difference time-domain) and the design parameters, such as the thickness of the metallic film, the inner diameter, and the outer diameter, were changed. The largest electric field happens when the metallic film thickness is 10 nm and the inner and outer diameters are 0.25 μm and 0.4 μm, respectively. The results are in good agreement with the theoretical predictions. In addition, the dimer geometry of the annular structures has also been examined by FDTD to observe the field enhancement. The coupled plasmons effects appear obviously when two annular structures are very close. It indeed makes the excited electric field in the dimer structure larger than in the single one for 397 times. In conclusion, a design of dimer constituted with two annular structures which have 0.25 μm and 0.4 μm inner and outer diameters with 20 nm overlap owns the best electric field enhancement property and has great potential for SERS applications.

7608-55, Session 12

Update on the type II strained layer superlattice progress and discussion of its development strategy

M. Z. Tidrow, U.S. Army Night Vision & Electronic Sensors Directorate (United States)

No abstract available

7608-56, Session 12

Performance analysis of InAs/Ga(In)Sb strained layer superlattice detectors and focal plane arrays

S. V. Bandara, U.S. Army Night Vision & Electronic Sensors Directorate (United States)

InAS/GaSb based type II superlattice attract increasing interest for the development of high sensitive large format mid and long wavelength infrared focal plane arrays. This paper will discuss the recent progress made in this technology and analyze the performance of few different device structures. This model includes calculation of the dark currents originated by various mechanisms and dependence on the minority carrier lifetime. The presentation also includes calculations of various noise contributions towards noise equivalent irradiance (NEI) and its limitations at a range of flux levels.

7608-58, Session 12

High operating temperature MWIR detectors

H. F. Schaake, DRS Sensors & Targeting Systems, Inc. (United States)

The HOT detector is simply a reverse-biased photodiode with minority and majority carrier contacts. The active volume, which is less than a diffusion volume, is in non-equilibrium due to the reverse bias, and the intrinsic thermally generated minority carriers are fully extracted through the minority carrier contacts. The reduction in majority and minority carrier concentrations in the active volume of the HOT device results in a significant reduction in the dark current generation rates in that volume, with the potential for BLIP performance at room temperature.

The detector concept is being pursued using the high density vertically integrated photodiode (HDVIP®) architecture and an n+-p device structure. Dark current densities as low as 2.5 mA/cm2 normalized to a 5 µm cutoff at 250K have been demonstrated on these diodes. These dark currents imply minority carrier lifetimes in excess of 300µsec. 1/f noise in these devices arises from the tunneling of charge into the passivation interface, giving rise to a modulation in the surface positive charge and hence to the width of the depletion region in the p-side of the device and a modulation in the total dark current. The measured 1/f noise is in agreement with the predictions of this model, with very low noise being observed when the lifetimes are high.

Recent work has centered on the application of these structures to 256x256 and 640x480 focal plane arrays. Recent results on these arrays will be presented.

This work is supported by the Defense Advanced Research Projects Agency (DARPA) under Contract No. NBCHC06001.

7608-59, Session 12

Comparison of nBn and nBp mid-wave barrier infrared photodetectors

J. F. Klem, J. K. Kim, M. J. Cich, S. D. Hawkins, Sandia National Labs. (United States); T. R. Fortune, Sandia Staffing Alliance (United States)

Much of the recent improvement in performance of mid- and long-wave infrared photodetectors has been enabled by the application of bandgap engineering to reduce dark currents. In particular, large-bandgap barrier layers have been employed with the intent of reducing Shockley-Read-Hall generation and allowing device isolation while maintaining effective surface passivation. We have fabricated mid-wave infrared diodes containing InAsSb absorber regions and AlAsSb barrier (B) layers in nBn and nBp configurations. Devices were characterized by current-voltage, capacitance-voltage, and photocurrent measurements. Due to the nearly symmetric structure of the nBn devices, collection of photogenerated carriers requires application of a small reverse bias resulting in a minimum dark current, while the nBp devices efficiently collect carriers at zero bias. When biasing both types of devices for equal dark currents, the nBn structure exhibits a differential resistance significantly higher than the nBp, although the nBp device may be biased for arbitrarily low dark currents at the expense of much lower dynamic resistance. Capacitance-voltage measurements allow determination of the electron concentration in the unintentionally-doped absorber material, and suggest the existence of a two-dimensional electron gas at the absorber/barrier interface that may result from defect states at that interface or in the barrier.

Finite element simulations were performed to understand the mechanisms of dark current generation in nBn, nBp, and conventional pn diode structures. We conclude that in idealized, passivated structures, the nBn structures benefit relative to the simple pn diode by the elimination of electron diffusion current and a reduction in depletion region Shockley-Read-Hall generation.

7608-93, Session 12

Mid-infrared quantum cascade detectors for applications in spectroscopy and pyrometry

D. Hofstetter, Univ. of Neuchâtel (Switzerland)

In this presentation, we will give an overview on the design, fabrication, and characterization of photovoltaic quantum cascade detectors for the mid-infrared wavelength region. Due to their asymmetric conduction band profile, these tailorable infrared photodetectors, which are based on intersubband transitions in semiconductor quantum wells, do not require an external bias voltage. Together with their narrow spectral linewidth, they thus profit from favorable noise behavior, reduced thermal load, and simpler readout circuits. Successful operation was demonstrated at wavelengths from the near infrared at 2 µm throughout the mid-infrared region and THz radiation at 87 µm using various semiconductor material systems. In a different line of research, we also investigated quantum cascade detectors with a broad spectral sensitivity for specific applications in pyrometry.

7608-60, Session 13

High-operating temperature MWIR photon detectors based on type II InAs/GaSb superlattice

M. Razeghi, B. Nguyen, P. Delaunay, E. K. Huang, S. Abdollahi Pour, P. Manukar, S. Bogdanov, Northwestern Univ. (United States)

Recent efforts have been paid to elevate the operating temperature of Type II superlattice Mid Infrared photon detectors. Optimized growth

parameters and interface engineering technique enable high quality material with a quantum efficiency above 50%. Intensive study on device architecture and doping profile has resulted in almost one order of magnitude of improvement to the electrical performance and lifted up the 300K-background BLIP operation temperature to 166K. At 77K, the ~4.2 um cut-off devices exhibit a differential resistance area product in excess of the measurement system limit (106 Ohm.cm2) and a detectivity of 3x10^13cm.Hz^(1/2)/W. High quality focal plane arrays were demonstrated with a noise equivalent temperature of 10mK at 77K. Uncooled camera is capable to capture hot objects such as soldering iron.

7608-61, Session 13

Type II heterostructures with InSb quantum dots inserted into p-n InAs(Sb,P) junction

K. D. Moiseev, M. P. Mikhailova, E. V. Ivanov, Y. A. Parkhomenko, S. S. Kizhaev, V. N. Nevedomsky, N. A. Bert, Y. P. Yakovlev, Ioffe Physico-Technical Institute (Russian Federation)

We report on study of electrical and optical properties of type II heterostructures with InSb quantum dots (QDs) placed on the interface of InAs-based p-n junction. InSb QDs were grown on InAs(100) substrate or InAs(Sb,P) buffer layer lattice-matched with InAs by LPE-MOVPE combine method. Overgrowth of self-assembled InSb QD arrays by InAs(Sb,P) capping layer was performed by MOVPE. High-resolution cross-sectional image of the InSb QDs buried into the InAs(Sb,P) matrix was obtained for the first time by transmission electron microscopy. Structural parameters of the InSb QDs such as size, shape, internal strain etc will be demonstrated and discussed. The uniform small QDs with high density (10^10 cm^-2) with dimensions of 3 nm in height and 14 nm in diameter were found to be self-assembled and dislocation-free without any extended defects whereas the low-density large QDs (10^8-10^9 cm^-2) with dimensions of 10 nm in height and 50 nm in diameter were relaxed and demonstrated interface strain with the InAs substrate. I-V characteristics of the mesa-diode heterostructures with the InSb QDs inserted into InAs p-n junction were studied at the wide temperature range T=77-300 K. Intense positive and negative electroluminescence for both p-InAs/InSb/n-InAs and n-InAs/InSb/p-InAs heterostructures was found in the spectral range 3-4 um. Evolution of the spectra in dependence on applied external bias (forward and reverse) and a doping of the matrix (n- and p-type) were observed at 77 K and 300 K. Energy band diagram of the type II broken-gap InAs/InSb/InAs heterostructure with hole subbands will be proposed.

7608-63, Session 13

Dark current and noise measurements in InAs/GaSb superlattice detectors

K. Jaworowicz, ONERA (France); C. Cervera, Univ. Montpellier 2 (France); O. Gravrand, Commissariat à l'Énergie Atomique (France); J. Rodriguez, P. Christol, Univ. Montpellier 2 (France); I. Ribet-Mohamed, ONERA (France)

InAs/GaSb superlattice (SL) detector has recently emerged as a promising technology for high performance infrared (IR) imaging system in the MWIR (3-5µm), as well as in the LWIR (8-12µm) and VLWIR (> 12µm) domains. Consequently, several research groups are now devoting increased efforts to the study of InAs/GaSb SL photodiodes. Especially in France, IES (Institut d'Electronique du Sud, from University of Montpellier 2), CEA/LETI and ONERA (French Aerospace Lab) decided, in 2008, to realize and characterize MWIR SL devices. The SL structures were grown by Molecular Beam Epitaxy (MBE) and different techniques were used for the etching, as well as for the passivation of the pixels. Electrical measurements were performed on diodes with different shapes and sizes in the temperature range 10K-100K. In this paper, we show that the etching step is at least as crucial as the passivation step in order to reduce the leakage currents. An original chemical solution was designed to obtain nice, smooth mesa sidewalls. It allowed us to decrease the leakage currents by 5 orders of magnitude and to reach the state-of-the-art R0A values. We also show that simple passivation techniques, such as deposit of a dielectric, prevent oxidation of the mesa sidewalls. The detectors fabricated were fully characterized, with particular emphasis on dark current measurements. Such measurements, realized both as a function of the bias voltage and the operating temperature, allowed us to identify the dominant dark current mechanism in each bias voltage range.

7608-71, Session 13

Composition and strain mapping of engineered interfaces in InAs/GaSb short-period superlattices using aberration-corrected high-resolution transmission electron microscopy

K. Mahalingam, Air Force Research Lab. (United States) and Universal Technology Corp. (United States); H. Haugan, G. J. Brown, K. G. Eyink, F. Szmulowicz, Air Force Research Lab. (United States)

Heterostructures derived from quaternary III-V semiconductor systems (such as those based on the InAs-GaSb and InAs-AlSb systems) are promising materials for a variety of next generation optoelectronic devices, such as mid-infrared lasers and tunable long-wavelength detectors. Interfaces are known to play a unique role in especially in these materials due to the distinctly different types of interfacial bonds obtainable depending on growth conditions (for instance the interfaces in InAs-GaSb heterostructures can be "InSb-like" or "GaAs-like"). Considerable attention is now focused on tailoring interface stoichiometry to optimize properties. A key requirement in this endeavor is the ability to accurately quantify the composition of interfaces (typically < 1 nm in width). Although several techniques based on high-resolution transmission electron microscopy (HRTEM) have been developed since the early 1990's, these are applicable only to ternary systems (such as those based on the AlAs-GaAs and InAs-GaAs systems).

We have recently developed a new approach for atomic scale compositional analysis of quaternary III-V semiconductor interfaces with mixing in both cation and anion sublattices. Our approach utilizes the principles of phase retrieval HRTEM based on the focal series reconstruction technique, used in combination with multivariate statistical analysis for quantitative image analysis. In this study we use this approach to investigate the role of interface engineering in optimizing properties of InAs/GaSb superlattices. We present results from several structures, including those in which the alternating InAs and GaSb layers are grown with no interface control, and the others in which each interface is tailored to be "InSb-like," wherein a controlled deposition of 0.8 ML (0.26 nm) of InSb precedes the growth of each InAs/GaSb layer. In addition, we have also used advanced image processing techniques to map the strain profiles across interfaces. Our studies show that untailored interfaces exhibit significant compositional grading in both the group-III (In-Ga) and group-V (As-Sb) sublattices. In the case of tailored interfaces, significant improvement in compositional abruptness is achieved at the InAs-on-GaSb interface. This effect is however observed to be less dramatic at the GaSb-on-InAs interface. Further studies on the correlations between the photoresponse spectra and the measured composition/strain profiles across each interface will be presented.

7608-64, Session 14

Electronic properties of InAs/GaSb superlattice detectors to evaluate high-temperature operation

P. Christol, C. Cervera, R. Chaghi, H. Ait-Kaci, J. B. Rodriguez, L. Konczewicz, S. Contreras, Univ. Montpellier 2 (France); K. Jaworowicz, I. Ribet-Mohamed, ONERA (France)

InAs/GaSb superlattice (SL) is now considered as a new material system for the fabrication of high performance infrared (IR) photodetectors for thermal imaging camera. To enhance performances and/or temperature operation, improvements of device technology as well as a better knowledge on fundamental properties of the SL photodiodes are still necessary. In particular, one needs to have a better understanding of carriers transport in this material.

In this communication, we present transport measurements realized on non-intentionally doped (nid) InAs/GaSb SL structures grown by Molecular Beam Epitaxy. The SL structure was made of 600 periods of 8 InAs monolayers (MLs) and 8 GaSb MLs, for a total thickness of 3µm. This structure exhibited a cutoff wavelength near 4.9µm at 80K. Transport measurements were performed on two kinds of samples, corresponding to the same SL structure grown on two different substrates: The first sample was a SL structure grown on semi-insulating GaAs substrate. The other was grown on p-type GaSb substrate with an InAsSb layer inserted between the SL and the substrate in order to remove the conducting GaSb substrate with an appropriate technological process.

Resistivity and Hall Effect measurements were carried out as a function of temperature (77-300K) for magnetic fields in the 0-1 Tesla range. Carrier concentrations and mobilities extracted from measurements are analysed and a change in type of conductivity is observed on the two samples but at different temperatures. These results are compared with electrical characterizations based on current-voltage (I-V) and capacitance-voltage (C-V) measurements performed on equivalent pin structures.

7608-65, Session 14

“XBn” barrier detectors for high operating temperatures

P. C. Klipstein, O. Klin, S. Grossman, N. Snapi, B. Yaacobovitz, M. Brumer, I. Lukomsky, M. Yassen, B. Yofis, A. Glozman, T. Fishman, E. Berkowitz, O. Magen, I. Shtrichman, E. Weiss, SCD Semiconductor Devices (Israel)

The maximum operating temperature of a solid state infrared detector is usually determined by its dark current, which increases exponentially with temperature. In standard MWIR photodiodes operating under background-limited conditions this dark current is almost universally produced by so called Generation-Recombination (G-R) centres in the depletion region of the device. These G-R centres provide energy levels in the bandgap of the device, thereby reducing the amount of thermal energy needed to excite an electron out of the valence band or into the conduction band. Recently, a new so called “XBn” device architecture has been proposed using heterostructures, in which no depletion layer exists in any narrow bandgap region. Instead, the depletion layer is confined to a wide bandgap barrier material. In such a “barrier device” the G-R contribution to the dark current is almost totally suppressed and the dark current becomes diffusion limited. This lowering of the dark current allows the device operating temperature to be raised relative to that for a standard photodiode made from the same photon absorbing material, with essentially no loss of performance. XBn devices can be designed in various ways, including both Bipolar and Unipolar arrangements. “Antimonide” materials based on alloys or superlattices of InAs, InSb, AlSb, AlAs and GaSb are ideal for achieving the correct band alignments. At SCD we have been developing XBn devices grown on GaSb substrates with an InAsSb photon absorbing layer and an AlSbAs barrier. The results of optical and electrical measurements will be presented on devices with a cut-off wavelength of about 4.1 micron. It will be shown that the doping in the barrier can have a strong influence on the suppression of the G-R current, and hence on the ultimate operating temperature. In properly optimized devices, BLIP temperatures in excess of 150K will be demonstrated. The results will also be discussed in the light of alternative approaches to XBn architecture, such as with an InAs/GaSb type II superlattice photon absorbing layer, and an AlGaSbAs barrier.

7608-66, Session 14

High operating temperature (HOT) MWIR Quantum Dot Infrared Photodetector

J. N. Vaillancourt, Applied NanoFemto Technologies (United States); X. Lu, Univ. of Massachusetts Lowell (United States)

We report middle-wave infrared (MWIR) quantum dot infrared photodetector (QDIP) with a high operating temperature of over 260 K. The hot QDIP avoid bulk and heavy cryogenic cooling systems and thus enable the development of ultra-compact energy-efficient IR sensing and imaging systems.

7608-72, Session 14

Interband cascade infrared photodetectors

Z. Tian, Z. Cai, R. Q. Yang, T. Mishima, M. R. Santos, M. B. Johnson, Univ. of Oklahoma (United States); J. F. Klem, Sandia National Labs. (United States)

Interband cascade (IC) infrared (IR) photodetectors (ICIPs) are a new type of detectors that combine features of conventional photodiodes with the discrete architecture of quantum-well IR photodetectors (QWIPs) and IC lasers. Photon absorption in ICIPs is based on interband transitions in type-II QW heterostructures, which, unlike QWIPs, permits normal-incidence detection. The operation of ICIPs takes advantage of very fast intersubband relaxation and interband tunneling for carrier transport, and relatively slow interband transitions for a long lifetime. As such, ICIPs can be tailored with superb flexibility to optimize device performance for specific application requirements. We will report our recent efforts in the development of ICIPs with the goals of better understanding of these interband cascade structures and improved device performance. Our initial efforts have led to the observation of the photocurrent from an InAs-based IC laser with a cutoff wavelength near 8 microns, and significant photocurrent from an ICIP device at an operating temperature up to 300K with a cutoff wavelength from 5 to 7 microns (depending on the temperature). Details of device performance and updated results will be presented.

7608-67, Session 15

A LWIR Quantum Dot Infrared Photodetector working at 298K

J. Vaillancourt, Applied NanoFemto technologies LLC (United States); X. Lu, Univ. of Massachusetts Lowell (United States)

We report a longwave infrared quantum dot infrared photodetector working at room temperature (RT) (298K). Photoresponsivity and photodetectivity of 0.02A/W and 9.0x106 cmHz1/2/W were achieved at 298K with a low bias voltage of -0.1V. The RT QDIP avoids bulk and heavy cryogenic cooling systems and thus enables the development of ultra-compact IR sensing and imaging systems.

7608-68, Session 15

Improving the operating temperature of quantum dots in well detectors

S. Krishna, The Univ. of New Mexico (United States)

Even as applications for infrared imaging system have increased, there is a need for driving the cost of the imaging system down. One of the main cost drivers of the imaging system is the cooling system. This presentation will be focused on the design, growth and fabrication of infrared detectors for higher operating temperature (HOT) using two material systems, which are emerging as promising technologies for mid infrared sensors. These are (i) InAs/InGaAs self assembled quantum dots in well (DWELL) Detectors and InAs/(In,Ga)Sb strain layer superlattices (SLS) Detectors

In the DWELL heterostructure, InAs quantum dots are placed in a thin InGaAs quantum well that is in turn placed in a GaAs matrix. Three-color DWELL detectors, operating at 78K, with spectral response in the MWIR (p1 ~ 4), LWIR (p2 ~ 8) and VLWIR (p3~ 23) regime have been fabricated in our group. Recently, we have fabricated the first long wave infrared quantum dot focal plane array (320x256 pixels). Images from this FPA along with the details of our research will be discussed in the presentation. The second material system we are investigating is the type II InAs/InGaSb superlattice for MWIR/LWIR detection. We have recently fabricated a high performance InAs/GaSb SLS detector with a 5   cut-off operating at room temperature and 320x 256 FPA based on a novel nBn design. This will be discussed in the presentation.

Acknowledgements: I wish to acknowledge my collaborators (Dr. Cardimona's group at AFRL, Prof. Perera's group at Georgia State University, Prof. Painter's group at Caltech, Dr. Toni Taylor's group at Los Alamos National Laboratory and researchers from ARL) and co-workers (Prof. L.R. Dawson, Prof. A. Stintz, , Dr. S.J. Lee, Dr. E. Plis, Dr. Y.D. Sharma, H.S. Kim, J. Shao, D. Ramirez, A. Barve, N.W. Bernstein, S. Myers, A. Khoshakhlagh, J. Montoya, M. Kutty, E. Jang and R. Shenoi). Work supported by AFRL, ARL, ARO, MDA, KOSEF-GRL, DARPA, and NSF

7608-69, Session 15

InAs/GaSb type II superlattices for advanced 2nd and 3rd generation detectors

M. Walther, R. H. Rehm, J. Schmitz, J. Fleissner, F. Rutz, Fraunhofer-Institut für Angewandte Festkörperphysik (Germany); R. Scheibner, J. Wendler, J. Ziegler, AIM INFRAROT-MODULE GmbH (Germany)

Over the last years, superlattice (SL) structures based on GaSb, InAs and AlSb have proven their great potential for high performance infrared (IR) detectors. Lots of interest is currently focused on the development of short-period InAs/GaSb SLs for advanced 2nd and 3rd generation infrared detectors between 3-30 µm. This has enabled IR-detectors with a quantum efficiency comparable to CdxHg1-xTe detectors. High effective masses and low Auger recombination rates result in low dark current in p-i-n InAs/GaSb SL photodiodes, making them very interesting for higher operation temperatures.

Besides a profound knowledge on the electro-optical properties, a scalable III-V process technology with high throughput and yield is a key requirement for cost sensitive applications. At Fraunhofer IAF, a manufacturing process for mono- as well as bi-spectral mid-wavelength IR (MWIR, 3-5 µm) InAs/GaSb SL detector arrays has been established. The technology is based on commercial 3"-GaSb substrates, solid source multi-wafer molecular beam epitaxy and a full wafer process technology for focal plane array fabrication. The integration of SL detectors into thermal imaging camera systems is done in cooperation with AIM Infrarot-Module GmbH. Monospectral as well as dual-color SL IR-imagers with a noise equivalent temperature difference (NETD) down to around 10 mK have been realized.

Material issues, design considerations for superlattice detectors as well as challenges related to the fabrication technology will be discussed.

7608-70, Session 15

Non-cryogenic operation of HgCdTe infrared detectors

C. H. Grein, S. Velicu, P. Dreiske, M. Carmody, EPIR Technologies, Inc. (United States); J. D. Phillips, Univ. of Michigan (United States)

High sensitivity HgCdTe infrared photon detector arrays operating at 77 K can be tailored for response across the infrared spectrum and are commonly utilized for high performance infrared imaging applications. However, the cooling systems required to achieve the desired sensitivity makes them costly, heavy and limits their applicability. Reducing cooling requirements, especially operating temperatures that can be realized with thermoelectric coolers, can lead to lighter and more compact systems. The challenge of elevated operating temperatures is that the thermal carrier concentrations become high and hence Auger processes typically dominate the dark current and noise characteristics. HgCdTe superlattice (SL)-based structures and novel HgCdTe device designs can suppress Auger processes in detector absorber layers. The two methods of Auger suppression can be combined, namely SL absorber layers employed with the novel device designs. In this work, we analyze Auger suppression in HgCdTe SL- and HgCdTe alloy-based device structures and identify the performance improvements (operation temperature, responsivity, detectivity) expected when Auger suppression occurs. We identify critical structure design (exclusion, absorber and extraction layer thicknesses and compositions), material (absorber dopant concentration and minority carrier lifetime) and device (passivation, annealing) requirements that must be satisfied for optimal performance characteristics from SL and HgCdTe alloy devices. We will also present an analysis and comparison of our theoretical and experimental device results in structures where Auger suppression was realized.

7608-73, Session 16

Quantum dot photodetectors based on structures with collective potential barriers

A. Antipov, G. Strasser, A. V. Sergeev, L. Chien, N. Z. Vagidov, V. V. Mitin, Univ. at Buffalo (United States)

The performance of current room-temperature semiconductor detectors is limited by extremely fast photoelectron relaxation/capture. Quantum-dot structures provide unique possibilities to control photoelectron kinetics and in this way to improve the photodetector performance. The photoelectron capture can be significantly suppressed by means of potential barriers, which separate the conducting electron states in the matrix from the localized states in quantum dots. The local potential barriers, i.e. barriers around every dot, can be formed by homogeneous doping of the interdot space. However, in real structures with a few electrons per dot, such barriers are relatively small and cannot substantially change photoelectron lifetime. In the current presentation, we report results of modeling, fabrication, and characterization of quantum-dot structures with collective potential barriers. We investigate and compare the lateral structures, where the potential barriers are produced by the dot planes, and the vertical structure with vertically correlated dot clusters (VCDC), where the barriers are created by the correlated clusters. We show that in these structures the photoelectron lifetime exponentially increases with an increase of the barrier's height. In the lateral structures, the height of the barrier is proportional to the distance between the quantum-dot planes and highly conducting electron states near the heterointerfaces. In the VCDC structures, the height of the barrier logarithmically depends on the distance between clusters in the quantum-dot plane. We also study the nonlinear effects of the electric field in the structures with collective barriers and optimize operating regimes of photodetectors.

7608-74, Session 16

Infrared detector epitaxial designs for suppression of surface leakage current

G. W. Wicks, G. R. Savich, J. R. Pedrazzani, S. Maimon, Univ. of Rochester (United States)

Excessive surface leakage currents, and their associated noise, deteriorates the performance of infrared photodetectors. The conventional approach to suppress surface leakage is post-epitaxy deposition of polycrystalline or amorphous passivation layers. Disadvantages of such passivation layers include the cost and complexity of the required additional processing steps, and the fact that they do not always work well. An alternative approach, presented here, is to design the photodetectors' epitaxial structures so that surface leakage currents are suppressed without the need for ex-situ deposition of passivation layers. In this approach, single crystal, epitaxial heterojunction barriers are designed so that surface leakage currents are blocked, but photocurrents are passed. Two examples of such epitaxial designs are the nBn detector and the unipolar barrier photodiode. These photodetector concepts can be implemented in devices that are constructed in a variety of semiconductor material systems and wavelength ranges. The present work provides experimental results on such detectors implemented in InAs(Sb)-based materials for operation in the mid-infrared wavelength region.

7608-75, Session 16

GaAs- and GaN-based high-operating temperature spin split-off band infrared detectors

A. G. U. Perera, S. G. Matsik, M. S. Shishodia, P. K. D. D. P. Pitigala, Department of Physics and Astronomy, Georgia State University, Atlanta, GA 30303 (United States)

Development of uncooled infrared detectors is important for astronomy, defence and security related areas. Recently developed high operating temperature (up to 330 K) GaAs/AlGaAs detectors responding in the 3-5 µm range and based on split-off (SO) transitions followed by escape by scattering to the light/heavy hole band or by direct quantum mixing of the states offer a viable alternative to detectors operating at cryogenic temperatures. This paper present ways to improve the performance of the GaAs based split off detectors. Including a graded barrier improves the performance by reducing the space charge buildup due to trapping at the emitter-barrier interface and the model suggests that a barrier offset of 20 meV will approximately double the responsivity. A double barrier resonant structure will increase escape of holes from the SO to the light/heavy hole bands by bringing the two bands into resonance and increases the response by a factor of ~85. The change of material system to GaN/AlGaN should extend the response to longer wavelengths (THz) as its zinc blende and wurtzite crystal structures have SO transition energies of 20 meV(~4.8 THz) and 8 meV (~1.92 THz) respectively. Using a modified SO model valid for the GaN/AlGaN material system, performance characteristics of a multiband detector in the ~ 6-10THz region will also be presented. As the GaAs/AlGaAs based detectors in SO mode exhibit increased temperature behavior compared to other operating modes, a similar improvement can be expected for GaN/AlGaN SO detectors.

7608-76, Session 16

Defect states in type-II strained-layer superlattices

M. E. Flatté, C. E. Pryor, The Univ. of Iowa (United States)

The electronic structure of isoelectronic defects, donors and acceptors is calculated within a full superlattice picture for InAs/GaSb and InAs/GaInSb superlattices. The properties are calculated using a three-dimensional real-space envelope-function technique that has been successfully applied to strained quantum dots as well as shallow and deep levels. The wavefunctions associated with these states extend beyond a typical layer width for the superlattices. Thus band alignments between the layers as well as interface properties are predicted to dramatically change these defects' binding energy as well as their influence on superlattice electronic, optical and transport properties. Defect properties are substantially modified by the defect location within a superlattice layer. The effect of electric fields on these defect states is also modified by their location within the superlattice unit cell.

7608-94, Session 16

Minority electron unipolar photodetectors based on type II InAs/GaSb/AlSb superlattices for very long wavelength infrared detection

M. Razeghi, B. Nguyen, S. Abdollahi Pour, S. Bogdanov, Northwestern Univ. (United States)

The bandstructure tunability of Type II antimonide-based superlattices has been significantly enhanced since the introduction of the M-structure superlattice, resulting in significant improvements of Type II superlattice infrared detectors. By using M-structure, we developed the pMp design, a novel infrared photodetector architecture that inherits the advantages of traditional photoconductive and photovoltaic devices. This minority electron unipolar device consists of an M-structure barrier layer blocking the transport of majority holes in a p-type semiconductor, resulting in an electrical transport due to minority carriers with low current density. Applied for the very long wavelength detection, at 77K, a 14um cutoff detector exhibits a dark current 3.3 mA/cm2, a photoresponsivity of 1.4 A/W at 50mV bias and the associated shot-noise detectivity of 4x10(10) Jones.

7608-79, Session 17

Photon-counting detectors for space-based laser receivers

M. A. Krainak, A. W. Yu, S. X. Li, G. Yang, X. Sun, NASA Goddard Space Flight Ctr. (United States)

Si avalanche photodiode (APD) single photon counting modules (SPCMs) are used in the Geoscience Laser Altimeter System (GLAS) on Ice, Cloud, and land Elevation Satellite (ICESat 1) , currently in orbit measuring Earth surface elevation and atmosphere backscattering. These SPCMs are used to measure cloud and aerosol backscattering to the GLAS laser light at 532-nm wavelength, with quantum efficiencies of 60 to 70% and maximum count rates greater than 13 millions/s. The performance of the SPCMs has been monitored since ICESat launch on January 12, 2003. There has been no measurable change in the quantum efficiency, linearity or afterpulsing. The detector dark counts rates monitored while the spacecraft was in the dark side of the Earth have increased linearly at about 55.5 counts/s per day due to space radiation damage. As the ICESat 1 mission nears completion, we have proposed ground-to-space optical and quantum communication experiments to utilize the on-orbit 1-meter optical receiver with multiple SPCMs in the focal plane.

For ICESat 2, major candidate photon counting detectors under evaluation include 532 nm and 1064 nm wavelength-sensitive photomultiplier tubes and Geiger-mode avalanche photodiode arrays. Key specifications are high maximum count rate, detection efficiency, photon number resolution, radiation tolerance, power consumption, operating temperature and reliability. Future NASA science instruments and free space laser communication terminals share a number of these requirements.

7608-80, Session 17

Utilization of 3D imaging flash lidar technology for autonomous safe landing on planetary bodies

F. Amzajerdian, M. D. Vanek, L. B. Petway, NASA Langley Research Ctr. (United States); D. F. Pierrottet, Coherent Applications, Inc (United States); G. E. Busch, Coherent Applications, Inc. (United States); A. Bulyshev, Analytical Mechanics Associates, Inc. (United States)

Flash Lidar is seriously being considered by NASA as a critical technology for enabling autonomous safe landing of future large robotic and crewed vehicles on the surface of the Moon and Mars. Flash Lidar can generate 3-Dimensional images of the terrain to identify hazardous features such as craters, rocks, and steep slopes during the final stages of the landing vehicle descent. The onborad flight comptuer can use the 3-D map of terain to guide the vehicle to a safe site. NASA Langley Research Center has been assessing the potentials of Flash Lidar technology as a landing sensor and working on its advancement under the Autonomous Landing and Hazard Avoidance (ALHAT) project. for the past 3 years. The ALHAT project, led by NASA Johnson Space Center, is established by NASA to develop and demonstrate a guidance, navigation, and control system for future lunar missions capable of terrain hazard avoidance and precision landing under any lighting conditions anywhere on the Moon.

The capabilities of Flash Lidar technology were evaluated through a series of static tests using a calibrated target and through dynamic tests oboard a helicopter and a fixed wing airctarft. The aircraft flight tests were perfomed over somewhat Moon-like terrain in the California and Nevada deserts. This paper briefly describes the Flash Lidar static and aircraft flight test results. These test results are analyzed against the landing application requirements to identify the areas of technology improvement. The ongoing technology advancement activities are then explained and their goals are described.

7608-81, Session 17

Progress in self-quenching InP-based single photon detectors

M. A. Itzler, Princeton Lightwave, Inc. (United States)

For the measurement of single photons, detectors based on avalanche photodiode (APD) structures operating above the APD breakdown voltage often provide the most advantageous combination of performance and practicality. Single photon avalanche diodes (SPADs) operating in Geiger mode based on Si and InGaAsP materials systems have gained increasing relevance for photon counting in the visible and near-infrared wavelength regimes, respectively. More recently, there has been a trend towards increasing the performance and functionality of SPADs using enhanced detector designs that provide self-quenching of the SPAD avalanche pulse. A number of different approaches have been adopted for achieving self-quenching with monolithically integrated structures in both Si and InGaAsP devices, and the resulting devices show promise for overcoming the limitations of canonical SPADs. Appropriately designed self-quenching can dramatically reduce the charge flow associated with each avalanche event, leading to associated reductions in afterpulsing and optical crosstalk. Operation of self-quenching devices requires just a fixed dc bias voltage and represents a considerable simplification relative to the complex bias circuitry required for SPADs. We survey recent progress in self-quenching detectors, and we describe our specific design for negative feedback APDs (NFADs) employing monolithically integrated quench resistors to achieve high-performance free-running photon counting at 1064 nm and 1550 nm. We present photon counting statistics that demonstrate highly deterministic single photon response and the potential for photon number resolving detectors created using multi-element NFAD arrays.

7608-82, Session 17

Large format avalanche photodiode imaging arrays

P. Yuan, R. Sudharsanan, X. Bai, J. Boisvert, P. McDonald, J. Chang, W. Hong, Spectrolab, Inc. (United States)

For LAser Detection and Ranging (LADAR) imaging under low light level conditions for many military applications, it is critical to develop large format and highly sensitive avalanche photodiode arrays, operating in the short wavelength infrared (SWIR) region. We have been developing single photon detection sensitivity Geiger-Mode (GM) focal plane arrays and cameras and recently 128 x 128 linear mode avalanche photodiode (APD) arrays for these applications.

In the case of Geiger-mode arrays, device parameters such as dark-count rate (DCR), photon detection efficiency (PDE), cross-talk, and jitter are critical parameters and by optimizing the device design, device growth conditions we have achieved DCR as low as <1000 Hz at 250K at 4V overbias, PDE of 32% at 1.06 micron, cross-talk less than 1%, and jitter value of <500 ps. At the meeting we will discuss the array uniformity in terms of detector performance parameters and the challenges in building larger format focal plane arrays.

7608-83, Session 18

Model for passive quenching of SPADs

M. M. Hayat, The Univ. of New Mexico (United States); M. A. Itzler, Princeton Lightwave, Inc. (United States); D. A. Ramirez, The Univ. of New Mexico (United States); G. J. Rees, University of Sheffield (United Kingdom)

Infrared single-photon avalanche photodiodes (SPADs) are used in a number of sensing applications such as satellite laser ranging, deep-space laser communication, time-resolved photon counting, quantum key distribution and quantum cryptography. A passively quenched SPAD circuit consists of a DC source connected to the SPAD to provide the reverse bias, and a series load resistor. Upon a photon-generated electron-hole pair triggering an avalanche breakdown, current through the diode and the load resistor rises quickly reaching a steady state value, after which it can collapse (quench) at a stochastic time. In this presentation we review three recent analytical and Monte-Carlo based models for the quenching time. In the first model, the bias after the trigger of an avalanche is assumed to be constant at the breakdown bias while the avalanche current is allowed to be stochastic. In the second model, the dynamic negative feedback, which is due to the dynamic voltage drop across the load resistor, is taken into account, albeit without considering the stochastic fluctuations in the avalanche pulse. In the third model, Monte-Carlo simulation is used to generate impact ionizations with the inclusion of the effects of negative feedback. The latter model is based on simulating the impact ionizations inside the multiplication region according to a dynamic bias voltage. In particular, it uses the time evolution of the bias across the diode to set the parameters for impact ionization in the Monte-Carlo phase. As such, this model includes both the negative feedback and the stochastic nature of the avalanche current.

7608-84, Session 18

Single-photon avalanche diode arrays and CMOS microelectronics for counting, timing, and imaging quantum events

F. Zappa, Politecnico di Milano (Italy) and Micro Photon Devices S.r.l. (Italy); A. Tosi, A. Dalla Mora, F. Guerrieri, Politecnico di Milano (Italy); S. Tisa, Micro Photon Devices S.r.l. (Italy)

The Single-Photon Avalanche Diode (SPAD) is reviewed and actual performances (detection efficiency, dark-counting rate, afterpulsing,

photon-timing resolution, etc.) are assessed. Both Silicon custom fabrication processing and standard CMOS technology are outlined; while the former enables the best performing detectors, the latter opens the way to monolithic arrays and dense imagers. The peculiarity of InGaAs/InP SPAD design for near-infrared detection is also highlighted.

It is described how the electronics plays an important role and can indeed boost the performance out of the detector. In particular the integration into smart pixels of both SPAD and on-chip quenching and processing electronics enables monolithic integration of complete photonic instruments for counting, timing and imaging quantum events.

7608-85, Session 18

High-throughput single-molecule fluorescence spectroscopy using parallel detection

X. Michalet, R. A. Colyer, G. Scalia, Univ. of California, Los Angeles (United States); T. Kim, Nesher Technologies Inc. (United States); M. Levi, D. B. Aharoni, A. M. Cheng, K. Arisaka, J. E. Millaud, Univ. of California, Los Angeles (United States); I. Rech, S. Marangoni, M. Ghioni, S. D. Cova, Politecnico di Milano (Italy); S. Weiss, Univ. of California, Los Angeles (United States)

Solution-based single-molecule fluorescence spectroscopy is a powerful new experimental approach with applications in all fields of natural sciences. The basic concept of this technique is to excite and collect light from a very small volume (typically femtoliter) and work in a concentration regime resulting in rare burst-like events corresponding to the transit of a single-molecule. Those events are accumulated over time to achieve proper statistical accuracy. Therefore the advantage of extreme sensitivity is somewhat counterbalanced by a very long acquisition time. One way to speed up data acquisition is parallelization. Here we will discuss a general approach to address this issue, using a multispot excitation and detection geometry that can accommodate different types of novel highly-parallel detector arrays. We will illustrate the potential of this approach with fluorescence correlation spectroscopy (FCS) and single-molecule fluorescence measurements obtained with different novel multipixel single-photon counting detectors.

7608-86, Session 18

Engineering of InAsP/InP quantum dot emission for long-distance quantum communications

R. Hostein, R. Braive, M. Larque, T. J. Karle, N. Gogneau, G. Beaudoin, L. Le Gratiet, A. Lemaitre, O. Krebs, J. Suffczynski, P. Voisin, E. Cambril, I. Robert-Philip, I. Sagnes, A. Beveratos, Ctr. National de la Recherche Scientifique (France)

Single photon sources and entangled photon sources are a key component for future quantum optical communication networks. These networks are based in Point-to-Point connections, over a single dark fiber, like for example in commercially available quantum cryptography links, or in more complex schemes like quantum teleportation or entanglement swapping, which are the quantum equivalent of repeaters and relays in classical telecommunications. All the above protocols are based on the ability to produce high quality single photon and entangled photon sources.

Single semiconductor quantum dots have the ability to produce both indistinguishable single photons and polarization entangled photons, and are imbedded in a semiconductor matrix, taking advantage of the mature semiconductor industry for their manipulation, as for example electrical pumping or surrounding them by photonic crystal cavities.

After introducing the possibilities offered by semiconductor quantum dots in future quantum communications networks and their advantages over existing sources, we will focus on two aspects.

First we will discuss the path towards the realization of an efficient source of entangled photons. We will demonstrate that real quantum dots generally do not produce entangled photons due to the exciton fine splitting structure, but this can be overcome by inserting the quantum dot in a high quality, small volume photonic crystal cavity. Tuning of the exciton fine splitting with the help of an electrical field will also be discussed.

Although quantum dots are extensively studied for the generation of non-classical states of light for quantum communications, their emission wavelength is generally below 1µm which is incompatible with standard telecommunication wavelength. By changing the material combination, from InAs/GaAs to InAsP/InP, it is possible to obtain quantum dots emitting at 1.55µm. We will present our results on the emission of single photons at telecommunication wavelength, as well as our progress towards the growth of single quantum dots on a predefined position.

7608-09, Session 19

Engineering vertical emission in THz quantum cascade lasers

A. Tredicucci, NEST, CNR-INFM (Italy) and Scuola Normale Superiore (Italy)

Terahertz quantum cascade lasers have already been employed as radiation sources in spectroscopy, imaging, and heterodyne systems. Their resonators are based on surface plasmon waveguides, most often in a double-metal configuration. From an application point of view, however, such waveguides typically present low radiative and collection efficiencies. The search for better performances has led to the implementation of horn antennas, silicon lenses, or photonic crystals, as well as gratings for vertical emission. The latter can be implemented simply by fabricating slits in the top metallization. Surface emission is particularly appealing because the devices are significantly easier to fabricate and allow two-dimensional integration.

For second-order distributed feedback (DFB) linear resonators, the waveguide is perturbed with a periodicity corresponding to the guided wavelength. The two band-edge eigenmodes are characterized by their different symmetry with respect to the grating. Unfortunately, the non-radiative mode is always the only one excited above lasing threshold. In real devices, surface emission can then be obtained by the use of appropriate boundary conditions or because of the finite length of the grating. Breaking the symmetry, as in quasi-periodic Fibonacci gratings, leads instead to considerable surface emission. These structures offer great flexibility in engineering the emission efficiency and angle. Alternatively, bending of the grating in a circular device can also be used, as demonstrated in microdisk lasers. These devices present a circular far-field, with a divergence determined by the ratio of device diameter and free-space wavelength. Recently, we have also investigated DFB ring resonators, demonstrating low-divergence, high-power devices.

7608-87, Session 19

High-sensitivity visible and IR (1550nm) Si nanowire photodetectors

Y. Lo, Univ. of California, San Diego (United States)

We present the physical model, simulations, and experimental results of vertical silicon nanowire detectors that show high phototransistive gain and high sensitivity. As a result, a Si nanowire detector can match the sensitivity of the state-of-the-art photoreceivers and, in theory, display single photon response. The Si nanowire detectors can be fabricated into a large array at low cost and find potential applications for medical imaging and giga-pixel image sensors.

7608-88, Session 19

Scalable routes to single and entangled photon pair sources: tailored InAs/InP quantum dots in photonic crystal microcavities

R. L. Williams, K. Mnaymneh, V. Sazonova, D. Dalacu, P. J. Poole, G. C. Aers, R. Cheriton, M. Reimer, J. Lapointe, P. Hawrylak, M. Korkusinski, E. Kadantsev, National Research Council Canada (Canada)

Self-assembled semiconductor quantum dots offer an extremely attractive route to electronic structure control. Size, shape, composition, strain can all be used to tune the electronic structure of individual dots. Although useful, this versatility can also be a major drawback; particularly in devices where one would wish to couple to an individual dot or in situations where one would like many identical copies of a particular single dot structure. By the very nature of the self-assembled growth process, the characteristics of individual dots can vary widely and their spatial location is generally uncontrolled. In this presentation I will discuss how these limitations may be overcome and I will present examples in which control structures such as optical microcavities or electrostatic gates are constructed around individual quantum dots to determine their coupling to the optical field or to tune their electronic structure. Using such techniques I will show how one can engineer the symmetries of individual dots, introduce optical transitions that were previously forbidden and so facilitate the emission of single and entangled photon pairs.

7608-89, Session 19

Digital-pixel focal plane array development

M. G. Brown, MIT Lincoln Lab. (United States)

Since 2006, MIT Lincoln Laboratory has been developing Digital-pixel Focal Plane Array (DFPA) readout integrated circuits (ROICs). To date, four 256 × 256 30 micron pitch format DFPA designs with in-pixel analog to digital conversion have been fabricated using IBM 90 nm CMOS processes. The DFPA ROICs have been shown to be compatible with a wide range of detector materials and cutoff wavelengths; HgCdTe, QWIP, InGaAs, and Silicon PIN photo-detectors with cutoff wavelengths ranging from 1 to 14.5 micron have been hybridized to the same digital-pixel readout. The digital-pixel readout architecture offers high dynamic range, AC or DC coupled integration, and on-chip image processing with low power orthogonal transfer operations. Development and characterization of the DFPA is presented along with applications for this new digital readout technology.

7608-90, Session 19

Blinking suppression and anti-bunching of quantum dots as single-photon sources

J. Tang, Academia Sinica (Taiwan)

Blinking suppression and anti-bunching of quantum dots as single-photon emitters

Chi-Tsu Yuan, Ping Yu, Jane Huang, Hsien-Chien Ko and Jau Tang*, Research Center for Applied Sciences, Academia Sinica, Taiwan

We will report our study on suppression of fluorescence blinking of colloidal CdSe/ZnS quantum dots which could have potential applications as high performance single-photon sources. Blinking is an interesting property for single quantum dots but is undesirable for their applications. We have demonstrated that by coupling these quantum dots to adjacent silver nanoprisms, we could not only completely suppress blinking [1] but also enhance the fluorescence quantum yield, and increase the fluorescence decay rates. These coupled quantum dots also exhibit anti-bunching behavior which is a signature for a single-photon emitter [2]. In addition, we have also achieved blinking suppression by confinement of the quantum dots in nano-cavities formed in agarose gel. The charge distribution on the inner surface of the cavity and the pore size could strongly affect the extent of blinking suppression. The mechanisms of blinking suppression will be discussed in the frame work of diffusion-controlled electron transfer model [3].

1. C. T. Yuan, P. Yu and J. Tang, Appl. Phys. Lett. 94, 243108 (2009).

2. C. T. Yuan, P. Yu, H. C. Ko, J. Huang, and J. Tang, (to be submitted).

3. J. Tang and R. A. Marcus, Phys. Rev. Lett. 95, 107401 (2005); J. Chem. Phys. 123, 054704 (2005).

Conference 7609: Photonic and Phononic Crystal Materials and Devices IX

Tuesday-Thursday 26-28 January 2010 • Part of Proceedings of SPIE Vol. 7609

Photonic and Phononic Crystal Materials and Devices X

7609-01, Session 1

Ultrafast switching and nonlinear response of quantum dots in a photonic band gap

S. John, Univ. of Toronto (Canada)

No abstract available.

7609-02, Session 1

All-optical switch and memory based on photonic crystal nanocavities

M. Notomi, NTT Basic Research Labs. (Japan)

No abstract available.

7609-03, Session 1

The evolution of nanocavities for efficient optical field enhancement

A. Scherer, California Institute of Technology (United States)

No abstract available.

7609-67, Session 1

Design and fabrication of three-dimensional rhombicubeoctahedral photonic quasicrystals

G. von Freymann, A. Ledermann, M. Wegener, Karlsruhe Institute of Technology (Germany)

No abstract available.

7609-04, Session 2

Reconfigurable optical filters and cavity QED with photonic crystal nanobeam cavities

M. Loncar, Harvard Univ. (United States)

High quality factor (Q) photonic crystal cavities (PhC), based on semiconductor slabs perforated with 2D lattice of holes, have emerged as a platform of choice for manipulation of optical signals at sub-wavelength volumes. Recently, we demonstrated that PhC nanobeam cavities, that consist of optical waveguides perforated with 1D lattice of holes, can also support ultra-high Q modes, on-par with those found in conventional PhC cavities.

For example, we realized silicon cavities with Q~106 operating at 1,550nm wavelength. In addition, we demonstrated that using the nanobeam concept, high-Q cavities can be made even in the materials with low and moderate refractive indices (1.5<n<2.5). These materials typically have a wide electronic bandgap and therefore are suitable for realization of a low-loss nanophotonic platform operating at visible wavelengths. As an example, I will present our work on silicon-nitride nanobeam cavities and discuss their potential for applications in QED experiments with nanocrystal quantum emitters (e.g. colloidal quantum dots, nano-diamonds).

The PhC nanobeam cavity can be viewed as a combination of a classic NEMS device, a double clamped nanobeam, with a text-book nanophotonics structure, one-dimensional grating. By taking advantage of mechanical degrees of freedom of this structure, we demonstrated reconfigurable optical filters that can be dynamically and reversibly tuned. In our system, an external bias voltage controls the separation between two coupled PhC nanobeam cavities (separated by ~50nm), via the electrostatic force, which in turn has a strong effect on the resonant wavelength of the coupled-cavity super-mode. Tuning range of ~10nm was achieved with less than 6V of external bias, and negligible steady-state power consumption.

7609-05, Session 2

Stretch-tuneable optical microcavities

N. Gibbons, B. Zheng, M. Kolle, U. Steiner, J. J. Baumberg, Univ. of Cambridge (United Kingdom)

Periodic multilayers of transparent dielectrics are among the most common optical elements, used to produce high reflectivity Distributed Bragg Reflectors (DBRs), broadband beamsplitters, optical low-pass, high-pass and notch filters, as well as optical microcavities. While the manufacture of polymeric DBRs has been reported (with resulting advantages in scalability, simplicity, cost, and weight) one of the greatest drawbacks of such multilayer optical components is their lack of tuneable performance due to their composition from rigid layers. Here we demonstrate fabrication of entirely elastomeric multilayer dielectric stacks, which can be stretched by more than 60% to achieve rapid and effective wavelength tuning. These are fabricated from an initial bi-layer of PDMS and the block co-polymer, PSPI. The film is cut into many small sections which are then individually floated from the substrate and stacked, folded or rolled on top of each other to create the DBR. The use of a single bi-layer greatly improves the layer conformity. Similarly, a resonant cavity is implemented within two DBRs achieving quality factors, Q>60. We demonstrate how the resonant cavity mode shifts in wavelength across the NIR to the UV when stretched by >60%. Because the device maintains its proportions upon stretching, the resonance remains always entirely within the Bragg stopband. Stretch tuneable DBRs can be directly employed for optical stress-strain sensing applications and by incorporating them in stretchable micro-cavities they can be employed in stretch-tuneable lasers and LEDs.

7609-06, Session 2

High-frequency tuning of photonic crystal defect cavity modes using surface acoustic waves

D. A. Fuhrmann, H. J. Krenner, Univ. Augsburg (Germany); J. Ebbecke, Univ. of Southern Denmark (Denmark); J. Jambreck, Univ. Augsburg (Germany); H. Kim, S. Thon, D. Bouwmeester, P. M. Petroff, Univ. of California, Santa Barbara (United States); A. Wixforth, Univ. Augsburg (Germany)

We present a combined theoretical and experimental study on the influence of a surface acoustic wave (SAW) induced deformation of a two-dimensional photonic crystal membrane. Here, we are especially interested in the effect on the resonance frequency of a defect cavity. Our approach combines the high optical quality of nanocavities and the high frequencies of SAWs. We employ FDTD-simulations to determine the resonance frequency and quality factor of a L3 cavity of a GaAs based structure containing a layer of self-assembled InAs quantum dots. We introduce a dynamic and periodic modulation of this structure by SAWs

with wavelengths ranging between 1 and 30µm and an amplitude of 1nm. We use an optimized design for the cavity with a calculated Q-factor ~80000 and a resonance wavelength of ~960nm. As the mechanical deformation varies with the SAW phase, the cavity undergoes a spectral shift up to Δ =2nm corresponding to >100 times the cavity linewidth. This shift is found to be almost independent on the SAW wavelength and decreases only weakly for short wavelengths. The Q-factor of the cavity varies by less than a factor of 2 and, therefore, remains sufficiently high to observe cQED effects or to efficiently extract single photons.

Initial experiments were performed using both standing and propagating SAWs with a wavelength of 1.6µm. In time-integrated photoluminescence experiments we observe a pronounced broadening of the cavity emission line corresponding to a spectral shift of >1nm.

The high frequencies (>5GHz) accessible by SAWs could lead to real-time control of light-matter interactions.

7609-07, Session 2

1D Si3N4 nanobeam cavities

M. M. Khan, T. Babinec, M. McCutcheon, P. B. Deotare, M. Loncar, Harvard Univ. (United States)

In this work, we are pursuing fabrication and experimental validation of 1D photonic crystal (PhC) nanobeam cavities for quantum information processing applications. In order to improve efficiency of quantum emitters, it is important to enhance the photon yield (production rate) as well as the collection efficiency of emitted photons. This can be achieved by embedding quantum emitters within optical cavities. Silicon nitride (Si3N4) cavities were designed to operate for quantum emitters in the visible wavelengths particularly near 637nm in order to strongly enhance the zero phonon line (ZPL) emission of the negatively charged nitrogen vacancy (NV-) color center in diamond nanocrystals (NC)s. In spite of the low-index of stoichiometric silicon nitride (n ~ 2.0), we were able to design optical cavities with quality (Q) factors of 1.4x10^6 and mode volumes of 0.78(/n)^3 respectively. The nanobeam cavities were fabricated using the standard techniques of electron beam lithography, reactive ion etching and wet etching in LPCVD Si3N4. A custom built confocal photoluminescence setup was utilized for testing the nanobeam cavities. Experimental investigation of Q factors, polarization and cavity mode characterizations show Q's as high as 16000. The presented work is an important step towards the realization of diamond based single photon sources. The planar nature of the fabricated structure also allows a large number of optical cavities with nanocrystals embedded within them to be integrated on the same chip.

7609-08, Session 3

Active photonic crystal devices: from switches and modulators controlled with sub-fJ energies to silicon-based light sources

J. Vuckovic, A. Faraon, A. Majumdar, D. R. Englund, M. O. Makarova, Y. Gong, Stanford Univ. (United States)

Cavity QED effects in photonic crystal nanocavities have been employed to build fast electro-optical switches and modulators controlled with sub-fJ energies, and silicon CMOS compatible light sources.

7609-09, Session 3

Plasmonic-photonic hybrid cavity for tailored light-matter coupling

M. Barth, S. Schietinger, T. Aichele, Humboldt-Univ. zu Berlin (Germany); N. C. Nüsse, B. Loechel, Helmholtz-Zentrum Berlin für Materialien und Energie GmbH (Germany); O. Benson, Humboldt-Univ. zu Berlin (Germany)

Surface plasmons can concentrate electromagnetic energy in volumes much smaller than the corresponding wavelength, providing intense interaction between light and matter. This interaction can be further enhanced through an appropriate feedback mechanism as provided by cavity structures. Various types of plasmonic cavities have already been realized, but the achieved quality factors Q were mostly limited to values Q<100 due to losses in the metal. On the other hand, dielectric microcavities can reach high quality factors, but the achievable field localization is inherently limited by the laws of diffraction.

Here, we report the realization and characterization of a hybrid cavity system which combines the benefits of both, plasmonic and photonic elements. Individual metal nanoparticles are deterministically placed and arranged on the dielectric backbone of a photonic crystal (PhC) cavity by using an AFM-based nanomanipulation technique. This type of hybrid structure can exhibit higher quality factors than conventional plasmonic cavities, as the optical feedback is solely provided by the dielectric material. At the same time, the metallic constituents create pronounced hot spots of the electromagnetic field, potentially enhancing the interaction of the cavity mode with active materials. A detailed analysis of the system reveals a highly polarization-selective coupling between the plasmonic and photonic resonances with an efficiency of ~40%, accompanied by a moderate decrease of the cavity quality factor to values Q~900. The combined effect of plasmonic field enhancement and high Q opens new routes for the control of light-matter interaction at the nanoscale.

7609-10, Session 3

Dynamically reconfigurable nanobeam photonic crystal cavities

I. W. Frank, P. B. Deotare, M. W. McCutcheon, M. Khan, M. Loncar, Harvard School of Engineering and Applied Sciences (United States)

We present dynamically reconfigurable photonic crystal nanobeam cavities that have continuously tunable optical modes over a range of 9.5 nm for devices operating near 1550 nm. The structures are formed by two coupled nanobeam cavities whose even supermodes can be tuned by varying the lateral gap between the nanobeams. We induce mechanical motion, and therefore resonance tuning, by applying a potential difference directly across the electrically isolated parallel nanobeams. The beams, which can be modeled as parallel-plate capacitors, subsequently experience an electrostatic attractive force. As long as the pull-in voltage - the voltage beyond which there is no balance achievable between the mechanical restoring and the capacitive attracting force - is not exceeded, the gap between the beams can be reproducibly and continuously varied, resulting in a highly stable and repeatable tuning of the even supermodes of the coupled cavities. The odd supermodes do not display the same large tuning, because the higher order effect of coupling induced frequency shifts (CIFS) cancels out the coupled-mode splitting. All optical modes were measured in a resonant scattering setup and the motion of the beams was confirmed by imaging the process, in real-time, in a scanning electron microscope. Finite element simulations were performed to confirm the observed tuning trends. By modeling the electrostatics and mechanics of our fabricated structures and subsequently finding the optical modes of the reconfigured geometries we were able to simulate results that closely match our experimental results.

7609-11, Session 3

Observations of fast light and Hartman effect in photonic crystal lattices and nanocavities

T. Gu, S. Kocaman, Columbia Univ. (United States); M. Yu, A*STAR Institute of Microelectronics (Singapore); X. Yang, Univ. of California, Berkeley (United States); D. Kwong, A*STAR Institute of Microelectronics (Singapore); C. Jiang, Shanghai Jiao Tong Univ. (China); C. W. Wong, Columbia Univ. (United States)

We present observations of fast light in photonic crystal lattices and coupled nanocavities, in both physical measurements and complete numerical simulations. Superluminal light, or fast light, is an interesting physical phenomenon enabled ab initio through artificial materials, with significant applications in integrated optical communications. Through finite-difference time-domain numerical simulations, we demonstrate temporally the superluminal pulse propagation in nanostructured photonic crystals. We illustrate our observations for both 2D and 1D photonic crystals, including the energy and group velocities, and dwell times, with remarkable match with coupled-mode theory. In 2D photonic crystals, the Hartman effect, pulse ringing as well as the relationship between energy storage and group delay are illustrated.

These numerical observations are complemented with actual physical measurements of fast light in nanofabricated photonic crystal nanocavities. These involved two-coupled cavities of deterministically-controlled two-pump-beam detuned resonances with in-plane interferences. The nanocavities are designed to operate in the overcoupled regime with intrinsic cavity Q of ~ 60,000, and fabricated rigorously in silicon CMOS foundry with statistically-analyzed disorder of ~ 20 A. The air-bridged nanomembranes are coupled to input-output fibers with inverse tapered couplers to minimize coupling losses and spurious reflections in spectral measurements with broadband and supercontinuum sources. In an all-optical-analogue to electromagnetically-induced-transparency, the fast- and slow-light regions are observed experimentally, with excellent match with coupled-mode numerical simulations.

7609-12, Session 3

Direct measurement of spectrally selective absorption enhancement in Fano resonance photonic crystal cavities on plastic substrates

L. Chen, H. Yang, Z. Qiang, The Univ. of Texas at Arlington (United States); L. Sun, Z. Ma, Univ. of Wisconsin-Madison (United States); R. Pate, A. Stiff-Roberts, Duke Univ. (United States); J. Xu, The Pennsylvania State Univ. (United States); G. J. Brown, Air Force Research Lab. (United States); W. Zhou, The Univ. of Texas at Arlington (United States)

Owing to the light-matter interaction modifications, spectrally selective absorption can be achieved in photonic crystal cavities. We reported earlier enhanced spectrally selective IR absorption in both defect-mode and defect-free photonic crystal cavities, via localized states and Fano resonances, respectively.

Here, we report theoretical and experimental investigations of infrared absorption characteristics for PbSe/PbS colloidal quantum dots (CQDs) in defect-free photonic crystal cavities, via Fano resonances. Experimental demonstration at the center absorption wavelength near 1550 nm was made on patterned single crystalline silicon nanomembranes (SiNMs) on transferred flexible PET substrates and on Si-on-insulator (SOI) substrates with PbSe/PbS CQDs backfilled into the air holes of the patterned SiNMs. Angle and polarization dependent transmission, reflection and absorption were directly measured. The Fano resonance showed red-shift due to increased refractive index in the air hole region of the patterned SiNMs. More importantly, significant absorption enhancement was found at Fano resonance due to the strong interaction between CQDs and matched Fano resonances. Otherwise, no absorption enhancement was observed. CQDs were filled into the air holes of the photonic crystal cavities, via simple drop cast, immersion, matrix-assisted pulsed laser evaporation (MAPLE) and supercritical fluidic deposition techniques. We will also report different CQD filling factors and the effectiveness of these techniques on the spectral and absorption properties of CQDs in both naorrow band Fano filters and broadband reflectors.

Work is supported by US AFOSR MURI program (FA9550-08-1-0337), AFRL/CONTACT program (FA8650-07-2-5061), AFOSR Nano programs (FA9550-06-1-0482 and FA9550-06-1-0487), and US NSF Nano-manufacturing program (DMI-0625728).

7609-13, Session 3

An analytical approach for evaluating the optical spectrum emitted from a strongly coupled single quantum dot photonic-crystal cavity system

E. Ahmadi, H. R. Chalabi, M. Bayat, S. Khorasani, Sharif Univ. of Technology (Iran, Islamic Republic of)

Photonic cavities that strongly confine light are finding applications in many areas of physics and engineering, including coherent electron-photon interactions, ultra-small filters, low-threshold lasers, photonic chips, nonlinear optics, and quantum information processing.

In this article, we present a rigorous medium-dependent theory for describing the quantum electromagnetic field emitted from a single quantum dot exciton. This quantum dot is assumed to be coupled strongly to a planar photonic crystal nanocavity. In addition, the dielectric is described macroscopically by a position-dependent dielectric function. It has been proved that the electric field in such a medium can be described using the so-called K-function. The K-function itself can be expressed in terms of the characteristic frequencies and the profile of the eigenmodes of the system.

We have assumed that the effect of a quantum dot embedded inside an inhomogeneous non-dispersive and lossless dielectric can be described as an electric dipole. We have written the Heisenberg equations to derive the time evolution of the operators. After evaluating the Fourier transformation of the operators, the differential equations transform to algebraic equations, which are easier to handle.

We derive a formula for obtaining the frequency spectrum, which is in agreement with previously published results. Furthermore, we present an analytical result for the optical spectrum, which is dependent on the K function.

Therefore, for using the obtained result to determine the optical spectrum, we need to know the K-function. To this end, we have considered a slab photonic crystal configuration with hexagonal structure containing a cavity to evaluate the frequency spectrum in such a medium. In the numerical simulations, we have used the FDTD method to calculate the generalized-transverse green function and the K-function everywhere in the medium.

7609-14, Session 4

Watt level performance of photonic crystal distributed feedback quantum cascade laser

M. Razeghi, B. Gokden, Y. Bai, S. R. Darvish, S. Slivken, Northwestern Univ. (United States)

We demonstrate room temperature, high power, diffraction limited operation of photonic crystal distributed feedback (PCDFB) quantum cascade lasers emitting around 4.7 μm. PCDFB gratings with three distinctive periods are fabricated on the same wafer. Peak output power up to 12 W is demonstrated. Lasers with different periods show expected wavelength shifts according to the design. Single mode emission spectrum and diffraction limited far field profiles are observed.

7609-15, Session 4

High extraction efficiency LED based on embedded 2D air-gap GaN photonic crystals

E. Matioli, L. Rangel, E. L. Hu, J. S. Speck, Univ. of California, Santa Barbara (United States); C. Weisbuch, Genewave (France)

We report on the growth, fabrication and characterization of high extraction efficiency LEDs based on 2D air-gap photonic crystals (PhCs) embedded in the LED structure. Theses structures are to be contrasted with usual PhC LEDs which rely mostly on surface etched PhCs. The low interaction of the surface PhCs with the guided modes limits their extraction efficiency. The alternative approach presented in this work is to embed the PhCs within the device. In addition to improved light extraction, advantages of the embedded PhCs include a simpler, planar contacting process, and the absence of possible etch-related damage introduced into the active region.

We developed a growth technique that avoids the use of dielectric mask to grow embedded air-gap PhCs. The LED structure presented here was grown by MOCVD on a sapphire substrate. We were able to form coalesced, 2D air-gap structures without a masking layer. The total thickness over the embedded PhCs was ~540 nm which is thin enough to ensure strong interaction between the guided modes and PhCs [3]. The extraction of the guided modes was assessed by angular measurements where very intense guided modes were observed, corresponding to modes confined in the layer above the PhCs (due to their lower average index of refraction), which have a high interaction with the PhCs.

An average of 3.7-fold enhancement of the vertical output power was observed. The IV characteristics were not changed by the embedded PhCs which shows that no additional series resistance was introduced into the device. These results show the strong enhancement of embedded PhCs in the LED light extraction.

References

1. A. David, B. Moran, K. McGroddy et al., Appl. Phys. Lett., 92, 113514, 2008.

2. H. Matsubara, S. Yoshimoto, H. Saito et al., Science, 319, 445, 2008.

3. E. Matioli, M. Iza, Y. Choi et al., Phys. Stat. Sol. (c), 6, No. S2, S675-S679, 2009.

7609-16, Session 4

InGaAsSb LED arrays (lambda = 3.7 µm) with photonic crystals

B. A. Matveev, Y. M. Zadiranov, A. L. Zakgeim, N. Il'inskaya, S. Karandashev, M. Remennyy, N. Stus', A. A. Usikova, A. E. Cherniakov, A. Fedorov, Ioffe Physico-Technical Institute (Russian Federation)

The interface nonuniformity of periodic or quasiperiodic two-dimensional (2D) photonic crystal (PC) pattern violates Snell`s law and provides diffraction of the guided light into the light escaping cone at supercritical incident angles and changes angle pattern in far field as well. There are several cases where photonic structure brings benefits not attainable by other means. Such are compact mid-IR LED arrays with high fill-factor for which immersion lens optics is of no practical use if high contrast and apparent temperature are of prime interest. The latter is important for a variety of applications including miniature spectroscopic modules with gratings that are capable recording transmission spectra by sequential activation of array elements. Formation of a 2D periodic relief on the light-extraction surface was widely used in LEDs operating in the visible and near-IR spectral range. However, to the best of our knowledge there have been no papers describing mid-IR arrays and LEDs with 2D PC. Mid-IR arrays and LEDs with 2D PC will be quite useful in the 3000-5000 nm spectral range where most gases have strong "fingerprint" absorption.

We present PC based n-In(Ga)As(Sb)/p-InAsSbP LEDs and arrays grown on InAs substrates with individual addressing of elements and emitting at lambda = 3700 nm, their I-V, L-I and spectral characteristics as well as near- and far-field radiation distribution at forward (positive luminescence) and reverse (negative luminescence) bias together with simulation of PC properties and analysis of PC impact onto beam propagation and emission spectra in our PC based devices.

7609-17, Session 4

Optical characteristics of one-dimensional photonic crystal waist cavity laser

J. Kang, B. Ahn, M. Kim, Y. Lee, Korea Advanced Institute of Science and Technology (Korea, Republic of)

Two and three dimensional (2D, 3D) photonic crystal (PhC) cavities with a high quality factor (Q) and a small mode volume (V) have been spotlighted for their applications in low threshold lasers, high speed modulation, single photon sources and cavity quantum electrodynamics. However, 2D and 3D PhC cavities need a large footprint for photonic band gap (PBG) mirrors. Recently, it is reported that one-dimensional (1D) PBG is enough to achieve a high Q and a small V.

Cutoff frequency of PhC modes can be locally pulled into the bandgap frequencies to confine photons. We suggest new method to control cutoff frequency gently and easily by just changing the width of 1D photonic crystal slab waveguide structure. 1D PhC waist cavity laser is fabricated based on three pairs of InGaAsP quantum wells emitting near 1.5 um. We increase the cutoff frequency of dielectric band edge at the central region of 1D PhC slab waveguide by decreasing the width of 1D PhC slab waveguide. Because the resonant modes are originated from dielectric band which has electric field maximum at dielectric region, strong interaction with gain medium is achievable. We make two kinds of cavities with different position of the waist, the thinnest position. One has its waist between two air holes and the other has its waist at the center of the air hole. We demonstrate lasing actions in both 1D PhC waist cavities and observe the emission profiles using CCD images. The fundamental mode photons of former cavity are vertically emitted because the vector summation of Ey field which have even symmetry becomes non-zero. Otherwise, summation of Ey field of latter one is zero and the vertical emission of photons is prohibited. We expect 1D PhC waist cavity laser can be useful for highly packing and compatible with 1D ridge waveguide of photonic integrated circuits.

7609-18, Session 4

Comparisons between defect and band-edge modes of GaN photonic crystal membrane laser structures

C. Lin, J. Wang, C. Chen, K. Shen, D. Yeh, Y. Kiang, C. Yang, National Taiwan Univ. (Taiwan)

The implementation of an H2-defect GaN photonic crystal membrane resonance cavities and its optically-pumped lasing behaviors are demonstrated. In particular, the lasing behaviors of the two defect modes and the photonic band-edge mode are compared. By moving the probe location around the H2-defect of the photonic crystal membrane structure, two lasing modes with spectral separation of 0.5 nm are observed. The lasing threshold condition of the band-edge mode is smaller, when compared with the defect modes (15 nJ versus 26 nJ in pump pulse energy of a 266-nm laser). The lasing wavelength of the band-edge mode (~367.5 nm) is shorter than those of the defect modes (369.4, 369.9 nm). Polarized laser output of the long-wavelength defect mode with a polarization ratio of about 2.55 is observed. The photonic crystal is composed of a triangular hole arrangement of slight anisotropy in GaN and an H2 defect structure. The air gap below the hole structure is formed with the band-gap-selective photoelectrochemical wet etching technique. The laser pump threshold of the band-edge mode is only 0.53 mJ/cm2. The measured laser operation spectral full-widths at half-maximum of all the modes are in the range of 0.15-0.20 nm, which is limited by the measurement limitation. This result corresponds to a Q factor of around 2400. Simulations based on the plane-wave expansion and finite-difference time-domain methods show quite consistent results.

7609-19, Session 5

Cascaded silicon-nitride integrated spectrometers for wideband high-resolution spectral interrogation

B. Momeni, E. Shah Hosseini, A. Adibi, Georgia Institute of Technology (United States)

The prospect of integrated photonic components for optical signal processing and sensing has stimulated considerable research activities in recent years. The possibility of performing spectral analysis in these integrated photonic platforms enables more versatile functionalities, including analyzing Raman and fluorescence spectra in sensing applications and multiplexing and spectral manipulation in signal processing applications. Here, we explore devices for realizing compact integrated spectrometers in silicon-nitride for the visible wavelength range. The focus of this presentation will be on the implementation of broadband high-resolution spectrometers. This goal is achieved by using a cascaded configuration consisting of a low-resolution wideband spectrometer followed by high-resolution spectrometers for each wavelength band separated in the first stage. An arrayed waveguide grating (AWG) is used for the coarse wavelength separation in the first stage of the device. Each output channel from the AWG goes through an array of resonators that sample the spectrum with a linewidth around 0.1 nm. The free spectral range (FSR) of the resonators in these arrays is designed such that it matches the resolution of the AWG in the first stage. In designing the array of resonators, two different schemes are studied. In the first scheme, the resonators are side-coupled to the waveguide carrying the signal of each of the AWG channels. All the resonators in this scheme are designed in the critical coupling regime, and the output signal is acquired using a CCD on top of the structure. In the second scheme, a drop waveguide is also coupled to each of the resonators in the array of resonators. These drop ports carry the signal from the resonators to the edge of the sample, and all the output channels are monitored by imaging the end-facet of the sample onto a camera. Note that the resonators are in the over-coupling regime in this case, and the linewidth of the spectral samples is determined by the amount of coupling. Future directions and potentials for alternative spectrometer devices for each stage will also be investigated in this presentation.

7609-20, Session 5

An efficient self-collimating photonic crystal coupling technique in the RF regime

J. N. Sabas, I. O. Mirza, S. Shi, D. W. Prather, Univ. of Delaware (United States)

The dispersion properties of photonic crystals (PhC) can be exploited to control the propagation of electromagnetic waves. Conventionally, photonic bandgaps, i.e., defect-based photonic crystals, have been used to attain strong confinement of light within the photonic crystal. In this research we intended to exploit an alternative PhC structure that does not require defects for confinement of light and yet can arbitrarily route light. These structures are said to exhibit self-collimating behavior and they are capable of very low propagation loss when implemented in slab photonic crystals, mainly due to the low out-of-plane scattering given that the mode resides below the light line. Since the dispersion of photonic crystals can be considerably more varied than that of materials found in nature, we used dispersion diagrams as a conceptual tool to understand and design our self-collimating photonic crystal.

In this research we focused on the design and experimental characterization of self-collimating PhC for applications in the RF and microwave frequency regimes. In order to improve the insertion loss due to the coaxial-to-PhC transition, we investigated several different techniques of coupling electromagnetic energy into the self-collimating photonic crystals. We designed input/output structures consisting of a coaxial-to-waveguide transition. We also implemented a horizontally-tapered slab coupler to link the waveguide to the PhC lattice. Using these techniques, we were able to simulate and subsequently demonstrate experimentally an insertion loss lower than 3 dB through a 24” photonic crystal lattice, and a coupling loss lower than 1 dB at each coupler-PhC interface.

7609-21, Session 5

A photonic crystal flat lens at optical frequencies

F. A. de Fornel, L. Lalouat, B. Cluzel, Univ. de Bourgogne (France); N. Fabre, O. Vanbesien, D. Lippens, Institut d’Electronique, de Microélectronique, et de Nanotechnologie (France)

If the feasibility of perfect lenses with centimeter sizes was demonstrated at the microwaves frequencies since few years using a metallic route, achieving this phenomenon at optical frequencies is a challenging task. As a matter of fact, reducing the operating wavelength of the perfect lens down to the visible range requires a miniaturization of the material patterning at the nanometre scale as well as drastic improvements of the instrumentation tools.

In this work, we first face the miniaturization of a flat lens using a full dielectric route by taking benefit from a photonic crystal slab etched in a III-V semiconductor and then challenges the direct visualization of the operating lens by using a Scanning Near-field Optical Microscopy (SNOM) technique. The results we obtained unambiguously demonstrate the focalisation of light by a photonic crystal flat lens at optical frequencies. Taking into account the different SNOM images we recorded as a function of the wavelength, we estimate the lateral size of the focused to 0.8 0 demonstrating the ability of the reported lens to produce sub-wavelength spots. Finally, in light of the reported results, the ability of the reported lens to produce sub-wavelength spots overcoming the Rayleigth limit (0.5 0) will be discussed

7609-22, Session 5

Chip-scale photonic interconnects for reconfigurable computing

A. S. Sharkawy, EM Photonics, Inc. (United States); M. J. Zablocki, S. Shi, Univ. of Delaware (United States); O. Ebil, EM Photonics, Inc. (United States); D. W. Prather, Univ. of Delaware (United States)

Our approach is based on a photonic crystal cross-bar switch that enables complete interconnectivity over large computational-block arrays. Perhaps one of the most attractive benefits of our approach is that it alleviates the need to perform place and route during processor layout. As such, our approach may allow for reconfigurable processors consisting of a higher density of computing-blocks along with a faster interconnect medium. Accordingly, this talk will present numerical studies, design and fabrication of various implementations of candidate photonic crystal devices for reconfigurable optically interconnected chip-scale networks, including both chip-scale reconfigurable Photonic crystal based switch and an optical analog to digital converter.

7609-23, Session 5

Compact Mach-Zehnder interferometer based on self-collimation of light in a silicon photonic crystal

H. Nguyen, Technische Univ. Delft (Netherlands)

Optical waveguides based on silicon-on-insulator and fabricated in CMOS compatible technology will likely replace electrical interconnects for high data rate circuitsIn this context, the Mach-Zehnder interferometer

(MZI) based on silicon waveguides is very promising as high speed modulator. However, the requirement of producing a pi-phase shift in one arm of the MZI implies a millimeter scale footprint of the device, which is a serious disadvantage for integration in micro-processors. Therefore, strong efforts are made to miniaturize MZI modulators without compromising the required phase shift, particularly using slow light engineering in photonic crystals (PhCs). Here, we demonstrate a different concept for a compact MZI built from a PhC operating in the special regime of self-collimation of light. To reach this regime, we have tailored the photonic band structure such as to produce self-collimated beams. The properties of these beams are such that we can manipulate them to form the arms of the MZI in a very small area of 20x20 um. Using an optical transmission spectroscopy and an infrared (IR) imaging microscopy, we have demonstrated the uni-directional output behaviour characterizing by the high contrast in the telecommunication-wavelength signal at the two outputs of the PhC MZI. The contrast in the transmission level at 1500-nm wavelength of the two outputs was observed, in agreement with our simulations. The output intensity contrast and evidences of the self-collimated beams were also observed in real IR images. Our approach holds a promise for a compact MZI modulator, inspired by recent reports of NEMS-based PhC membranes.

7609-24, Session 6

Conformal coating of 3D polymeric photonic crystals fabricated by multiphoton lithography

V. W. Chen, Y. Fang, K. H. Sandhage, J. W. Perry, Georgia Institute of Technology (United States)

Multiphoton lithography (MPL) is a powerful technique for fabricating 3D micro- and nanostructures with feature sizes down to 65 nm[1]. The ability to induce photochemistry in arbitrary 3D patterns makes MPL a versatile tool for the fabrication of tailored photonic crystals (PC) structures[2,3,4], including ones with designed defects[5]. These structures have generated considerable interest as micro-optical devices for their filtering, stop-band, dispersion, resonator, or waveguide properties. Polymeric PCs have been widely studied due to the range of readily available photoresist systems, as well as highly efficient two-photon absorbing photoiniators[2].

However, the applications of polymeric PCs have been limited by their low refractive indices.

There is currently great interest in post-fabrication processes for backfilling or conformally coating these polymeric PCs with high index materials in order to enhance their optical properties and to broaden their potential applications[6].

We have developed a sol-gel method to conformally grow titania onto the surface of MPL fabricated cross-linked acrylate polymer PCs. PCs with various lattice parameters were fabricated in order to investigate the relationship between coating thicknesses, stop band wavelengths, and peak reflectivites. Uniform and smooth titania coatings of cross-linked acrylate polymer PCs were achieved as observed by scanning electron microscopy and focused ion beam etching. FT-IR microscopy was used to measure the reflection spectra of the polymeric PCs prior to and after coating. Stop band positions ranging from 1.3 to 3.88 µm were observed in reflection for polymer photonic crystal templates with reflectivities ranging from 20% to over 80% depending upon structure parameters. Controllable shifts up to 400 nm were obtained upon coating with titania coatings(~ 100 nm thick) of the polymeric PC structures, with similar reflectivities for the coated and uncoated structures. Results on the selective coating of polymeric photonic crystal structures with silver and calculations of the stop-bands and shifts upon coating will be presented.

References

[1] W. Haske, V. W. Chen, J. M. Hales, W. Dong, S. Barlow, S. R. Marder, J. W. Perry, Opt. Express, 15(6), 3426-3436 (2007).

[2] B. H. Cumpston, S. Ananthavel, S. Barlow, D. L. Dyer, J. E. Ehrlich, L. L. Erskine, A. A. Heikal, S. M. Kuebler, I.-Y. Sandy Lee, D. McCord-Maughon, J. Qin, H. Röckel, M. Rumi, X.-L. Wu, S. R. Marder and J. W. Perry, Nature 398, 51-54 (1999), S. M. Kuebler, M. Rumi, T. Watanabe, K. Braun, B. H. Cumpston, A. A. Heikal, L. L. Erskine, S. Thayumanavan, S. Barlow, S. R. Marder, and J. W. Perry, J. Photopolym. Sci. Tech. 14, 657-668 (2001).

[3] H.-B Sun, S. Matsuo, H. Misawa, Appl. Phys. Lett., 74(6), 786-788 (1999).

[4] M. Deubel, G. Von Freymann, M. Wegener, S. Pereira, K. Busch, and C. M. Soukoulis, Nature Mat., 3, 444-447 (2004).

[5] W. Lee, S. A. Pruzinsky, P. V. Braun, Adv. Mat., 14(4), 271-274 (2002).

[6] N. Tétreault, G. von Freymann, M. Deubel, M. Hermatschweiler, F. Pérez-Willard, S. John, M. Wegener, G. A. Ozin, Adv. Mat., 18(4), 457-460 (2006).

7609-25, Session 6

Templating highly robust 3D photonic crystals

S. Yang, Univ. of Pennsylvania (United States)

No abstract available.

7609-26, Session 6

Five-beam holographic fabrication of 3D photonic crystal templates using a single diffractive optical element

Y. Lin, A. Harb, K. Lozano, The Univ. of Texas-Pan American (United States); D. Xu, K. Chen, Univ. of Pittsburgh (United States)

This conference paper presents a new approach for laser holographic patterning of three-dimensional photonic lattice structures using a single diffractive optical element. The diffractive optical element is fabricated by recording gratings in a photosensitive polymer using a two-beam interference method and has four diffraction gratings oriented with four-fold symmetry around a central opening. Four first-order diffracted beams from the gratings and one non-diffracted central beam overlap and form a three-dimensional interference pattern. The phase of one side beam is delayed by inserting a thin piece of microscope glass slide into the beam. By rotating the glass slide, thus tuning the phase of the side beam, the five beam interference pattern changes from face-center tetragonal symmetry into diamond-like lattice symmetry with an optimal bandgap. Three-dimensional photonic crystal templates are recorded in a photoresist and show the phase tuning related photonic structure changes.

7609-27, Session 6

GaAs-based woodpile photonic crystal fabricated by two-directional etching method

L. Tang, T. Yoshie, Duke Univ. (United States)

A complete photonic band gap (PBG) inhibits light propagation in all directions regardless of the polarization. This likely provides a means of molding light at the level of physical limits. For example, a complete PBG can be applied to construct nanocavities with ultra-high quality (Q) factor while maintaining a small mode volume, and low-loss waveguide. These are useful for the applications, such as thresholdless lasers, nonlinear optics and 3D optics. Only three-dimensional (3D) photonic crystals can possess a complete PBG. However, the application of 3D photonic crystal is restricted because of the difficulties in precisely fabricating the structures in optical wavelength. Here, we report the fabrication of large-area woodpile photonic crystal in GaAs at 1.55µm wavelength by two-directional etching method without wafer bonding technique. A woodpile with 150x150x2 unit cells is fabricated in a two-patterning process, in which high-resolution electron beam lithography (EBL) defines 2D patterns, and then chemically assisted ion beam etching (CAIBE) provides high-aspect-ratio, anisotropic and deep GaAs etching at an

angle of 45 degree relative to the wafer surface. The two-directional etching method is simple and precise. The only alignment required in this process is performed by EBL overlay, which has a resolution of 30nm. With our designs of ultra-high-Q nanocavities by unit cell size modulation, we can construct woodpile nanocavities with active materials, such as epitaxially-grown quantum well (QW) and quantum dot (QD) layers, using the same fabrication method without wafer bonding process.

7609-28, Session 7

Optomechanical crystals

O. J. Painter, California Institute of Technology (United States)

No abstract available

7609-29, Session 7

Photonic crystal assisted high-efficiency photovoltaic generation

I. F. El-Kady, Sandia National Labs. (United States); M. F. Su, B. Farfan, M. R. Taha, The Univ. of New Mexico (United States); T. Luk, Sandia National Labs. (United States)

Photonic crystals (PhC) are artificially fabricated crystals with a periodicity in the dielectric function. This periodic electromagnetic potential in turn results in the creation of energy gaps where propagation of photons is prohibited. Fundamentally, this novel property arises from the redistribution of the photon density of states1. Many applications based on the ability to mold and control the photonic density of states have been proposed. Of particular interest is the possibility of modifying the thermal emission spectrum and funneling the emitted radiation into a narrow spectral band in contrast to the usual broad spectrum associated with a Planckian distribution in Lambertian emitters or the solar energy spectrum.

The mechanism by which PhC's limit the emission to the desired narrow band differs drastically from the usual passive filtering approach conventionally undertaken to remove emission bands that reside outside the functional band of interest. In the latter, undesired bands are simply truncated, redirected, or reflected back to the heat generating source. This scenario inevitably leads to a cap on the device efficiency governed purely by the overlap between the radiation in a Planckian spectrum and the functional band at a given temperature. In a metallic PhC, in particular one with a network topology, complete suppression of long wavelength states that lie below the PhC-gap cutoff wavelength occurs2. The photon states, as a result, are redistributed and amplified at the photonic band-edge1. This redistribution of the photon states allows us to recycle the energy that would otherwise have been emitted in non-functional bands and funnel it into the desired operational bands. This leads to the enhancement of the overall device efficiency, now capped only by the total energy emitted from the heating source. The scaling law of PhC's3 together with the topological parameters of the crystal structure, allow us to further engineer the narrow emission band to match any desired spectral band of interest.

This novel property of metallic PhC's can have a profound impact on the development of high efficiency thermal emitters essential for thermal photovoltaic energy generation4. Another application that is bound to benefit substantially is thermal scene generation for thermal sensors and seekers where captive field testing using real seekers and targets is prohibitively complex and expensive5. We present a detailed theoretical and experimental analysis of a novel thermal photovoltaic generation scheme based on the use of a metallic photonic crystal emitter. A two-fold TPV-device enhancement efficiency is observed6,7.

Alternately, for quantum dot based solar cells, energy harvesting through radiative emission instead of charge extraction may offer an alternative path to harvesting exciton energies. Through integration of a self-assembled, close packed monolayer of PbS quantum dots with a L3-type silicon photonic crystal cavity, we achieve a spontaneous emission enhancement (Purcell) factor of 116 for quantum dots emitting at 1574-nm, due to a local photonic density of states enhancement when the emission wavelength resonates with the cavity. We believe this Purcell factor, achieved with a cavity quality factor of 2860 for the L3P cavity with field polarization perpendicular to the waveguide direction, is the highest yet reported for a colloidally-derived QD device8. The key factor enabling this performance is our ability to transfer a macroscopically uniform, close-packed, 20-nm thick QD monolayer to the photonic crystal. This fabrication approach maintains direct QD contact with the cavity, achieves the highest possible QD density, and guarantees optimal coupling to the microcavity. Our results emphasize that combining top-down lithography and bottom-up self-assembly is a viable approach for advancing the nanophotonics field.

This work was supported by Sandia National Laboratories operated by the Sandia Corporation, a Lockheed Martin Co., for the U. S. DOE-NNSA under Contract No. DEAC04-94AL85000.

1. I. El-Kady, W.W. Chow, Phys. Rev. B, 72(1), (2005).

2. J. G. Fleming, S.Y. Lin, I. El-Kady, R. Biswas and K. M. Ho, Nature 417, 52-55(2002).

3. J.D. Joannopoulos, R. D. Meade, and J.N. Winn, "Molding the Flow of Light", Princeton University Press, USA, (1995).

4. S-Y Lin, J. G. Fleming. Proc. of the Opt. Soc. of Photo-Opt Instr. Eng. (SPIE), 5000, 1-7 (2003).

5. J. Caulfield; B. Burckel; G. Ten Eyck; I. El-Kady; F. McCormick; J. Curzan; M. Massie; R. Stockbridge; D. Snyder, Proceedings of the 2008 SPIE Defense and Security Symposium, Vol. 6942, March 2008.

6. G. B. Farfan, R. Rammohan, M. F. Su, I. El-Kady and M. M. Reda Taha, Photonics and Nanostructures-Fundamentals and Applications, Accepted, (2008).

7. I. El-Kady, G. B. Farfan, R. Rammohan, M. M. Reda Taha, Applied Physics Letters, 93 (15), (2008).

8. T-S. Luk, S. Xiong, B. G. Farfan, W. W. Chow, I. El-Kady, X. Miao, P. J. Resnick, M. F. Su, G. Subramania, M. R. Taha, C. J. Brinker, Nature Nano-Photonics, In Review, (2009).

7609-30, Session 7

Compact high-Q phononic crystal resonators for wireless communications and sensing applications

S. Mohammadi, A. A. Eftekhar, A. Khelif, A. Adibi, Georgia Institute of Technology (United States)

Phononic crystals (PnCs) are subwavelength mechanically-periodic structures that can strongly modify the propagation characteristics of elastic (or acoustic) waves and can lead to new type of devices with performances not obtainable using conventional bulk materials. On the other hand, micro/nano-mechanical (MM) devices are well-known for their superior performance especially at high frequencies used in wireless communication and sensing applications. High-Q MM resonators are a main building block for compact and high-performance MM devices as they can provide efficient frequency-selective devices with low insertion loss. Therefore, there has been a great interest in realizing MM resonators with higher quality factors. PnCs with phononic band gaps (PnBGs) are great candidates to be used to realize high-performance MM resonators as they can efficiently suppress the propagation of elastic waves in the medium; further, by providing mechanical support to the resonating structure, PnCs eliminate the need for separate mechanical support to the resonant mass which is a major source of loss in high-Q MM resonators.

In this presentation, we will use the PnBG of a PnC slab structure with fabricated on silicon to obtain compact MM resonators that can efficiently confine different types of modes with quality factors of more than 10,000 in air at ~130MHz. Both resonant-tunneling and direct transduction using piezoelectric films are used to interact with the resonators. Various resonator structures are designed, fabricated and tested to assess the trade offs involved in the characteristics of PnC slab resonators. Elementary devices based on PnC MM resonators are also designed and fabricated based on such high-performance MM resonators.

7609-31, Session 7

Elastic filter based on coupled resonator waveguides in phononic crystal slabs

A. Khelif, S. Mohammadi, A. Adibi, Georgia Institute of Technology (United States)

Recently, phononic band gap materials, the so-called phononic crystals, have been made possible by using periodic structure by analogy to photonic and semiconductor (or electronic) crystals. These materials allow the propagation of elastic waves to be regulated. In other words, they play the role of perfect mirrors for elastic waves in the frequency window of the band gap, i.e., forbidding elastic waves for all polarizations and directions. This area of research has received much attention because of the fundamental interest in localization of elastic energy and the vast potential applications. Among the promising prospects are acoustic devices that have been extensively used for high-frequency applications, such as radio-frequency filters for mobile phones and wireless networks in the form of surface acoustic wave (SAW) devices or thin film bulk acoustic resonators (FBARs). In this paper, we focus on employing the phononic band gap concept in the conventional acoustic systems to enhance the performance or even widen their range of applications. The coupled resonator acoustic waveguide (CRAW) structure is an illustration of the capabilities of these new materials to confine the elastic energy and enable novel functionalities through control and engineering of the dispersion of acoustic waves by only using the geometry of the phononic crystal structure.

In this paper we demonstrate experimentally the possibility of forming a new acoustic filter structure based on the CRAWs with superior performance over the conventional filters. The structures are made by etching an array of microsize holes in a silicon membrane. This phononic slab structure exhibit a complete phononic band gap. The filter is composed of several single resonators that are coupled periodically through evanescent waves due to the complete acoustic band gap of the slab. Under certain conditions, selective filter modes occur within the omnidirectional bang gap. In this case, the elastic energy is localized in the extended defect formed by the collective coupled resonators. The frequencies of the filters are sensitive to the geometrical parameter of the defect line and to the separation distance between the single resonators. The phononic crystal slab structures are made by etching a honeycomb array of microsize holes with 15 µm period in a silicon membrane. The thickness of the membrane is equal to 15 µm. This phononic slab structure exhibits a complete phononic band gap in the frequency range of (115-150 MHz). An acoustic filter based on CRAW within the band gap frequency range with excellent flat frequency response over a relative bandwidth of 10% is demonstrated.

7609-53, Poster Session

Large translation blueshift of the bandgap in the nonlinear photonic structures

L. Dekkiche, R. Naoum, Lab. of Optical Communication and Microwaves (Algeria)

Photonic crystals (PCs), an analog of semiconductors for light waves, are composite periodic dielectric materials that provide novel land unique ways control many aspects of electromagnetic radiation. Harnessing the nonlinear properties of PCs offers an opportunity to create the all-optical devices. It is shown that the negative optical Kerr effect taking place in third order can be used effectively to obtain a large blueshift of the band gap for two dimensional (2D) photonic crystals (2DPC). Since the blueshifting relies on the geometry of the 2DPC, it becomes possible to use highly nonlinear materials. The aim of this contribution is to demonstrate a highly efficient triangular lattice of circular Kerr-nonlinear dielectric rods suspended in air. The Finite Difference Time Domain (FDTD) method was used to analyze the transmission spectrum of this 2DPC. Results show a large translation (blueshift) of the band gap at wavelength between 1300 nm and 1800 nm; this is due to the nonlinearity, the incident intensity and precisely to the cell geometry. We explain how the factor of the geometry can play an important part in the reduce or the increase of the blueshift of the band gap, and we show why this kind of the 2DPC is more suited to a switching and limiting application accurately than the other one. The improvement relies on idea which originates from papers by I. S. Maksymov, L. F. Marsal, and J. Pallarés.

7609-54, Poster Session

Simultaneous two-dimensional nanometric-scale position monitoring by probing a two-dimensional photonic crystal plate

K. Hsu, C. Chen, C. Chan, National Central Univ. (Taiwan); P. Chung, Y. Lai, National Chiao Tung Univ. (Taiwan)

The recent rapid progress of nanophotonics research urgently requires the technique to control the position of objects with nanometric precision. The nanometric-scale position monitoring method in the literature mainly combines the delicate optical methods with mechanical tuning elements. Though the best achievable resolution can reach nanoscale, the above methods suffer from not only the limitation of detection length but also the lack of simultaneous two- or even three-dimensional displacement measurement in a simple setup.

In this work, simultaneous two-dimensional nanometric-scale position monitoring is achieved in a simple and cost-effective interferometric setup by real-time probing a two-dimensional hexagonal photonic crystal glass substrate. To real-time monitor the two-dimensional translational movement in nanometric-scale, an optical imaging system is built by probing a hexagonal photonic crystal glass with a 633-nm He-Ne laser beam. The translation movements in both directions are recorded in the phases of the fields of the diffracted six spots in a linear relation. By carefully aligning the two first-order spots and the zero-order spot to form chessboard-like interference pattern on the CCD camera, the individual nanometric-scale movement information can be determined by the phase change of the chessboard-like interference pattern before and after moving. In principle it can attain the nanometric-scale accuracy of position reading in both orthogonal moving directions. The minimum detectable translational movement is dependent on the period of the probed photonic crystal (1.35µm) and can be down to 20nm as demonstrated in the present work.

7609-55, Poster Session

Refraction properties of fcc and hcp SiO2-based colloidal crystals

J. C. Salcedo-Reyes, Pontificia Univ. Javeriana (Colombia)

Close-packed 3D colloidal crystals, regular arrangement of mono-disperse silica or polymer spheres with diameter within the wavelength range of visible light, show many novel optical phenomena that are strongly dependent of the sphere-packing symmetry. From both analytical and experimental results, is well known that there are two predominant ways of stacking mono-disperse spheres to minimize the interstitial volume in a colloidal crystal. One of them leads to a close packed face-centered-cubic (fcc) packing, called synthetic opal, and, the other one, to an hexagonal close packed (hcp) packing. Although computer simulations show that the fcc structure is more stable, there are a lot of papers in which a hcp phase is observed. In this work, the photonic band structure of the fcc and hcp 200nm SiO_2 based colloidal crystals are calculated using the plane wave expansion method (PWEM). A refraction-like phenomenon with an effective refractive index, due to band folding effect, has to be expected for light impinging on the [001]-direction of the 200nm hcp SiO_2-based colloidal crystal. A kinematic analysis of refraction properties of both structures is done.

 Return to Contents

7609-56, Poster Session

Tunable birefringent selectively liquid-filled photonic bandgap fibers

J. Liou, S. Huang, C. Yu, National Sun Yat-Sen Univ. (Taiwan)

By selectively filling the liquid into the PCFs cladding, we can form birefringent selectively liquid-filled PCFs. In this work, we consider three types of birefringent liquid-filled PCFs with the liquids filled in one-line air holes parallel to x-axis, two-line air holes parallel to y-axis, and three-line air holes parallel to x-axis. The birefringent properties of these liquid-filled PCFs are theoretically investigated by using the finite-difference frequency-domain (FDFD) method. The PCFs in our simulation have lattice constant 2.3 um and air-hole diameter 1.61 um, and the refractive index of the filling liquid is 1.434. The numerical results show that very high birefringence 7.1× 10-3 can be achieved at 1.55 um as the liquid infused in one-line air holes parallel to x-axis. Besides, the highly birefringent selectively liquid-filled PCFs possess tunable birefringence by varying the refractive index of the filling liquid.

To fabricate the highly birefringent selectively liquid-filled PCFs, we use polished single-mode fibers (SMFs) to selectively block the air holes of the PCFs. During the blocking process, an optical alignment technique is utilized to achieve fiber alignment between the PCF and the gel-stained SMF. The PCF is then touched with the gel-stained SMF to selectively fill the gel into the specified air holes. After the curing by UV exposure, the liquid is infused into the open air holes to form the selectively liquid-filled PCFs. By coupling the linear-polarized light into our selectively liquid-filled PCFs, the birefringence can be deduced from the measured beat length and compared with the simulation results.

7609-57, Poster Session

Loss-reduced internally liquid-filled photonic crystal fibers

J. Liu, C. Yu, National Sun Yat-Sen Univ. (Taiwan)

Photonic crystal fibers (PCFs) with air holes along the entire fiber length have attracted many research interests for their useful optical properties controlled by their geometric parameters. However, once the PCF was fabricated, these optical properties are fixed and can not be tuned. To introducing tunable optical properties into the PCF structures, one can infiltrate high-index liquids with tunable refractive indices into the PCFs. The guiding mechanism of the liquid-filled PCFs is based on the PBG effect which can be tuned by the temperature or the external electric field.

It is found that the propagation losses of the liquid-filled PCFs are highly increased due to the lossy infiltrating liquids. To efficiently reduce the losses, we propose the internally liquid-filled PCFs with air-hole layers lying outside the inner liquid-hole layers. The outer air-hole layers function as a second cladding to reduce the penetration of the light field and the inner liquid-hole layers can simultaneously maintain the tunable PBG guiding. We used polished single-mode fibers (SMFs) with an optical alignment technique to selectively block the outer air holes of the PCFs and infused the high-index liquid into the inner air holes to form the internally liquid-filled PCFs. From the measured loss spectra of variant bending radii R, it can be observed that the losses of the internally liquid-filled PCFs can be significantly reduced. Besides, our proposed internally liquid-filled PCFs are shown to be less sensitive to the bending radius than the liquid-filled PCFs with the liquid filled in all the air holes.

7609-58, Poster Session

2D periodic array of convex and concave nanostructures for the efficient SERS templates

A. Zenidaka, Y. Tanaka, T. Miyanishi, T. Sakai, M. Obara, Keio Univ. (Japan)

We present the 2D periodic array of convex and concave nanostructure for the efficient Surface Enhanced Raman Scattering (SERS) templates. A variety of templates have been studied towards biosensing applications of SERS. The templates are categorized into two types: convex and concave nanostructure. Gold particles on the gold substrate are defined as convex structure, while concave structure where empty hemispheres are buried in gold substrate, called void. The convex template shows strong field enhancement, while the concave template has the advantage of simple fabrication. The interparticle distance is a crucial parameter governing the magnitude of near-field enhancement due to the inter-particle scattering field coupling for 2D array. The SERS signal obtained on the template with the optimum distance is several ten times higher than that obtained around the contact points of the aggregated particles. This means that the investigation of the 2D periodic array effect is important for SERS templates. Thus the interparticle and inter-void distance dependence of the near-field distribution at a 532 nm pumping light is investigated. The void template also shows a unique dependence of the enhancement on the inter-void distance. With optimum distance, the SERS signal enhancement is several ten times higher than the closely-packed void template. With oblique incidence excitation, the optimum distance is shifted and several ten times higher SERS signal is obtained. Finally, the periodic arrays and random templates are compared as well. The results will provide useful design parameters for efficient unique SERS templates.

7609-60, Poster Session

Direct demonstration of photonic band-edge shift in a randomly mixed photonic crystal system

S. Kim, H. Seok, J. Lee, H. Jeon, Seoul National Univ. (Korea, Republic of)

To open a new paradigm for implementing and exploiting photonic heterostructures, the authors have proposed and demonstrated mixed PCs and band-gap shift in an analogy to mixed semiconductors and the associated band-gap engineering. In this work, we have confirmed in high accuracy the concept of mixed PCs and the resultant band structure shift by directly tracking the lasing wavelengths of two-dimensional (2D) band-edge lasers (BELs) composed by random mixing of two kinds of air-hole PCs.

To investigate the behaviour of band-edges of mixed PC with high accuracy, we employed surface-emitting PC BELs based on the gamma-point band-edge of honeycomb lattice.We fabricated the PC BELs for four different mixing compositions: x = 0, 0.33, 0.66, and 1, where x is the occupation ratio of the larger holes. For a given composition x, the positions of each type of holes were randomly chosen.

Using a micro-photoluminescence setup, the fabricated mixed PC BELs were individually excited by a 980 nm laser diode, and the resultant lasing spectra were recorded. The BELs lased at the dipole gamma-point band-edge mode for all the mixing compositions. The gamma-point band-edge monotonically shifted as the mixing ratio changed. To account for the band-edge shift, we employed the virtual crystal approximation, a semi-empirical theory originally developed for mixed semiconductors.

In this experimental study, we have provided a direct proof that photonic band-edges can be controlled with composition ratio in a mixed PC system, much alike mixed semiconductors and the associated bandgap engineering.

7609-61, Poster Session

Refractive index sensor based on fiber-coupled photonic crystal band-edge laser

S. Kim, J. Lee, H. Jeon, Seoul National Univ. (Korea, Republic of)

Over the past years, optics-based biochemical sensors have become one of the key elements in optofluidics. Photonic crystals (PCs) can offer high Q factor (or high resolution) and ability to confine light in an extremely small volume. In this study, we used a surface-emitting gamma-point PC bandedge laser (BEL) coupled to butt-end fiber in building a refractive index sensor characterized by alignment-free and high coupled output power. The key element of our setup is the surface-emitting PC BEL that takes advantage of gain enhancement at the gamma-point in the k-space so that laser emission occurs in vertical direction, which implies that laser output can be efficiently coupled to fiber.

In order to utilize the BEL as a refractive index sensor, we have designed and fabricated the BEL structure so that it lases at the first gamma-point bandedge. The device was an air-bridge type InGaAsP multiple-quantum-well slab that contained a honeycomb lattice of air-holes.

To evaluate the device's ability to detect any environmental change in a quantitative manner, several index matching liquids were used. The BEL device was immersed in the various IMLs in sequence and pumped at a fixed excitation power of 4 mW. The resultant lasing spectra are shown in Fig. 2 The lasing wavelength red-shifted systematically as nenv increased, which is consistent with theoretical prediction. From the results, our device was estimated to have the index sensitivity of 120nm/RIU (RIU: refractive index unit), which corresponds to the index resolution of ~ 10-3.

7609-62, Poster Session

Numerical investigation of photonic crystal microcavities in silicon-on-insulator waveguides

S. Burger, Konrad-Zuse-Zentrum für Informationstechnik Berlin (Germany); F. Schmidt, L. Zschiedrich, JCMwave GmbH (Germany)

Photonic crystal microcavities can strongly confine light within a small volume. High Q factors of such structures have been reported experimentally [1,2].

Fast and accurate 3D Maxwell solvers are needed for designing structural parameters.

In particular, the accurate computation of the Q factor of the resonances in 3D geometries can be numerically challenging. We have developed finite-element method (FEM) based solvers for the Maxwell eigenvalue and for the Maxwell scattering problems.

The method is based on higher order vectorial elements, adaptive unstructured grids, and on a rigorous treatment of transparent boundaries.

We have simulated experimental setups reported in the literature [1,2]. We present a convergence analysis of the numerical results, and we present good agreement with experimental results.

We further investigate the influence of structural parameters, such as placement and tilt of photonic crystal air holes, on the microcavity Q factor.

[1] P. Velha, J. C. Rodier, P. Lalanne, J. P. Hugonin, D. Peyrade, E. Picard, T. Charvolin, E. Hadji, Ultra-high-reflectivity photonic-bandgap mirrors in a ridge SOI waveguide, New J. Phys. 8, 1 (2006).

[2] A. R. M. Zain, N. P. Johnsoin, M. Sorel, R. M. De La Rue, Ultra high quality factor one dimensional photonic crystal/photonic wire micro-cavities in SOI, Opt. Expr. 16, 12084 (2008).

[3] S. Burger, L. Zschiedrich, J. Pomplun, F. Schmidt, JCMsuite - an adaptive FEM solver for precise simulations in nano-optics, in Int. Phot. and Nanophot. Res. and Appl. (OSA), ITuE4 (2008).

7609-63, Poster Session

Highly nonlinear and dispersion flattened photonic crystal fibers for medical applications

T. Kinjo, Y. Namihira, T. Koga, S. Nozaki, Univ. of the Ryukyus (Japan)

Optical coherence tomography (OCT) is an imaging technology for micron-scale cross-sectional imaging of biomedical tissue and materials. Previously, it has been currently used to ophthalmology. Currently, it is attempted to apply other fields such as skin, mucosal membrane and teeth. Now, we focus on skin or endoscopic OCT for early detection of cancer. 1.0 μm wavelength band is useful to observe the biomedical tissue. The OCT systems use low coherent light source, so it is required to use the supercontinuum (SC) light. Photonic crystal fibers (PCFs) can obtain superior properties compared with conventional optical fibers by arranging the crystal structure. The best conditions for high efficiency generation of SC light are small its effective area, zero-dispersion and single-mode operation at desired wavelength. Therefore, we designed a PCF for SC light generation at the OCT waveband. In this paper, we will report the optimum parameters and structure of the PCF.

7609-64, Poster Session

A new fitting curve method for group delay of photonic crystal fibers

S. Nozaki, Y. Namihara, K. Miyagi, T. Kinjo, Univ. of the Ryukyus (Japan)

In optical fiber, chromatic dispersion is most important properties to apply to optical communications or other applications. To obtain the chromatic dispersion, group delay has to be measured. From measured group delay, the chromatic dispersion is obtained by the use of Sellmeier's equation. The Sellmeier's equation is used as taking the fitting curve of the group delay and uses the least-square technique and based on polynomial. The order of the Sellmeier's equation depends on type of fibers. Photonic Crystal Fibers (PCFs) are new attractive fibers and its structure mainly consists of air holes and silica. The properties of the PCFs are superior to conventional fibers and will be used to various applications. However, its group delay has large nonlinearity and cannot be obtained by conventional fitting curved method such as the Sellmeier's equation. In this paper, we will report the new fitting curve method of the group delay of the PCF.

7609-65, Poster Session

Photonic band structure in a one-dimensional photonic crystal containing single-negative materials

C. Wu, National Taiwan Normal University (Taiwan)

The angle- and thickness-dependent photonic band structure in a one-dimensional photonic crystal containing the single-negative (SNG) materials is theoretically investigated. The photonic crystal is made of two alternating SNG materials, including that one has a negative permittivity (ENG) and the other has a negative permeability (MNG). It is found that there are two types of SNG gaps. In the normal incidence, the thickness-dependent gap map is successfully analyzed by using the composite right-and-left hand (CRLH) transmission line model. In the oblique incidence, we find that the second SNG gap is strongly dependent on the incident angle for both TE and transversal magnetic (TM) waves. It will close at the zero bandgap frequency when the impedance match and the phase match in the constituent ENG and MNG layers are simultaneously satisfied. The inclusion of the loss enables us to further clarify two fundamentally distinct second SNG gaps which are separated by a threshold angle of incidence.

Return to Contents

7609-66, Poster Session

Negative refraction of Rayleigh waves through 2-D phononic crystals

B. Bonello, L. Belliard, J. Pierre, O. Boyko, Univ. Pierre et Marie Curie (France)

As for the photonic crystals which are their optical counterpart, unusual effects related both to the opening of forbidden band gaps and to the subsequent folding of the dispersion curves, are expected to occur in the phononic crystals (PC's). Among these, the refraction of an elastic wave impinging on a PC is probably one of the most topical issues for the physicists studying the dynamic behavior of elastic periodic structures. Indeed, it is now well established that under certain conditions, the refracted beam propagates along a direction lying within the same half space as the incident acoustic beam, leading to negative refraction. This effect has recently been observed with longitudinal bulk acoustic waves [1] but not yet with surface acoustic waves (SAW's). Our goal in this work was to experimentally investigate under which conditions Rayleigh waves can also undergo negative refraction.

To this end, we have elaborated samples with a spatial periodicity of a few micrometers consisting of a periodic lattice of holes drilled into silica substrates. The lattice of holes had the squared symmetry and the filling ratio was around 0.75. The refraction at frequencies around 1 GHz was investigated using the picosecond ultrasonic technique: SAW's were excited by illuminating the surface of the sample with an ultrashort laser pulse. The normal component of the deformation field was detected, using a stabilized Michelson interferometer, in an area lying a few mm apart from the excitation area, after the waves have travelled through the PC. We have detected elastic energy in the negative refraction zone of the sample that we attribute to the refraction of the first folded branch of the dispersion curve. These experimental findings are then compared to theoretical predictions.

[1] A. Sukhovich, L. Jing, and J. Page, Phys. Rev. B 77, 014301 (2008).

7609-32, Session 8

Recent applications of photonic crystal fibers

P. S. J. Russell, The International Max-Planck Research School for Optics and Imaging (Germany)

No abstract available.

7609-33, Session 8

Double bandgap hollow-core photonic crystal fiber

F. A. Benabid, F. Couny, P. S. Light, Univ. of Bath (United Kingdom)

We used the photonic tight-binding model to explain the guidance mechanism in photonic bandgap hollow-core photonic crystal fiber and to design, fabricate and characterize a novel hollow-core photonic crystal fiber that exhibits two robust bandgaps and a record air-filling fraction of 97%. The two bandgaps bridge the benchmark laser wavelengths of 1064nm and 1550nm and can be scaled to allow guidance of the other benchmarks of laser wavelength pairs such as 1μm and 800nm, or 800nm and 633nm. The higher-order bandgap arises due to the extremely thin struts of the silica cladding and their fine-tuning relative to the apex size.

7609-34, Session 8

The high nonlinear photonic crystal fiber with high relative index core for dental OCT applications

T. Koga, Y. Namihira, T. Kinjo, S. Nozaki, Univ. of the Ryukyus (Japan)

Optical coherent tomography(OCT) is a technology that supplies the tomographic image by using the optical interference. Recently, the use of 1.31μm wavelength is attempted for dental applications. There are some problems for improvement of the OCT technology. One of them is to improve its resolution. In order to improve the resolution, to use of the supercontinuum(SC) light source is attractive approach since low coherent light can be obtained from wide frequency band. Photonic Crystal Fibers(PCFs) can generate the SC light. The desired conditions for the SC light generation by using the PCF are zero or nearly zero dispersion and small effective area at 1.31μm wavelength. In this study, we will propose high nonlinear PCF to generate SC light in 1.31μm efficiently. The validity of the proposed method will be demonstrated by computer simulations. In the computer simulation, the finite difference method(FDM) was used.

7609-35, Session 8

Long-period fiber gratings based on liquid-filled photonic crystal fibers

C. Chen, C. Yu, National Sun Yat-Sen Univ. (Taiwan)

Photonic crystal fibers (PCFs) with an air-hole array in the fiber cladding are one of the most successful applications based on photonic crystals. They have attracted many research interests for their wide single-mode frequency range, large mode area, high nonlinearity within a small core, and large birefringence by appreciate arrangement of air holes. In previous studies, PCF-based long-period fiber gratings are proposed. The periodic perturbations are fabricated by using lasers or fusion slicers. However, geometry damage in the core of PCFs may appear during the fabrication.

In this work, we propose long-period fiber gratings based on liquid-filled PCFs. The PCF we used is LMA 8, and the lattice constant and air-hole diameter are 5.6 um and 2.7 um, respectively. Using the vacuum pump system, we can successfully infuse the UV-gel into the air holes of the PCFs. After the exposure of UV-light with weighting masks, some regions of the PCF cladding are solidified and the refractive index is changed to form the periodic perturbation. From the optical microscopy images, we can clearly observe the gratings. Our fabricated long-period PCF gratings possess periods of 600 um, 700 um, and 800 um. From the measured output spectra, several deeps due to the coupling between the core modes to the cladding modes can be observed in the transmission bands. By varying the temperature, the influences of the temperature on our long-period PCF gratings are discussed.

7609-36, Session 8

As3S2 suspended core microstructured optical fibers for mid-IR supercontinuum generation: modeling and experimental results

G. Renversez, Univ. d'Aix-Marseille (France); M. Szpulak, Wroclaw Univ. of Technology (Poland); M. El-Amraoui, J. Jules, G. Gadret, Univ. de Bourgogne (France); L. Brilland, J. Troles, Univ. de Rennes 1 (France); I. Skripatchev, C. Polacchini, Y. Messadeq, State Univ. of São Paulo (Brazil); F. Smektala, Univ. de Bourgogne (France)

Supercontinuum generation is one of the key application of microstructured optical fibers (MOFs).

Several noticeable results have already been obtained from silica but its high material losses above 3.14 µm makes it not useful above this wavelentgh. Other glasses like bismuth or tellurite ones have already been used as MOF matrix, ensuring extended supercontinuum thanks to a zero dispersion wavelength below 1.55 µm and to powerful sources. ZBLAN fluoride conventional fibers have also been used to generate power mid-IR supercontinuum nevertheless in this last case, the long wavelength edge of the spectrum is limited by the glass absorption.

In our case, we report the use of the first suspended core low loss highly nonlinear As2S3 MOF.

We present the fabrication and optical characterization of this suspended core chalcogenide MOF. We use an alternative process to the stack-and-draw technique in order to minimize the overall losses. The loss level is below the one we get previously for small core chalcogenide MOFs using a two-step stack-and draw procedure. The MOF cross section have been designed to shift downward the zero dispersion wavelength using a strongly positive waveguide dispersion. We pump the fiber slightly above 2 µm with 100 fs pulses. We compare the experimental spectrums with our numerical simulations obtained using the nonlinear Schrödinger equation. When coupled in the MOF, these pulses result in a supercontinuum bandwidth of around 3.5 µm range. We describe the influence of the injected peak power and of the MOF length on the spectrum.

7609-37, Session 9

Chalcogenide glass photonic crystals: progress and prospects

C. Grillet, B. J. Eggleton, M. W. Lee, The Univ. of Sydney (Australia); X. Gai, S. J. Madden, The Australian National Univ. (Australia); C. Monat, S. Tomljenovic-Hanic, E. C. Mägi, D. J. Moss, The Univ. of Sydney (Australia); D. Choi, D. Bulla, B. Luther-Davies, The Australian National Univ. (Australia)

No abstract available.

7609-38, Session 9

Photonic crystal optofluidics for electrochromatography on a chip

M. Haque, N. Zacharia, T. Rafique, S. Ho, L. E. Abolghasemi, P. R. Herman, Univ. of Toronto (Canada)

Three dimensional (3D) photonic crystals (PC) present a novel medium at the interface of optofluidics for exploiting ordered nano-structures for both chromatography and optical sensing cytometry. An integrated PC sensor promises new functionality in micro-total-analysis-systems (µ-TAS) such as label-free molecular tagging of analytes and rapid, in-situ optical detection without chemical alterations. In this paper, we present 3D-photonic crystals integrated within microfluidic channels that demonstrate two benefits for lab-on-a-chip devices: (1) improved analyte separation through the periodically ordered nano-structured medium based on capillary electrochromatography (CEC) and (2) real time optical sensing of the PC stop bands as they shift with the separation of the mobile phase.

Open microfluidic channels (Micralyne unbounded MC-BF4-SC baseplate) were filled with a negative photoresist (SU-8 2050) and exposed with a focused Yb-fiber amplified femtosecond laser (IMRA FCPA µJewel, 100 kHz, = 522 nm) for direct laser writing of a porous 3D woodpile-type PC. A thin silica coating was deposited by chemical vapor deposition (CVD) to improve bio-compatibility and surface functionality for electroosmotic flow (EOF). Enhancement of electrophoretic separation of various analytes by the embedded PC column was analyzed by fluorescence excitation recordings and contrasted with the shifting photonic stop bands recorded via laser-written optical waveguides.

Progress on optimizing the PC design for both high efficacy CEC and bandgap-based optical sensing will be presented.

7609-39, Session 9

Photonic crystal switching by the electrophoretic movement of dye ions

J. D. Krabbe, Univ. of Alberta (Canada); M. J. Brett, Univ. of Alberta (Canada) and National Institute for Nanotechnology (Canada)

Glancing angle deposition (GLAD) facilitates the fabrication of nanostructured thin films with varying density. A motion control algorithm governs the movements of the substrate during film growth, engineering the structure of a film with nanometer precision. Film architectures for specific optical applications including photonic crystals (PCs) are easily produced with GLAD. 1D PCs such as rugate-filters as well as 3D PCs composed of square spirals structures have been fabricated using GLAD.

A challenge in the PC field has been the realization of in-situ control of optical characteristics such as bandgap center wavelength and depth for switching applications. Such switching can be achieved by inducing changes in lattice dimension and/or refractive index contrast, ideally though an electromagnetic mechanism. Mechanical stretching of polymer PCs and PC infiltration with mixed liquids have achieved measured success.

We have demonstrated partial control of stopband optical characteristics in a GLAD film using the electrophoretic movement of absorbing dye ions. TiO2 deposited by GLAD on an ITO coated glass substrate is infiltrated with a methylene-blue dye solution; an ITO counter electrode completes the cell. The presence of dye ions in different positions through the film modifies the PC's characteristic spectrum and is controlled by an electric field. In this paper, the development of the technique will be presented as well as a discussion of the parameters governing the effectiveness of this device for spectral control.

7609-40, Session 9

Structural color printing: full color printing with single ink

H. Kim, Seoul National Univ. (Korea, Republic of); J. Ge, Univ. of California, Riverside (United States); J. Kim, S. Choi, H. Lee, H. Lee, W. Park, Seoul National Univ. (Korea, Republic of); Y. Yin, Univ. of California, Riverside (United States); S. Kwon, Seoul National Univ. (Korea, Republic of)

Many creatures in nature, such as butterflies and peacocks display unique brilliant colors, known as “structural colors”, which result from the light interaction with periodic nanostructures on their surface. Unlike chemical dyes, structural color originating from the physical structures shows iridescent, metallic, and free from photobleaching. Mimicking such nanostructures found in nature, however, requires state-of-the-art nanofabrication techniques that are expensive and not scalable. Especially, productions of multicolors and high resolution patterning of such structures were hard to achieve. Here in this report, we demonstrate high resolution patterning of multiple structural colors within seconds, based on successive tuning and fixing of color using a single material along with a special instrumentation. Also, we demonstrate flexible photonic crystal for a realizable possibility of structural color printing using a single material. With the superior simplicity, controllability, and scalability, our structural color printing scheme is believed to show realizable possibilities of full color printing with single material.

Material system we developed here is three-phase system, M-Ink, which is composed of superparamagnetic colloidal nanocrystal clusters (CNCs), solvation liquid, and photocurable resin. Under external magnetic field, the superparamagnetic CNCs are assembled to form chain-like structures along the magnetic field lines. Attractive magnetic force due to the superparamagnetic core is balanced with repulsive electrostatic

and solvation force, both of which determine the inter-particle distance. The inter-particle distance in a chain determines the diffracted color from the chain. Thus, the color can be tuned by simply varying the interparticle distance using external magnetic fields. Once the desired color is obtained, it can be fixed by solidifying the photocurable resin through instantaneous UV exposure with spatial light modulator. The particle chains can be frozen in the solidified polymer network without distorting its periodic arrangements, thus retaining the structural color. High resolution patterning of structural color with single material was demonstrated by sequential process involving cooperative actions of magnetic field modulation and spatially controlled UV exposure. Fast production (<100ms) of structural color and high resolution color patterning (~10μm, 1500DPI) was achieved. For the proof-of-concept demonstration, we reproduced Mona-Lisa by structural color printing. Unique optical characteristic dependent on incident angle and direction of chain was investigated using generalized Mie theory and finite element analysis based near-field calculation. We believe that the M-Ink based system opens a door to the wide use of structural color for various potential applications including design material and color printing.

7609-41, Session 9

Photonic crystal filter integrated with photodiodes

C. Chen, W. Chiu, National Central Univ. (Taiwan)

We demonstrate the monolithic integration of photonic crystal waveguides, a photonic crystal demultiplexer, a conventional waveguide and photodiodes. InGaAsP-based materials are chosen for the fabrication of the device to obtain high absorption efficiency at the operating wavelengths. The refractive index of the guiding material is designed to be higher than that of the cladding layer to obtain the vertical confinement in the input/output conventional slab waveguides. For the photodiodes, the partially p-doped photo-absorption layer is adopted to accelerate the diffusion of the electron form absorption layer to the depletion layer. The photonic crystal demultiplexer consists of hexagonally arranged air holes. The inputted light at the wavelengths of 1530nm and 1550nm can be separated by the demultiplexing system. The operation speed can be upto 22GHz.

7609-42, Session 10

Wide bandwidth photonic crystal waveguide bends

M. Askari, A. Adibi, Georgia Institute of Technology (United States)

We present experimental demonstration of very high efficiency wide bandwidth Photonic Crystal Waveguide bends. We show that by careful modification of the bend region we can improve transmission bandwidth by 45 nm or 60% of total guiding bandwidth of a simple bend with no modification to the bend region. We also show that our design performs much better than other experimentally reported results.

7609-43, Session 10

Implementation scheme for phase switching through quantum dots in slow-light photonic crystal waveguide

J. Gao, C. W. Wong, Columbia Univ. (United States)

Cavity-dipole system has been well discussed in quantum optics and quantum information processing but with typical limitations such as narrow operation bandwidth, inefficient photon extraction, scalability and integrability. Here we present an implementation scheme for phase switching in slow-light photonic crystal waveguide system with two properly located semiconductor quantum dots. The system show dipole induced transparency and large dispersion without high Q cavity assistance. Large Purcell factor and   -factor in photonic crystal waveguide contributes to the high reflectance and sharp dispersion. Tight optical confinement and slow light mode in the waveguide provide large interactions between Quantum dot and the propagation mode, which generates very strong optical nonlinearities. Optically shifting the dipole resonance can be created by a small number of stark filed photons, or even a single photon in this system. A full π phase switching can be achieved with proper design of a hetero-photonic crystal structure. It shows that we can drive the system on resonance but without suffering from large loss and the reflection is always 80% or more. Compared to cavity-assisted schemes, excitation and extraction can be extremely efficient and chip-scale integration is possible. Also it is much easier to realize the frequency match condition between the central frequency of two quantum dots and waveguide mode because photonic crystal waveguide slow-light mode has relatively broad frequency region than high Q cavities. All these advantages show QD-photonic crystal waveguide system is very promising to be a critical component in quantum information processing.

7609-44, Session 10

Low-dispersion slow-light in silicon-on-insulator slot photonic crystal waveguide

A. Hosseini, R. T. Chen, H. Subbaraman, D. N. Kwong, The Univ. of Texas at Austin (United States)

A slow group velocity and low group velocity dispersion photonic crystal slab waveguide is designed on a silicon-on-insulator substrate. We show that based on the high light-confinement provided by the slot waveguide inside the line-defect photonic crystal waveguide, the band corresponding to the even fundamental mode is pushed below the silicon dioxide light line. Therefore, the useful part of the band and consequently, the slow-down factor [SF= (normalized bandwidth) X(group index)] increases. Theoretical studies using three-dimensional Plane Wave Expansion simulations show that by adjusting the inner hole sizes, we can achieve nearly flat band photonic crystal waveguides with SF>0.35 which shows over 10% improvement over air-bridged photonic crystal waveguide structures. The silicon-on-insulator structure is advantageous over the air-bridged structures in terms of fabrication, stability and possible 3D stacking. The total design includes, tapered photonic crystal waveguide and mode conversion sections. Pictures of the fabricated samples and the measurement results will be included in the final submission.

7609-45, Session 10

Compact couplers for overmoded three-dimensional photonic crystal waveguides

B. Cowan, M. Lin, Tech-X Corp. (United States); C. McGuinness, E. R. Colby, R. J. England, R. J. Noble, J. E. Spencer, SLAC National Accelerator Lab. (United States); R. L. Byer, Stanford Univ. (United States)

A photonic crystal waveguide based on the three-dimensional woodpile lattice has been proposed for a high-energy charged particle accelerator. Critical to overall accelerator efficiency is the ability to couple power into the accelerating waveguide with high transmission in a very small volume. In addition, this coupling must be achieved without interrupting the vacuum-core waveguide, as any material will result in particle beam scattering. Another inherent challenge is that while the accelerating waveguide supports several modes, only one particular mode, propagating in the forward direction, can drive a particle beam. We present designs and simulations of high-efficiency coupling to a vacuum-core waveguide from a waveguide adjoining it at 90 degrees. The designs were carried out using high-performance, parallel, 3D simulations of the coupling structure. An optimization routine was developed to

analyze the simulation data to compute the coupling efficiency, and modify the geometric parameters of the coupler for the subsequent iteration. We present details of the simulation and optimization routine, and the resulting transmission through the coupler. In addition, we discuss estimates of the fabrication tolerance for these devices. Some background material on laser-driven acceleration in photonic crystal structures is also covered.

7609-46, Session 11

Metamaterial-inspired high-absorption surfaces for thermal infrared applications

D. W. Peters, P. Davids, J. R. Wendt, A. A. Cruz-Cabrera, S. Samora, Sandia National Labs. (United States)

We present design, fabrication, and characterization results of a highly absorptive thin surface in the thermal infrared that draws on concepts from the frequency selective surface and metamaterials communities. These surfaces show promise for thermal infrared applications such as detectors and emission control. These surfaces exhibit high absorption over a broad angular range. The surface is optically-thin: roughly a quarter wavelength in thickness. The simple structure is composed of a reflective metal layer, a layer of lossy dielectric, and a top metal layer that is patterned with an array of subwavelength apertures. The design of the aperture allows spectral and angular control of the absorption band.

The apertures in the upper metal layer produce surface waves bound to the metal surface. These surface waves have much stronger electric field strengths than does the incident radiation, facilitating high absorption in a thin layer of dielectric such as silicon dioxide or silicon nitride. We will present rigorous coupled wave analysis and FDTD simulation results that illustrate the absorption of the incident radiation and the design parameters that affect the structure's performance. We will also show measured data showing absorption as a function of wavelength and angle.

7609-48, Session 11

Propagation loss analysis in photonic crystal waveguides using a complex-band technique

C. M. Reinke, A. A. Eftekhar, B. Momeni, A. Adibi, Georgia Institute of Technology (United States); X. Zhang, Oak Ridge National Lab. (United States)

We present a semi-analytical Green's function-based technique for analyzing propagation loss in photonic crystal waveguides (PCWGs). The method only requires the complex band structure of the PCWG to calculate the transmission (or loss) of the structure. The plane-wave expansion method was used in this work to calculate the complex band behavior, and the power of this technique is demonstrated by comparing the results with the brute force simulation results for a PCWG. The possibility of extending this technique to the more practical arrangement of a random distribution of defects using a configurational average with coherent potential approximation theory will also be discussed.

7609-49, Session 11

A stable semi-analytical method for analysis of plasmonic propagation on periodically patterned metallic thin films

N. Yasrebi, S. Khorasani, H. Karami Taheri, B. Rashidian, Sharif Univ. of Technology (Iran, Islamic Republic of)

The need for antennas with improved characteristics for communication and radar applications has resulted in an ever-increasing demand for research in the field of high impedance surfaces, which can work as an artificial magnetic conductor. One method in fabrication of these surfaces is formation of a metamaterial by patterning a metallic surface in the shape of space filling curves (e.g. Hilbert or Peanu Curves). In this paper, we present a novel semi-analytical solution to the problem of plasmonic propagation on these surfaces. The method is based on a previously presented Green's function formalism [1]. We have modified and improved the method for analysis of periodic structures with a large number of spatial harmonics, and used different methods to get the necessary stabilization. Here propagating modes of different structures and their corresponding frequencies are calculated, and the possibility of frequency gap formation and stability of the method are investigated.

[1] H. Zandi, A. Hosseini, S. Khorasani, K. Mehrany, B. Rashidian, and A. Adibi, "Plasmonic Propagation Modes of a Structured Two-dimensional Conducting Interface," Journal of Optics A: Pure and Applied Optics, vol. 10, no. 2, 025202 (2008).

7609-50, Session 11

Surface modes of 1D photonic crystals in the regime of transmission and guidance

N. Malkova, S. Polyakov, A. Migdall, G. W. Bryant, National Institute of Standards and Technology (United States)

Existence of surface modes in electromagnetic spectrum of active photonic structures considerably affects the properties of photonic devices. Therefore understanding of underlying physics which governs basic properties of the surface modes in photonic structures is highly desirable. We investigate theoretically and experimentally transmission and guiding of electromagnetic waves through finite 1D photonic crystals (multilayer stacks). We analyze the dependence of transmittance and density of modes on termination of the structure, propagation constant, and spacing between high index layers. We focus on surface modes that fall inside stop bands and localized at the surface layer. When decreasing the propagation constant we follow the evolution of these modes from guided surface modes till transmitting surface resonances where they evident through the traversal time delay. We show that the surface modes are supported in structures terminated with the high index layer (lower index layer) in the guiding mode (transmission) regime. Through detail analysis we show that these modes can be classified as Tamm-like surface modes known in solids. Our theoretical predictions correlate with experimental observations.

7609-51, Session 11

Influence of asymmetry on the band structure of photonic crystals

S. Khorasani, S. H. Mousavi Mehr, Sharif Univ. of Technology (Iran, Islamic Republic of)

To study the band structure of a photonic crystal, it generally suffices to consider the irreducible zone inside the first Brillouin zone: a small area around the origin in k-space. This simplification is taken a step further in most computer simulations, whether frequency-domain or time-domain, when the boundary of the irreducible Brillouin zone is examined for photonic band gaps instead of the Brillouin zone itself . Luckily, and seemingly with little rationale, the band gap always ends up on the boundary, where the degeneracy is broken due to periodic perturbations of the medium, saving us the trouble of looking at samples on the whole k-space.

This work seeks to show that the above phenomenon relies crucially on unit cell symmetry. Through computer simulations using the MIT Photonic Bands (MPB) package, along with a few in-house automation scripts, we show that one could miss the band gap in low-symmetry unit cells if the search is restricted to the boundary. As proof of the concept, two rectangular lattices, one high-symmetry and one low-symmetry, are tested, with band structure data collected over both the Brillouin zone and its boundary. Comparisons show that the boundary alone gives suboptimal results in the low-symmetry case, i.e, band gaps according to the whole Brillouin zone are noticeably smaller than those according to its boundary.

Proceeding further, we aim to identify those essential symmetry elements which guarantee that the simpler method of looking at the boundary gives correct band gap energies. Brief treatment also is given to direct transitions and the possibility of engineering band gap location.

7609-52, Session 11

Ultracompact wave plates by air holes periodic dielectric waveguides

W. Zhang, Xi'an Institute of Optics and Precision Mechanics (China); J. Liu, Xi'an Institute of Post and Telecommunications (China); W. Huang, McMaster Univ. (Canada); W. Zhao, Xi'an Institute of Optics and Precision Mechanics (China)

Ultracompact wave plates (UWPs) will be one of the key elements in future all-optical photonic integrated circuits (PICs). In this paper, we demonstrate the UWPs based on periodic dielectric waveguides (PDWs) with air holes in conventional dielectric waveguides. The mode characteristics (for both TE and TM) and birefringence of PDWs are calculated by plane wave method (PWM). The transmission efficiencies and phase changing of TE and TM wave in PDW are obtained by finite-difference time-domain (FDTD) scheme. Based on the PDWs, the quarter-wave plates (QWPs) and half-wave plates (HWPs) are designed. Calculating results show that the proposed PDW has large birefringence ($\Delta n>1$) and can introduce 2π phase difference in a short length being less than . The size of low order UWPs are compact. Profiting from the waveguide guiding, the UWPs have low beam divergence and can be easily integrated with other photonic components. The UWPs have many potential applications in future PIC systems such as optical communications, optical measurements and sensors.

Conference 7610: Quantum Dots and Nanostructures: Synthesis, Characterization, and Modeling VII

Sunday-Wednesday 24-27 January 2010 • Part of Proceedings of SPIE Vol. 7610

Quantum Dots and Nanostructures: Synthesis, Characterization, and Modeling VII

7610-01, Session 1

Quantum dot to high mobility charge carrier channel nonradiative resonant energy transfer: a new paradigm for solar energy conversion

A. Madhukar, S. Lu, The Univ. of Southern California (United States)

No abstract available.

7610-02, Session 1

Exciton transfer for light harvesting and light emitting applications

P. G. Lagoudakis, Univ. of Southampton (United Kingdom)

The brightness, large absorption cross-section and flexibility of organic semiconductors and colloidal nanocrystal quantum-dots (NQDs) renders them promising new materials for light harvesting and light emitting applications. However, both material systems are plagued by low-charge-transfer efficiency that limits the overall power conversion efficiency of these materials in photovoltaic devices (PVs) when compared to silicon-based or epitaxial p-n junction PVs, and epitaxial light emitting diodes (LEDs). A route to circumvent altogether issues associated to low charge transfer in organic semiconductors and NQDs is to engineer devices that utilise alternative pumping schemes to electrical injection and transport while benefiting from the large oscillator strength of these materials. In nature, funnelling of energy between different chromophores predominantly occurs through a nonradiative dipole-dipole coupling mechanism, first studied by Förster, that does not involve charge transfer or emission and absorption of photons between donor and acceptor and that can exceed the radiative energy transfer routinely used in phosphor light emitting devices. Here I will present recent advances in the field of hybrid optoelectronics where nonradiative energy transfer is used to combine the high carrier mobility of single crystal inorganic semiconductor heterostructures and the versatility offered by organic materials and colloidal NQDs both in light harvesting and light emitting applications [1-5].

[1] Stefan Rohrmoser, Julia Baldauf, Sameer Sapra, Alexander Eychmüller, Ian M. Watson, Richard T. Harley and Pavlos G. Lagoudakis, Appl. Phys. Lett. 91, 092126 (2007).

[2] S. Chanyawadee, P.G. Lagoudakis, R.T. Harley, D.G. Lidzey, M. Henini, Phys. Rev. B 77, 193402 (2008).

[3] S. Chanyawadee, R. T. Harley, M. Henini, D. V. Talapin, and P. G. Lagoudakis, Phys. Rev. Lett. 102, 077402 (2009).

[4] Soontorn Chanyawadee, Richard T. Harley, David Taylor, Mohamed Henini, Andrei S. Susha, Andrey L. Rogach, and Pavlos G. Lagoudakis, Appl. Phys. Lett. 94, 233502 (2009).

[5] S. Chanyawadee, P. G. Lagoudakis, Richard T. Harley, Martin D. B. Charlton, Dmitri V. Talapin, and Sean Lin, arXiv:0907.5072v1 [cond-mat. other] (2009).

7610-03, Session 1

Nonradiative energy transfer to colloidal nanocrystal quantum dots

J. Xu, The Pennsylvania State Univ. (United States)

No abstract available.

7610-04, Session 1

Numerical evidence of phonon memory effect in PbSe and CdSe quantum dots: ab initio and model calculations of carrier relaxation

D. S. Kilin, Univ. of Florida (United States)

The relaxation rate in a photo-excited semiconductor quantum dots is considered from a numerical and analytical perspective. We focus on the time-resolved dynamics of average excitation energy in PbSe and CdSe quantum dots. The density functional theory in a time domain is applied to simulate the time-resolved atomistic relaxation dynamics of charge carriers and average excitation energy for modeling semiconductor systems. From analytical point of view, the Heisenberg equations of motion for conventional electron and phonon operators are used to calculate the time-dependence of the average excitation energy evolving between initially prepared excitations. For PbSe and CdSe materials the ab-initio simulated relaxation of average excitation energy is found to have a complex, non-exponential character. The transition of electron-phonon interaction from a dynamical regime to a delta correlated regime occurs at earlier instant of time for CdSe quantum dots in respect to PbSe quantum dots and illustrates faster loss of coherence in CdSe in respect to PbSe. The analytically calculated evolution of the average excitation energy shows qualitative correspondence to the results of surface hopping non-adiabatic dynamics averaged over multiple molecular dynamics trajectories. This provides physical insight regarding mechanism and size-dependence of the phonon-assisted relaxation in semiconductor quantum dots.

7610-05, Session 1

Effect of surface states on excitons in HgS dots

N. Malkova, G. Bryant, National Institute of Standards and Technology (United States)

HgS quantum dots (QD) are very attractive both for fundamental interest in quantum confinement effects in QDs with negative (inverted) band gap and for their promising applicability in tunable IR devices. In the strong confinement regime, the spectrum of HgS QDs changes from negative-gap through the gapless state to positive-gap with decreasing size. Furthermore, intrinsic surface states (which are not caused by the dangling bonds) appear under the negative-gap - positive-gap transition.

It is the goal of this work to investigate the evolution of the optical response of the HgS QDs with decreasing size. We identify how states evolve from a negative gap to a positive gap as the confinement is increased. We determine the origin of the surface states and analyze their effect on optical response of the HgS QDs. We first study the single-particle spectrum in the empirical tight-binding model and use these states to determine the exciton states by incorporating Coulomb and exchange interaction. We investigate the Coulomb shift, exchange splitting. We finally calculate the optical response of the QDs as a function of size. We demonstrate non monotonic behavior on size of the

lowest optical excitations. We correlate this effect with negative gap - positive gap transition followed by appearance of the surface states.

7610-06, Session 2

Quantum dot sensitized solar cells

X. Sun, Nanyang Technological Univ. (Singapore)

Abstract not in yet.

7610-07, Session 2

Energy transfer and plasmon-exciton interaction in hybrid organic/inorganic nanocomposites

T. Stöferle, G. Raino, IBM Zürich Research Lab. (Switzerland); H. Kim, IBM Almaden Research Ctr. (United States); R. F. Mahrt, IBM Zürich Research Lab. (Switzerland)

The integration of optical components at the chip level demands for novel device concepts and material systems. Hybrid organic/inorganic materials are expected to exhibit large optical nonlinearities which could become essential in realizing fast all-optical switches. We present a study on the underlying electronic energy transfer processes in a model system constituting of an amorphous polyfluorene donor and an inorganic nanocrystal acceptor. Furthermore, we report on first results of plasmon-exciton interaction in order to tailor the optical properties of hybrid nanocomposites.

7610-08, Session 2

Luminescent thiol capped colloidal PbTe quantum dots synthesized using laser ablation

D. Burigo Almeida, E. Rodriguez, A. A. de Thomaz, L. C. Barbosa, Univ. Estadual de Campinas (Brazil); E. Villar Jiménez, Univ. de València (Spain); C. Lenz Cesar, Univ. Estadual de Campinas (Brazil)

Semiconductor colloidal quantum dots (QDs) have attracted great attention during past years because of their physical and chemical properties. For this reason, several techniques, both chemical and physical, have been developed to obtain QDs of many different materials and properties. Among them, there is the laser ablation in liquid media. However, in general, QDs obtained with this technique had null or quenched photoluminescence. One of the causes for this effect is the presence of dangling bonds on the nanocrystals surface. This could be attenuated by introducing thiol molecules adsorbed to the QDs surface providing more stability and photoefficiency. In this work we obtained thiol capped PbTe luminescent colloidal QDs using a novel technique, based on laser ablation. These QDs were produced by hitting a PbTe target, immerse in a liquid solution of 3-mercaptopropyltrimethoxysilane (MPS) or thiol, with nanosecond and femtosecond lasers. The colloid photoluminescence as well as other optical and structural properties were studied.

7610-09, Session 3

InGaAsSb quantum dots

A. G. Taboada, J. M. Ripalda, D. Alonso-Álvarez, B. Alén, A. Rivera, J. M. Llorens, J. Martin-Sanchez, J. M. García, Y. Gonzalez, L. Gonzalez, Instituto de Microelectrónica de Madrid (Spain); A. M. Sánchez, A. M. Beltrán, D. L. Sales, T. Ben, P. L. Galindo, S. I. Molina, Univ. de Cádiz (Spain); R. Kudrawiec, M. Syperek, J. Misiewicz, Wroclaw Univ. of Technology (Poland); M. Bozkurt, J. M. M. Ulloa, P. M. Koenraad, Technische Univ. Eindhoven (Netherlands)

Almost invariably, III-V semiconductor quantum dots (QD) are nucleated by deposition of either indium or antimony. Indium compounds, particularly InAs quantum dots, have received much more attention than the antimonides. Deposition of both In and Sb on a GaAs substrate results in complex quaternary nanostructures opening new opportunities to tune the properties of III-V self assembled QDs. We have studied the deposition of GaSb, GaAsSb, and pure Sb; before, during, and after InAs QD nucleation. We have found that the effects of Sb on the atomic and electronic structure of InAs QDs are drastically different depending on how and at what stage Sb is incorporated.

To characterize the effects of Sb on InAs QDs, we have used a large set of experimental techniques, such as tunnel microscopy, in situ stress measurements, electron diffraction, transmission electron microscopy and spectroscopy, atomic force microscopy, micro and macro luminescence at high magnetic fields, time resolved photoluminescence, photocurrent, and capacitance vs. voltage spectroscopy.

We have found that Sb incorporation, depending on the deposition conditions, can lead to luminescence redshifts to wavelengths above 1.6 µm,[1] or blueshifts of up to 100 meV. The room temperature luminescence, under specific growth conditions, can increase by an order of magnitude in comparison with reference InAs QDs, or decrease by several orders of magnitude if the growth conditions are not optimized. Lately we have focused our efforts on optimizing the room temperature luminescence at 1.3 µm. Our best results have been obtained by exposing the InAs QDs to Sb immediately before capping with GaAs. We have obtained an order of magnitude enhancement of the room temperature luminescence intensity and simultaneously redshifted the emission from 1260 nm up to 1370 nm [2], while in the QD literature, redshifts have most often been obtained at the expense of the luminescence intensity.

The focus of our research effort has recently shifted to understanding the causes of the observed changes in the optical and electronic properties. RHEED observations during sample capping [2] and TEM after sample growth, clearly indicate that Sb helps to preserve the size of the QDs during capping. Evidence of Sb incorporation inside the QDs has also been found [3], but quantification of the effect of Sb incorporation on the electronic structure of the QDs is still work in progress.

Figure 1 (unable to include here)

Room temperature photoluminescence corresponding to (a) InAs QDs, (b) QDs exposed to Sb, (c) QDs capped with a 2ML GaSb layer. (d) InAs QDs exposed to Sb, capped with a 3 ML GaAs barrier and then a 2 ML GaSb layer.

References

[1] J. M. Ripalda, et al, Applied Physics Letters 87, 202108 (2005).

[2] J. M. Ripalda, et al., Applied Physics Letters 91, 012111 (2007).

[3] S. I. Molina, et. al., Applied Physics Letters 91, 263105 (2007).

7610-10, Session 3

Capping effect of GaAsSb and InGaAsSb on the optical properties of type II GaSb/GaAs quantum dots

J. He, C. J. Reyner, A. T. Lin, K. Nunna, B. Liang, D. L. Huffaker, Univ. of California, Los Angeles (United States)

We systematically investigate the effects of GaAsSb and InGaAsSb capping layers (CLs) on the optical propertie s of self-assembled GaSb/GaAs QDs using photoluminescence (PL). Three samples were grown via solid source molecular beam epitaxy. Each sample features a different 5 nm capping material: GaAsSb, InGaAsSb, and GaAs on self-assembled GaSb/GaAs QDs.

The results from the GaAs sample correspond with previous works. However, the GaAsSb and InGaAsSb extend the QD PL peak under the same measurement condition with GaAs capped sample. At 77K, a long wavelength emission of 1.2 um is achieved for the GaAsSb CL while the GaAs capped sample at 1.043 m. We believe this is caused by the suppression of Sb-As intermixing at the interface of the QDs and the CL. The PL from the InGaAsSb sample is red-shifted even further. As the Sb-As composition remains unchanged, this is attributed to strain reduction in the GaSb QDs. Temperature-dependent PL is also used to calculate the activation energy of the GaSb QDs with the different capping layers: 130 meV for GaAs, 121 meV for GaAsSb, and 99 meV for InGaAsSb, respectively.

In summary, our results show that by reducing the strain in type II GaSb/GaAs QDs, and suppressing the Sb-As intermixing at the interface, enhanced PL intensity and a long wavelength emission of 1.3 um are achieved at RT. By using an optimized capping layer, we believe that high performance GaAs-based GaSb nanostructures for devices can be realized in the future.

7610-11, Session 3

Change of InAs/GaAs quantum dot shape and composition during capping

H. Eisele, A. Lenz, R. Timm, M. Dähne, Technische Univ. Berlin (Germany)

Cross-sectional scanning tunneling microscopy (STM) the one of the most favorite methods to study the structural parameters of buried semiconductor nanostructures such as InAs/GaAs quantum dots with atomic resolution. Thus, we can determine the size, shape and material composition. The latter one is assisted by comparisons with theoretical calculations of the strain relaxation of the originally strained material upon cleavage. These calculations are performed on an atomic basis using continuum mechanics.

From the determination of the structural parameters of InAs/GaAs quantum dots after capping and comparing them to the ones of uncapped dots grown under the same conditions using molecular beam epitaxy and studied with plan-view STM, we found a drastic change. The originally pyramidal shaped quantum dots become truncated, resulting in a flat (001) top face. Complex material intermixing procedures lead the dots to get intermixed with the GaAs capping material. Intermixing before the capping can be excluded due to sharp base interfaces with the underlying matrix material. The resulting material is found to be arranged in a so-called trumpet-shaped composition profile. Also upon the wetting layer segregation and thus intermixing with the capping material is found. This segregation leads to a wetting layer composition starting with a maximum InAs content at the base and further decaying exponentially. All these intermixing processes can be attributed to the additional strain being applied with the capping material.

7610-12, Session 3

Growth of InAs/Sb:GaAs quantum dots by the antimony surfactant mediated metal organic chemical vapor deposition for laser fabrication in the 1.3 um band

D. Guimard, The Univ. of Tokyo (Japan) and QD Laser Inc. (Japan); D. Bordel, The Univ. of Tokyo (Japan) and LIMMS/CNRS-IIS (UMI 2820) (Japan); M. Ishida, M. Nishioka, Y. Wakayama, The Univ. of Tokyo (Japan); Y. Tanaka, H. Sudo, T. Yamamoto, Fujitsu Labs., Ltd. (Japan); H. Kondo, QD Laser Inc. (Japan); M. Sugawara, QD Laser Inc. (Japan) and Fujitsu Labs., Ltd. (Japan); Y. Arakawa, The Univ. of Tokyo (Japan) and Institute of Industrial Science (Japan) and LIMMS/CNRS-IIS (UMI 2820) (Japan)

The antimony surfactant-mediated-growth (Sb-SMG) offers a novel degree of control for the fabrication of InAs quantum dots (QDs). Most particularly in the case of metal organic chemical vapor deposition (MOCVD), InAs/Sb:GaAs QDs yield significant advantages over conventional InAs/GaAs QDs, such as low coalescence, high density and suppression of the emission blueshift upon annealing [1]. Thanks to all of these advantages, ground-state lasing over 1.3 µm could be demonstrated for MOCVD-grown InAs/Sb:GaAs QD lasers [2]. InAs/Sb:GaAs QDs have also been successfully implemented in other photonic devices, such as 3D-photonic crystals [3], 2D-photonic nanocavity laser-on-silicon [4], and very recently, solar cells [5]. In order to fully benefit from the beneficial effects of the Sb-SMG though, the control of the localization and amount of Sb species turns out to be crucial. When trapped at the QD interfaces, the Sb species can induce non-radiative recombination centers, and hinder in turn the QD optical quality [1, 6]. We will present our latest results on the growth of InAs/Sb:GaAs QDs, and in particular, on the control of the dynamic behavior of the segregating Sb species and its impact on the QD and laser characteristics. We will show the demonstration of QD lasers in the 1.3 µm band with low threshold current density and modal gain above 30 cm-1, closing thereby the gap on MBE-grown QD lasers.

[1] D. Guimard et al., Appl. Phys. Lett. 89, 183124 (2006). [2] D. Guimard et al., Appl. Phys. Lett. 90, 241110 (2007). [3] A. Tandaechanurat et al., Appl. Phys. Let. 94, 17115 (2009). [4] K. Tanabe et al., Opt. Express 17, 9, 7036 (2009). [5] D. Guimard et al., to be submitted. [6] D. Guimard et al., Appl. Phys. Lett. 94, 103116 (2009).

7610-13, Session 3

The critical thickness of the 2D to 3D transition of GaSb/GaAs quantum dots

H. Eisele, R. Timm, A. Lenz, L. Ivanova, M. Dähne, Technische Univ. Berlin (Germany)

GaSb/GaAs nanostructures are most promising for future data storage applications. While the growth process of InAs/GaAs is understood widely and the critical parameters for structural phase transitions are in a close range, up to now for the GaSb/GaAs system large differences of e.g. the critical thickness for the 2D 3D phase transition are reported, ranging from 0.5 up to 4 monolayers (ML) of pure GaSb.

We investigated both systems insensitively by cross-sectional scanning tunneling microscopy, to study their spatial structure with atomic resolution as it appears after capping by the matrix material. From these experiments on samples grown with different growth parameters such as the temperature, growth rate, V/III flux ratio, conditions of growth interruption, and the growth method, we are able to illustrate a comprehensive scheme of the growth itself and of the material redistribution and segregation during its different stages.

While the critical thickness of the 2D 3D phase transition in InAs/GaAs is of about 1.7 ML, we could determine it for GaSb/GaAs between 1.0 and 1.5 ML of pure GaSb material deposited on GaAs(001), more or less independent of the applied growth conditions. This experimental finding is supported by strain energy calculations of the wetting layer before quantum dot (QD) evolution. A 34% higher strain energy results for GaSb/GaAs compared with InAs/GaAs, even if the lattice mismatch and the stiffness constants of both systems vary only little. From the strain energies a theoretical critical thickness for the GaSb/GaAs system of 1.2 ML is derived.

7610-15, Session 4

Flying Q-bits and entangled photons

D. Bimberg, A. Lochmann, I. A. Ostapenko, G. Hönig, S. Rodt, A. Schliwa, E. Stock, J. A. Töfflinger, W. Unrau, T. Warming, M. Winkelnkemper, Technische Univ. Berlin (Germany); V. A. Haisler, A. I. Toropov, A. K. Bakarov, A. P. Moschenko, D. V. Dimitriev, A. K. Kalagin, Institute of Semiconductor Physics (Russian Federation)

Efficient generation of polarized single or entangled photons is the crucial requisite for novel quantum key distribution systems and quantum information processing. Single semiconductor quantum dots are capable of emitting such photons on demand using pulsed current injection.The realization of highly efficient electrically driven single photon sources (SPS) operating at very high repetition frequencies based on well established semiconductor technology is presented. The resulting resonant (Q =170) single-QD diode generates single polarized photons at a repetition rate of 1 GHz [1] exhibits a second order correlation function g(2)(0) = 0.

QDs grown on (111) oriented substrates of cubic semiconductors are proposed [2] and demonstrated [3] as source of entangled photon pairs. Intrinsic symmetry-lowering effects leading to the splitting of the exciton bright states are shown to be absent for this substrate orientation. As a result the biexciton to exciton recombination cascade of a QD can be used for the generation of entangled photons without further tuning of the fine-structure splitting via QD size and/or shape, as long as there are not large shape anisotropies.

Complementary studies of c-plane GaN/AlN QDs [4] reveal their potential as emitters of single or entangled photons still at high temperatures paving the way to true applications.

References

[1] D.Bimberg et al., IEEE Photonics Journal 1, 58 (2009).

[2] A. Schliwa, M. Winkelnkemper, and D. Bimberg, PCT patent application 2008.

[3] I. Ostapenko et al., in print.

[4] M.Winkelnkemper et al., J.Phys. Condens. Matter 20 (2008),4542111.

7610-16, Session 4

Quantum dot photonic crystal waist cavity lasers

B. Ahn, J. Kang, M. Kim, Y. Lee, Korea Advanced Institute of Science and Technology (Korea, Republic of)

Up to now, people have employed 2D or 3D photonic crystal cavities to achieve a strong local confinement of light. The cavities are very useful for various elements such as low-threshold lasers, high-efficiency single photon sources, and cavity quantum electrodynamics. Recently, having one dimensional structure, a new cavity design with ultra-high quality (Q) factor and small mode volume has been investigated. This extremely high Q/V value is crucial for the strong coupling between light and quantum dots.

To make a cavity with high Q factor and small mode volume using this 1D structure, it is important that the field envelope needs to be tailored to a Gaussian shape. This means the photonic crystal pattern is to be tapered. There are several methods to taper a structure. One is to change the lattice constant and the radius of holes. However, this way is difficult to match the field envelope with a Gaussian form. So, we propose to taper the structure width and call this structure photonic crystal waist cavity. This method makes the field envelope close to a Gaussian profile and allows the cutoff frequency to change more gradually, which has an advantage to get high Q/V value. In addition, the fact that the maximum of electric field is placed to the dielectric region where the quantum dots exist enhances the coupling factor. We investigate the characteristics of the cavity through the 3D finite-difference time-domain (FDTD) method and confirm the lasing action with the quantum dot photonic crystal waist cavity.

7610-17, Session 4

Nonpolar InGaN quantum dots for semiconductor quantum light sources

Y. Wu, National Taiwan Univ. (Taiwan); P. Ku, Univ. of Michigan (United States)

The ability to exploit the quantum nature of light in semiconductor materials and do so above the cryogenic temperature can greatly advance quantum information processing. InGaN quantum dots (QDs) are an attractive candidate owning to their large exciton binding energies, large oscillator strengths, large band offsets, and matched emission wavelengths to efficient single photon detectors. However, small Bohr radii (~3 nm) in InGaN have imposed a stringent requirement on the dimensions of InGaN QDs. Importantly, closely-spaced valence band states in InGaN QDs grown on c-plane substrates can considerably limit the temperature range in which these QDs can be used as efficient quantum light sources.

It has been shown that the closely spaced valence band states in c-plane InGaN QDs is due to the symmetry of strains perpendicular to the c-axis. Indeed, our calculations showed that it is very difficult to achieve an energy spacing greater than 6 meV even for very small QDs. To increase the energy separation, we must break this symmetry. This can be achieved by growing the QDs off the c-axis, e.g. on m-plane. On the m-plane, |X> and |Y> liked states are separated for more than 100 meV in energy. To model it, we have adopted the valence force field model for strain distribution and the 6-band k-dot-p model for bandstructure calculations. By including the polarization effect, our results showed that with proper indium composition, the energy separation between the first two valence bands can be very large, e.g. 44 meV for 40% indium.

7610-18, Session 4

Remote pumping of self-assembled quantum post using surface acoustic waves

H. J. Krenner, S. Völk, F. Knall, Univ. Augsburg (Germany); H. Kim, J. He, P. M. Petroff, Univ. of California, Santa Barbara (United States); A. Wixforth, Univ. Augsburg (Germany)

Surface acoustic waves (SAW) can be used to induce large electric fields in piezoelectric semiconductors like GaAs. These fields laterally modulate the confinement potential of a Quantum Well (QW) and spatially separate electrons and holes along the SAW propagation. Thus, the radiative recombination becomes efficiently suppressed and the carriers are transported with the propagating SAW [1]. We use this bipolar charge conveyance principle to transport carriers to remotely located self-assembled Quantum Posts (QPs). Since self-assembled In0.4Ga0.6As/GaAs QPs are formed within a shallow In0.1Ga0.9As matrix [2] which we directly employ as the transport channel. Electrons and holes are photogenerated by a focused excitation laser in an area without QPs. When the SAW is turned on, electrons and holes are transported to the position of the QP in which they sequentially relax. Due to the deep confinement potential, the injected carriers remain within the QP until they radiatively recombine and we observe optical emission from QPs located along the SAW propagation direction. Using spatially resolved detection, we can distinguish between different QPs and verify SAW-driven pumping down to the limit of a single QP. Taking into account the single photon emission of QPs [3] and the high frequency and triggering accuracy of SAWs this concept provides potential for an acoustically driven single photon sources or lasers with sequential electron-hole injection.

[1] C. Rocke et al., Phys. Rev. Lett. 78, 4099 (1997).

[2] J. He et al., Nano Lett. 7, 802 (2007).

[3] H. J. Krenner et al., Nano Lett. 8 1750 (2008).

7610-19, Session 5

Spatial and spectral control of individual quantum dots

O. G. Schmidt, Leibniz-Institut für Festkörper- und Werkstoffforschung Dresden (Germany)

Abstract not yet in.

7610-20, Session 5

Influence of ex-situ AFM treatment on epitaxial growth of self-organized InAs quantum dots

N. Y. Gordeev, Ioffe Physico-Technical Institute (Russian Federation) and St. Petersburg Physics and Technology Ctr. for Research and Education (Russian Federation); V. K. Goncharov, V. M. Lantratov, N. Kalyuzhnyy, S. Mintairov, Ioffe Physico-Technical Institute (Russian Federation); P. N. Brunkov, Ioffe Physico-Technical Institute (Russian Federation) and St. Petersburg State Polytechnical Univ. (Russian Federation)

Self-assembled InAs quantum dots (QDs) have been the subject of intense research in part due to their potential for quantum information systems. However, many quantum information schemes require placing quantum dots at pre-determined positions. Local anodic oxidation (LAO) on the base of atomic force microscope (AFM) is considered to be an effective tool for ex-situ patterning of GaAs substrate for further site-controlled growth of InAs quantum dots. We have experimentally shown that ex-situ AFM scanning without LAO (both in tapping and contact mode) of epitaxial GaAs surface modifies locally its properties while the surface topology remains unchanged. It has been revealed that AFM-treated area shows nucleating processes in MOCVD growth completely different from that of untreated area. The processes are found to be critical for growing of self-organized InAs quantum dots. Local surface density of grown quantum dots is significantly reduced in the AFM-treated area and its value depends on the number of the scan cycles. In the same epitaxial process the local surface density of quantum dots may be varied from 1e11 cm-2 to 1e7cm-2. We discuss the nature of the observed phenomenon in particular the model assuming existence of AFM-induced charge. The observed effect in combination with LAO may be considered as a new tool for engineering surface density and position of epitaxially grown quantum dots.

7610-21, Session 5

Surface plasmon resonance tunable and linear and nonlinear large responses of colloidal gold nanoparticles

E. J. S. Fonseca, M. A. R. C. Alencar, C. E. A. Santos, S. F. A. Morais, M. A. Gelesky, M. R. Meneghetti, J. M. Hickmann, Univ. Federal de Alagoas (Brazil)

Metallic nanoparticles (MNP) properties have been largely investigated aiming their applications in the development of new photonic devices and optical. Metallic nanostructured solids and colloids may present large local and nonlocal nonlinear optical responses owing to the surface Plasmon excitation. The geometry, i.e. size and shape, control of MNP is essential to significantly improve their optical properties. On the other hand, their high probability of agglomeration is a limiting point for their practical use. In fact, there is a huge interest to develop methods that produce stable colloids, with an effective control over the surface plasmon resonance (SPR) of the MNP. In this work, we report on the successful use of myristic acid (MA) to modulate the SPR of gold nanoparticles (AuNP) dispersed in castor oil and the investigation of the third-order nonlinear optical response of the resulting colloidal systems. We observed that the colloids SPR frequency could be controlled adding myristic acid during the synthesis process as a tuning agent. Colloids with different filling factors (FF) were produced and characterized by TEM, UV-Vis spectroscopy, and Atomic Absorption spectrometry. Z-scan technique was employed to measure the nonlinear refraction and absorption of these colloids, using a Ti:Sappire laser (820 nm, 200 fs, 1 kHz). The largest value of n2 was equal to -3.96 x 10-13 cm2/W for the colloid with the highest AuNP concentration. It was also observed that the modulus of n2 increased linearly with the AuNP FF, but nor saturation of refraction, neither nonlinear absorption were detected in these systems. The third-order nonlinear susceptibilities of the metallic particles were also measured. Our results indicate that this approach can be very useful in the development of colloids containing MNP controlling optical effects associated with the SPR.

7610-22, Session 5

Shape changes in patterned planar InAs as a function of thickness and temperature

K. G. Eyink, Air Force Research Lab. (United States); L. Grazulis, Univ. of Dayton Research Institute (United States); K. Mahalingam, Universal Technology Corp. (United States); M. Twyman, J. Shoaf, Southwestern Ohio Council for Higher Education (United States); J. Hoelscher, B. Claflin, Wright State Univ. (United States); D. H. Tomich, Air Force Research Lab. (United States)

Quantum dots have the potential to produce devices with enhanced properties. However, many quantum dot devices require the quantum dots to have a precise size and a precise location for optimum operation. So far approaches such as directed assembly and self assembly have failed due to the random effects resulting during nucleation of the quantum dots. InAs grown under metal rich conditions can remain planar as opposed to forming the self assembled quantum dot morphology. Recently we have demonstrated that planar InAs when patterned via tip-based scribing and then annealed under an As pressure typical for self-assembled quantum dot growth reorganizes and assumes a 3D morphology. We have been studying this process as a potential method to precisely locate quantum dots with definable sizes. In this work we report change in the morphology for different thickness of planar InAs for various pattern dimensions and annealing temperatures. We have analyzed the composition of the films after annealing to determine the effect induced in the films from patterning resulting from scribing. Using this approach, arrays of 3D InAs mounds have been formed with mounds having a base dimensions of 800, 500, and 350Å. These results demonstrate that the smaller patterns are less stable and coarsening becomes more dominant.

7610-37, Session 5

1.55-um InAs quantum dot number and size control on truncated InP pyramids and integration by selective area epitaxy

H. Wang, J. Yuan, P. J. van Veldhoven, R. Nötzel, Technische Univ. Eindhoven (Netherlands)

Number and size control of InAs quantum dots (QDs) on truncated InP

pyramids grown by selective area Metal Organic Vapor Phase Epitaxy (MOVPE) is reported. The facet composition of the pyramid top surface and the relative facet sizes are determined by the shape of the pyramid base and the pyramid height for a certain base size. This allows the precise position and distribution control of the QDs due to preferential nucleation on the {103} and {115} facets. The QD number, related to the specific shape of the pyramid top surface, is reduced by the shrinking pyramid top surface size during growth. The size of the QDs is adjusted by the growth parameters, e.g., InAs amount and growth rate together with the pyramid top surface size. Well defined positioning of four, three, two, and single QDs is realized successfully. Regrowth of a passive InP structure around the pyramids establishes submicrometer-scale active-passive integration for efficient microcavity QD nanolasers and single photon sources operating in the 1.55-µm telecom wavelength region and their implementation in photonic integrated circuits.

7610-23, Session 6

Submonolayer quantum dots for 850 nm-range VCSELs

J. A. Lott, VI Systems GmbH (Germany); S. A. Blokhin, A. Mutig, G. Fiol, Technische Univ. Berlin (Germany); V. A. Shchukin, N. N. Ledentsov, VI Systems GmbH (Germany); D. Bimberg, Technische Univ. Berlin (Germany)

We present the epitaxial growth and characterization of sheets of InGaAs submonolayer (SML) quantum dot (QD) structures within an AlGaAs matrix or separation material for applications in 850 nm-range vertical cavity surface emitting lasers (VCSELs). Experimental and device active region calibration structures are prepared, each containing one or more sheets of SML QDs of variable QD size and material composition. The structures are characterized using x-ray diffraction, transmission electron microscopy, and photoluminescence (PL) and PL excitation (PLE) measurement techniques. Finally, VCSELs containing SML QDs are produced and characterized resulting in record performance high-speed (> 20 Gb/s) and temperature performance.

7610-24, Session 6

Vertical-geometry all-optical switches based on InAs/GaAs quantum dots in a cavity

C. Jin, O. Kojima, T. Kita, O. Wada, Kobe Univ. (Japan); M. Hopkinson, The Univ. of Sheffield (United Kingdom); K. Akahane, National Institute of Information and Communications Technology (Japan)

Quantum dots (QDs) within a vertical cavity structure have great advantages to realize low-power, polarization insensitive and micrometre-size switching devices for the future optical communication network [1]. Due to the three-dimensional confined carrier state and the broad size distribution of self-assembled InAs/GaAs QDs, it is crucial to enhance the interaction between QDs and the cavity with an appropriate design of the one dimensional periodic structure. In this work, enhanced QD nonlinearity is theoritically observed by increasing the GaAs/AlAs pair number of the bottom mirror whilst the linewidth of the cavity mode becomes narrower, which indicates there is a trade-off between the QD/cavity nonlinearity and the ultra-fast response of the cavity structure. By this consideration, we have designed and fabricated vertical-reflection type QD switches with 12 periodes of GaAs/AlAs for the top mirror and 25 periodes for the bottom mirror to give an asymmetric verticle cavity. Optical switching via the QD excited state shows a fast decay with a time constant down to 23 ps, confirming that the fast intersubband relaxation of carriers inside QDs is an effective means to speed up the switching process. A technique by changing the light incident angle realizes a wavelength tunability over 30 nm for the QD switches.

[1] C. Y. Jin et al, Appl. Phys. Lett. 95, 021109, 2009.

7610-25, Session 6

Theory of relaxation oscillations and modulation response of a quantum dot laser

L. V. Asryan, Virginia Polytechnic Institute and State Univ. (United States); R. A. Suris, Ioffe Physico-Technical Institute (Russian Federation)

A discrete energy spectrum of carriers in semiconductor quantum dots (QDs) enables stimulated emission at low threshold current and with high temperature-stability in QD lasers. High bandwidth of direct modulation of optical output by injection current is also anticipated for QD lasers due to their high differential gain, but has not been demonstrated so far. Even with currently available advanced technologies for QD structures growth and fabrication, the modulation bandwidth of QD lasers is still below that of conventional quantum well lasers. In this work, dynamic effects in a QD laser are studied theoretically and the factors limiting its modulation bandwidth are identified. The small-signal analysis of the rate equations for the electron-photon system is used. The conditions under which the system is either underdamped or overdamped are described. The decay rate and frequency of relaxation oscillations, and the modulation response are analyzed as functions of the injection current and parameters of the laser structure (cavity length, number of QD layers and surface density of QDs in a layer, and uniformity of QDs). The "best-scenario" modulation characteristics (particularly the highest achievable bandwidth) of a QD laser are estimated.

7610-26, Session 6

Emission dynamic of the InAs quantum dots coupled to InGaAs quantum well

T. J. Ochalski, N. Pavarelli, K. Gradkowski, G. Huyet, Tyndall National Institute (Ireland); B. Liang, D. L. Huffaker, Univ. of California, Los Angeles (United States)

Quantum dots (QDs) are the most suitable nanostructures for the development of the next generation optoelectronic devices and semiconductor lasers. The fast injection of carriers from the continuum of states of the optical confinement layer into the discrete levels of the dots is thus becoming a basic requirement to increase the global efficiency of optoelectronic devices.

In this work, the study of the carrier transfer dynamics between a single InGaAs QW and a single layer of InAs QDs in tunnel injection structures has been investigated using time-resolved photo-luminescence (TRPL) technique. The investigated structures consist of a single InGaAs quantum well and a single layer of InAs quantum dots separated by a GaAs barrier. The thickness of the barrier is 100 nm for the uncoupled sample and 4 nm for the coupled one. Experimental results show that the quantum well decay time decreases from 0.7 ns of the uncoupled structure to 0.1 ns for the coupled one, indicating a fast transfer of carriers from the injector to the emitter in case of the 4 nm barrier. This behaviour is reflected in the emission dynamics of the quantum dots.

The fast transfer of carriers from the quantum well to the quantum dots through the 4 nm GaAs barrier alters the emission of the coupled structure in terms of intensity and timescale. These properties can be employed in the realization of the high performance and high speed optoelectronic devices.

7610-27, Session 6

Tunneling injection quantum dot laser: effect of the wetting layer

D. Han, L. V. Asryan, Virginia Polytechnic Institute and State Univ. (United States)

To suppress bipolar population and hence electron-hole recombination

outside quantum dots (QDs), tunneling-injection of electrons and holes into QDs from two separate quantum wells (QWs) was proposed earlier [1]-[4]. Close-to-ideal operating characteristics were predicted for such a tunneling-injection laser. In the Stranski-Krastanow growth mode, a two-dimensional wetting layer (WL) is initially grown followed by the formation of QDs. Due to thermal escape of carriers from QDs, there will be bipolar population and hence electron-hole recombination in the WL, even in a tunneling-injection structure. In this work, the light-current characteristic (LCC) of a tunneling-injection QD laser is studied in the presence of the WL. Since (i) the n- and p-side of a tunneling-injection structure are only connected by the current paths crossing QDs and (ii) the WL is located in the n-side of the structure, the only source of holes for the WL is provided by QDs. It is shown here that, due to zero-dimensional nature of QDs, the rate of the hole supply to the WL remains limited with increasing injection current. For this reason, as in the other parts of the structure outside QDs (QWs and optical confinement layer), the parasitic electron-hole recombination remains restricted in the WL. As a result, even in the presence of the WL, the LCC of a tunneling-injection QD laser becomes increasingly linear at high injection currents, which is a further demonstration of the potential of such a laser for high-power operation.

[1] L.V. Asryan, S. Luryi, IEEE J. Quantum Electron., 37, 905 (2001).

[2] L.V. Asryan, S. Luryi, Solid-State Electron., 47, 205 (2003).

[3] D.-S. Han, L.V. Asryan, Solid-State Electron., 52, 1674 (2008).

[4] D.-S. Han, L.V. Asryan, Appl. Phys. Lett., 92, 251113, (2008).

7610-28, Session 7

Charge injection and transport in nanowires

F. Leonard, Sandia National Labs., California (United States)

Semiconductor nanowires show promise in electronic, optoelectronic, and sensing devices. To realize this promise, a fundamental understanding of charge injection and electronic transport in these novel nanomaterials is necessary. I will discuss recent work that couples experiment and theory to address these issues. For example, in GaN nanowires, we achieve efficient charge injection and find that space-charge-limited currents are unusually strong. In contrast, charge transport across individual Au-nanoparticle/Ge-nanowire interfaces is injection-limited, and surprisingly, the conductance increases with decreasing diameter due to a dominance of electron-hole recombination. MOre generally, our results indicate that size effects governs the properties of semiconducting nanowires even when quantum effects are unimportant.

7610-29, Session 7

Lithography-free synthesis of 1D Au nanoparticle arrays encapsulated within freestanding silica nanowires

T. S. Mayer, W. Hu, B. Liu, Y. Yu, S. E. Mohney, The Pennsylvania State Univ. (United States)

This presentation will discuss the lithography-free synthesis and optical properties of 1D noble metal (Au) nanoparticle arrays that are encapsulated within freestanding silicon dioxide (SiO_2) nanowires. The process begins by thermally oxidizing groups of Au-coated silicon nanowires to form individual SiO_2-coated Au nanowires. Additional thermal treatment causes the Au nanowires to break into a linear chain of Au nanoparticles following the Rayleigh instability, where the Au nanoparticle diameter and spacing is determined entirely by the starting diameter of the silicon nanowire. This method has been used to produce collections of freestanding 1D nanoparticle arrays for bottom-up assembly, as well as well ordered patterns of vertically-oriented 1D nanoparticle arrays on silicon substrates. Such simple lithography-free methods for producing 1D noble metal nanoparticle arrays encapsulated within dielectric nanowires provide new opportunities for realizing nanoparticle-based plasmonic devices and metamaterials.

7610-30, Session 7

The in-situ formation and electrical characterization of GaAs nanopillar P-N junctions on nanopatterned GaAs surfaces by MOCVD

P. Wong, A. Lin, G. Mariani, P. N. Senanayake, B. Liang, D. L. Huffaker, Univ. of California, Los Angeles (United States)

Nanowires provide a bottom-up approach for semiconductor fabrication to serve as building blocks for nano-sized structures and devices with designed dimensions and properties at desired locations. We report successful in-situ p-n homojunction formation of GaAs nanopillars on nanopatterned GaAs surfaces by MOCVD in the catalyst-free growth mode, and the electrical characterization of single nanopillars and nanopillar arrays.

Majority of nanowires are formed in the vapor-liquid-solid growth mode, where metal particles (usually Au) serve as catalysts. Wide choices of material combinations are available for nanowires and substrates even when they are highly lattice mismatched, and the nanowire growth temperature is generally lower than the comparable epitaxial growth. A different approach is to grow nanopillars on nanopatterned substrates in the catalyst-free growth mode. Vertically aligned, highly faceted nanopillar arrays with high aspect ratio and density are available on designed patterns through electron beam lithography. The catalyst-free growth mode avoids possible reactor contamination and introduction of deep level traps through the incorporation of Au catalytical particles, and offers possibility for abrupt axial heterojunction interfaces and simpler integration platform through lateral overgrowth.

We have demonstrated, through the control of growth conditions, the in-situ formation of axial and core-shell p-n junctions of GaAs nanopillars on SiO_2-masked GaAs (111)B substrates. In the environment of high growth temperatures and low V-III ratios, the catalyst-free growth of GaAs nanopillars favors the axial direction, while the lower growth temperature and a higher V-III ratio promote the preferential incorporation of Ga and As adatoms on vertical {110} sidewalls, and hence the formation of core-shell p-n homojunctions. The electrical properties of axial and core-shell p-n junctions are characterized by two techniques. The surface-state density, doping concentration and carrier dynamics can be derived from the current-voltage measurement by direct probing of free-standing nanopillars with a Au-coated AFM tip. On the other hand, the blanket-deposition of transparent-conducting ITO layer over the GaAs nanopillar array provides the benefit of combined optical and electrical characterizations. Room-temperature and low-temperature photoluminescence of these nanopillars are characterized and studied.

7610-31, Session 7

Coupled thermo-electromechanical effects in quantum dots and nanowires

R. V. N. Melnik, S. R. Patil, Wilfrid Laurier Univ. (Canada); O. Tsviliuk, JSC Rodovid Bank (Ukraine)

In this contribution, we report the analysis of coupled multiphysics effects on properties of low dimensional semiconductor nanostructures (LDSNs), focusing on thermopiezoelectric and nonlinear electromechanical effects in quantum dots and nanowires. This analysis is based on a coupled model of partial differential equations accounting for thermal, electric, and mechanical fields in a systematic manner. First, we investigate thermopiezoelectric field distributions and their effects on electronic properties of the highly strained CdTe/ZnTe quantum wires with the full 3D coupled thermoelectromechanical formulation, consisting of balance equations for heat transfer, electrostatics and the mechanical field, developed earlier by us in [Phys. Status Solidi A, 206(5), 960-964, 2009]. We discuss the effects of thermal loadings on piezoelectric fields in CdTe/ZnTe quantum wire systems and quantify the conduction band edge shifts due to thermoelectromechancial loadings. Although for these particular systems, piezoelectric quantities are observed to be relatively

less sensitive to thermal loadings, we demonstrate that the coupled effects are important in the determination of electronic/optoelectronic properties of such quantum wire systems. Next, we analyze GaN/AlN quantum dot systems of different geometries. We observe that GaN/AlN nanosystems are more sensitive to thermopiezoelectric effects than those of CdTe/ZnTe previously analyzed with the fully coupled models. Finally, we demonstrate noticeable qualitative and quantitative variations in electromechanical fields in GaN/AlN systems as a consequence of taking into account nonlinear electromechanical effects. The results presented here help improve our understanding of the classical effects on electronic structures and optoelectronic properties of LDSNs as key components in advanced quantum and optoelectronic applications.

7610-32, Session 8

Controlling exciton states of self-assembled InAs/GaAs quantum dots with applied strain

N. Malkova, G. W. Bryant, J. S. Sims, National Institute of Standards and Technology (United States)

Dynamical control of excitons in quantum dots (QDs) is highly desirable for applications of QD optics. For QDs embedded in nanomechanical structures, dynamical control could be obtained by using externally imposed mechanical strain to reengineer the QD excitons to modify exciton fine structure, polarize optical transitions, induce entanglement, all capabilities needed to use dots in optical nanodevices and quantum information processing. To exploit the potential of hybrid nanomechanical/QD devices, one must understand the coupling between internal strain due to lattice mismatch, externally imposed mechanical strain, and the excitons in the QDs in the nanomechanical structure. To identify the effects of mechanical strain, we consider symmetric and asymmetric pyramidal InAs QDs in a GaAs nanomechanical bridge. The bridge is strained by a mechanical bend or an applied surface acoustic wave to reengineer the QD excitons. We use atomistic tight-binding theory and a configuration-interaction approach for the exciton states. Relaxation of local strain due to lattice mismatch and the strain imposed by bending the structure are equally important, so both are included via atomistic valence force field theory. We show that the applied strain can make large changes in the exchange splitting between exciton bright states to modify the exciton fine structure induced by QD asymmetry or atomistic effects, can induce crossing between the bright states for certain strains, and can be used to rotate the polarized response of the bright states. These capabilities should be critical for applications such as entangled photon sources or cavity-coupled QDs.

7610-33, Session 8

The effects of electric and magnetic field on the hydrogenic donor impurity in GaN/AlxGa1-xN spherical quantum dot

H. Wang, H. Wu, Qufu Normal Univ. (China); Q. Gong, S. Feng, Shanghai Institute of Microsystem and Information Technology (China)

In recent years, many theoretical and experimental investigations have been performed on the issue of the hydrogenic binding energy of an electron to a donor impurity which is confined within low dimensional heterostructure. A uniform method to study the electronic states of a hydrogenic donor impurity in semiconductor nano-structures in the framework of effective-mass envelope-function theory using the plane wave basis has been proposed[1]. The method can be widely applied in the calculation of the electronic states of hydrogenic donor impurities in nano-structures of various shapes and can easily be extended to study the effects of external fields and other complex cases. In the previous, we have calculated the electronic structure properties of quantum dots (QDs) under the external electric field using this method[2,3]. In this paper, we adopt the plane wave basis to calculate the donor binding energy in ZB GaN/AlxGa1-xN spherical QD within the framework of effective mass approximation. The dependencies of the binding energy on electric field, magnetic field, QD radius and impurity position are obtained. The maximum of impurity binding energy is shifted from the centre of QD and the degenerating energy located for symmetrical positions with respect to the centre of QD are split in presence of the external electric field. The binding energy increases with the increases of magnetic field when the impurity located at the centre of QD. In the presence of electric and magnetic field simultaneously, an increase in the electric field strength leads to a decrease of the maxima of binding energy with an increase in magnetic field.

References

1. S.S. Li and J.B. Xia, Phys. Lett. A 366, 120 (2007).

2. H.T. Wu, H.L. Wang, L.M. Jiang, Q. Gong and S. L. Feng, Physica B 404, 122 (2009).

3. L.M. Jiang, H.L. Wang , H.T. WU, Q. Gong and S. L. Feng, J. Appl. Phys. 105, 053710 (2009).

7610-34, Session 8

Purely radiative recombination up to room temperature in GaN/AlN QDs with microsecond decay times

B. Gayral, J. Renard, Commissariat à l'Énergie Atomique (France); H. Mariette, Commissariat à l'Énergie Atomique (France) and Institut NÉEL (France); E. Monroy, Commissariat à l'Énergie Atomique (France)

Due three dimensional confinement, carriers trapped in quantum dots are expected to be less prone to nonradiative recombination than in quantum wells. This difference should be particularly acute in semiconductors with high structural defect densities such as III-nitrides. Besides, III-N heterostructures grown along the c-axis are subject to a huge electric field (up to 10 MV/cm). Due to the quantum confined Stark effect, transitions are strongly red shifted and their oscillator strengths decrease. In this work we demonstrate the absence of nonradiative recombination in polar GaN/AlN QDs at room temperature (RT), even for long-lived QDs. We have analyzed the optical properties of GaN/AlN QD and QW superlattices deposited on AlN-on-sapphire templates by MBE. We have compared the temperature-dependent behavior of the time-resolved photoluminescence from QWs and QDs emitting in the same energy range. The decay time of the PL from QWs strongly decreases above 50 K, losing a factor 4 between 50 and 150K. We attribute this feature to the delocalization and diffusion of carriers towards nonradiative recombination centers. In contrast, QDs present a constant decay time (up to ~850 ns for QDs emitting around 450 nm) up to RT. This demonstrates that nonradiative recombination does not occur in the QDs up to RT and that no leakage to the wetting layer takes place, as expected from the large band-offset between GaN and AlN. A lower limit for the nonradiative lifetime of 10 µs can be estimated, which demonstrates the extreme inefficiency of nonradiative recombination processes in GaN/AlN QDs.

7610-35, Poster Session

Optical characterization of ZnO nanoparticles and nanorods prepared by wet chemical technique at low temperature

R. Kumar, K. Murari, Ctr. of Excellence in Lasers and Optoelectronic Sciences (India) and Cochin Univ. of Science & Technology (India); M. Kailsnath, International School of Photonics (India) and Cochin Univ. of Science & Technology (India); P. Radhakrishnan, Ctr. of Excellence in Lasers and Optoelectronic Sciences (India) and Cochin Univ. of Science & Technology (India); V. P. N. Nampoori, International School of

Photonics (India) and Cochin Univ. of Science & Technology (India)

We report here one of the simplest and cost effective aqueous route for the synthesis of zinc nanoparticles and nanorods. Zinc Oxide nanoparticles and nanorods were synthesized at a low temperature of 600C using aqueous solution of zinc acetate dihydrate and potassium hydroxide in methanol. Particle and rod like structures were obtained by merely varying the relative concentration of the reagents. Effect of capping agent polyvinyl pyrrolidone (PVP) was also studied. A variety of techniques like UV-Vis absorption spectroscopy, X-ray diffraction (XRD), photoluminescence (PL), Fourier transform infrared spectroscopy (FTIR) and scanning electron microscopy (SEM) were used to carry out structural and spectroscopic characterizations. The average size estimated from Debye-Scherrer's formula was <30nm for all the cases. Presence of one-dimensional structures in case of rod sample was confirmed both by SEM images and XRD graph. Difference in the nature of clusters and decrement in aspect ratio of rods due to capping action of PVP were also confirmed by the SEM images. A blue shift was observed in UV-emission peak from 384nm to 417 nm due to different excitation wavelength of 280nm and 370nm respectively, but the position of green emission peak remained invariant. Enhancement in the UV emission intensity along with the suppression of green emission intensity was also observed due to the capping action of PVP. The preparation method is not only cost-effective but can also be followed for their preparation on large scale for many potential applications like solar cells, gas sensors, laser diodes, nanolasers, field effect transistors, LEDs etc.

7610-36, Poster Session

Optical properties in InGaAs quantum dots on SiO2-patterned vicinal (001) GaAs substrate

H. J. J. Kim, S. Y. Yoo, H. J. Ko, M. Han, D. Kim, S. Hann, S. H. Kim, H. C. Ki, Korea Photonics Technology Institute (Korea, Republic of)

We previously fabricated single- or double-row aligned self-assembled quantum dots (SAQDs) by utilizing SiO2-patterned 5 degree-off (001) GaAs substrates. In order to maintain define interval of multi-atomic steps equal to the interval of step lines on unpatterned vicinal (001) GaAs substrate, it is effective to use vicinal substrate having higher misorientation angles. In this study, we reported the energy states in In0.8Ga0.2As SAQDs which depended on W(001) and the misorientation angle of the substrate. Starting materials used in this study were SiO2-patterned exact and 5o-off (001) GaAs substrates. The direction of misorientation angles and stripe pattern were [1-10] and the thickness SiO2 is 20 nm. SiO2 patterns had different widths of opening region (W0) which were varied from 300 to 700 nm. The growth temperature for the GaAs buffer layer, SAQDs, and capping layer were 700, 500, and 500 oC, respectively. The corresponding nominal thickness were 200 nm, 3.2 ML, and 150 nm, respectively. According to results, SAQDs have regular interval for SiO2-patterned 5 degree-off (001) GaAs substrates, whereas random interval for SiO2-patterned exact (001) GaAs as reported. In0.8Ga0.2As SAQDs had only ground state emissions for SiO2-patterned exact (001) GaAs substrate, whereas those had ground and excited state emissions for SiO2-patterned 5 degree-off (001) GaAs substrate. The intensities of excited states was increased as W(001) was wider. These results suggest that discrete nature of the density of states in SAQDs was improved by using SiO2-patterned vicinal (001) GaAs substrate with higher msorientation angle of substrate.

7610-38, Poster Session

Ultrafast optical response of luminescent magnetic nanocomposites: CdSe/ZnS quantum dots encapsulated in gamma-Fe2O3 nanotubes

G. You, H. Fan, Q. Xu, S. Tang, T. Venkatesan, National Univ. of Singapore (Singapore)

In recent years, the luminescent magnetic nanocomposites, such as Fe2O3-CdSe/ZnS, Fe2O3-CdS, Fe3O4-ZnS, have attracted much attention due to their interesting bifunctional properties and promising applications in biomedical fields, such as magnetic separation and optical detection of cancer cells, drug delivery, and hyperthermia.

Though considerable effort has been made in fabrication of these nanocomposites, there are less detailed studies on their optical properties, especially the ultrafast time-resolved optical studies, which is a powerful tool to explore the involved excitation and relaxation mechanisms determining their electronic and optical properties. In the present work, the ultrafast optical response of a type of luminescent magnetic nanocomposites, CdSe/ZnS quantum dots

(QDs) encapsulated in gamma-Fe2O3 nanotubes, were studied by using the femtosecond transient absorption and time-resolved photoluminescence techniques. In the timescale of hundreds of femtosecond to picosecond, the relaxation behavior of transient absorption response of the composites is similar to pure Fe2O3 nanotubes, however, the entire spectral shape show a clear red-shift more than 50 nm compared with pure Fe2O3 nanotubes, which indicates that the possible mutual interactions between QDs and Fe2O3, such as electron transfer and/or energy transfer, take place in an ultrashort timescale comparable or faster than the laser pulse duration ~100 fs, the succedent transient response in picosecond regime is dominated by the excited Fe2O3 component due to its high volume ratio in the composites and the large absorption cross-section of excited d electrons. In nanosecond timescale, we found that, compared with pure CdSe/ZnS QDs, the composites show faster fluorescent decay at the peak wavelength of emission band, however, slower decay in the red side. The present studies show that the dynamical optical responses of the composites have different behavior from the separate components due to the possible mutual interactions between the coupling components.

Conference 7611: Advances in Photonics of Quantum Computing, Memory, and Communication III

Wednesday-Thursday 27-28 January 2010 • Part of Proceedings of SPIE Vol. 7611

Advances in Photonics of Quantum Computing, Memory, and Communication III

7611-01, Session 1

What is a quantum computer and how do we build one?

P. Kok, The Univ. of Sheffield (United Kingdom)

The DiVincenzo criteria for implementing a quantum computer have been seminal in focussing both experimental and theoretical research in quantum information processing. These criteria were formulated specifically for the circuit model of quantum computing. However, several new models for quantum computing (paradigms) have been proposed that do not seem to fit the criteria well. The question is therefore what are the general criteria for implementing quantum computers. To this end, a formal operational definition of a quantum computer is introduced. It is then shown that according to this definition a device is a quantum computer if it obeys the following four criteria: Any quantum computer must (1) have a quantum memory; (2) facilitate a controlled quantum evolution of the quantum memory; (3) include a method for cooling the quantum memory; and (4) provide a readout mechanism for subsets of the quantum memory. The criteria are met when the device is scalable and operates fault-tolerantly. We discuss various existing quantum computing paradigms, and how they fit within this framework. Finally, we lay out a roadmap for selecting an avenue towards building a quantum computer. This is summarized in a decision tree intended to help experimentalists determine the most natural paradigm given a particular physical implementation.

7611-02, Session 1

LPCVD of rare earth-doped multilayer structures for spectral storage applications

F. J. Bezares, Z. U. Hasan, Temple Univ. (United States)

Europium-doped thinfilms have been produced using Laser Pulse Chemical Vapor Deposition (LPCVD) technique. Different Eu-centers were created in these thinfilms by changing their growth environment inside a hi-vacuum vapor deposition chamber, the composition of the target material to be ablated for thinfilm deposition, or both. For example, introducing trace amounts of oxygen, or alternatively HCl in some cases, inside the LPCVD chamber while producing MgS:Eu as well as CaS:Eu thinfilms results in the formation of impurity associated centers across lattice sites throughout the deposited structures. The addition of these impurity ions into the MgS or CaS lattice of a thinfilm will alter the crystal field environment around Eu ions thus creating new optical centers with a shift in energy of their characteristic Zero Phonon Lines. Time-resolved fluorescence spectroscopy measurements performed on these structures shows evidence of the creation of these new optical centers. Furthermore, emission and absorption spectroscopy confirm that they are suitable candidates to be used in conjunction with power-gated spectral holeburning technique and provide ultrahigh, terabits per square inch, storage densities.

7611-03, Session 1

Engineering and coherent control of single spins in diamond

D. D. Awschalom, Univ. of California, Santa Barbara (United States)

Nitrogen vacancy (NV) centers in diamond are emerging as a promising system for spin-based applications in quantum information and communication at room temperature. Using a combination of confocal microscopy and spin resonance, the spin of individual NV centers can be initialized, manipulated and read out. These techniques have been used to study the long room temperature spin coherence times of NV centers, their coherent interactions with individual dopants, and the interactions of a single spin with its environment . Progress in the growth of high-quality, single-crystal diamond continues to fuel efforts in developing this material as a platform for solid state technologies. There remain significant challenges, however, both in understanding the physics of these defects as well as the development of technologies based on their quantum properties. We describe experiments aimed at spin-engineering this system using spatially and isotopically selective ion implanting techniques into synthetic films. Using single-spin resonant spectroscopy, we observe the electron spin levels of implanted spins and find strong hyperfine coupling to the nitrogen nuclear spin in the excited state. Finally, we extend coherent control of individual spins to the chip level with the fabrication of coplanar waveguide structures onto diamond substrates. The ability to drive these devices at high Rabi frequencies enables single electron spin flips within a few processional cycles. Within large driving fields, conventional models of spin dynamics break down, offering new research opportunities in this regime.

7611-04, Session 1

Intrinsic properties of the NV center in diamond

N. B. Manson, L. Rogers, R. McMurtrie, The Australian National Univ. (Australia)

Review of Nv center in diamond

7611-05, Session 1

Recent progress in quantum information processing with trapped ions

D. Hanneke, National Institute of Standards and Technology (United States)

Quantum information processing (QIP) promises significant gains for some important computational tasks as well as the potential to simulate interesting physical systems. Storing quantum bits in the internal states of trapped atomic ions has proven a successful approach to QIP because of long coherence times and precise interaction with light fields for coherent control and entanglement generation. Here we present some recent results in the field, including those related to information transport and advanced quantum algorithms.

NIST work is supported by IARPA, DARPA, NSA, and the NIST Quantum Information Program.

7611-06, Session 1

Demonstration of an efficient quantum memory for light

M. P. Hedges, M. J. Sellars, J. J. Longdell, The Australian National Univ. (Australia)

We have demonstrated a solid-state memory for light for with a total efficiency greater than 65%. We present results for coherent pulse storage, both intense pulses and at the few-photon level. Measurement of the shot to shot variance demonstrates higher fidelity reproduction than can be achieved classically.

The memory uses a gradient echo technique on the 606 nm optical transition in Pr3+:YSO. A narrow spectral feature, 100kHz wide, is prepared using persistent spectral hole burning. An applied electric field gradient Stark-shifts this feature linearly as a function of depth along the propagation direction. To create a 1.8 MHz wide feature with 13 dB of absorption. An optical pulse absorbed by this feature is recalled by reversing the applied field gradient. Homodyne detection was used to analyze the output of the memory.

7611-07, Session 2

Observation of the dynamic Jahn-Teller effect in the excited states of nitrogen-vacancy centers in diamond

K. C. Fu, C. M. Santori, P. E. Barclay, Hewlett-Packard Labs. (United States); L. Rogers, N. B. Manson, The Australian National Univ. (Australia); R. G. Beausoleil, Hewlett-Packard Labs. (United States)

The understanding of the coherence properties of photons emitted from negatively charged nitrogen-vacancy (NV) centers in diamond is essential for the success of quantum information applications based on indistinguishable photons. Here we study both the polarization of photons emitted from and the linewidth of photons absorbed by single NV centers as a function of temperature T. We find that for T < 100 K the main dephasing mechanism contributing to the linewidth broadening is phonon-mediated population transfer between the two excited orbital states. The observed T5 temperature dependence of the population transfer rate and linewidth is experimental evidence of a dynamic Jahn-Teller effect in the excited states.

7611-08, Session 2

NV centers in diamond nanopillars

N. Dinyari, H. Wang, Univ. of Oregon (United States)

We report experimental studies on the fabrication and characterization of diamond nanopillars and on the coupling of nitrogen vacancy centers in these pillars to whispering gallery modes in a silica microsphere.

7611-09, Session 2

High-Q microcavities coupled to NV-centers in single crystal diamond

P. E. Barclay, K. C. Fu, C. M. Santori, R. G. Beausoleil, Hewlett-Packard Labs. (United States)

We demonstrate optical coupling between diamond nitrogen vacancy (NV) centers and microcavities fabricated from a hybrid gallium phosphide and single crystal diamond material system. Whispering gallery mode cavities with Q > 20 000 are measured experimentally, and we report on progress to realize photonic crystal cavities with wavelength-scale optical confinement in this system.

7611-10, Session 3

Optimization of linear optical quantum computing circuits

J. Dowling, Louisiana State Univ. (United States)

7611-11, Session 3

Approaches to Heisenberg-limited quantum sensing using coherent states

C. C. Gerry, Lehman College (United States)

There has been much discussion on the efficacy of the so-called N00N states, maximally path-entangled states of N photons, for Heisenberg-limited quantum metrology and quantum sensing. In Heisenberg-limited interferometry the uncertainty in the measured phase shift goes as 1/N. But one must start with Fock states containing N photons and these are hard to generate, especially for arbitrarily large N. As an alternative, I discuss an approach using coherent states, relatively easy to generate, which are subsequently converted into maximally path-entangled coherent states, which then lead to Heisenberg-limited phase uncertainty in terms of the average photon number of the coherent state if the measured quantity is photon number parity at one output of the interferometer. I shall discuss several ways of producing maximally entangled coherent states and for measuring the photon number parity. I shall discuss a design of a quantum sensor which could operate continuously, that is, a design where maximally entangled coherent states are continuously (unitarily) generated from input coherent states and where parity measurements at the output can be performed continuously. Nonlinear interferometers involving self-Kerr interactions only are required.

7611-12, Session 3

Noiseless linear amplification and distillation of entanglement

G. J. Pryde, Griffith Univ. (Australia)

7611-14, Session 3

Quantum tripwire

P. M. Anisimov, B. McCracken, D. Lum, J. P. Dowling, Louisiana State Univ. (United States)

A quantum tripwire is a quantum interrogation technique based on single photon interference in a Mach-Zehnder interferometer (MZI). This interference is lost if one arm of the interferometer is blocked, and this change in signal trips an alarm.

The original approach of Elitzur and Vaidman was based on the probability of a photon arriving at the dark port of the interferometer if an object was present, yielding 50% maximal efficiency. Kwiat's improved scheme was based on a quantum Zeno effect (QZE) which promised to be 100% efficient under ideal conditions and the limit of infinite circulation through the MZI. More importantly, the probability based detection becomes known only in the limit of an infinite number of photons.

Our analysis assumes a limited number of photons, and presence or absence of an object is determined based on the outcomes. Symmetric hypothesis testing and the Chernoff bound were used to estimate the error of a wrong decision in one trial. Finally, Chernoff distance was calculated to provide error estimation after N trials and the inefficiency of previous schemes was confirmed.

The final piece of the puzzle was a "partial" QZE. We deliberately introduce a controlled loss in the detection arm such that QZE takes place only partially and results in high photon loss. If the path is blocked then full QZE is achieved leading to low photon loss. System optimization has shown that detection error after N trials can be exponentially small without the single photon being lost to the object.

7611-15, Session 4

Photonic quantum circuits and its application

S. Takeuchi, Hokkaido Univ. (Japan)

In this talk, our recent activities on the manipulation of the quantum states of photons and its applications are reviewed. In the former part of this talk, we present our recent demonstration of `an entanglement filter' (Science 323 (2009) 483) that passes a pair of photons if they have the desired correlations of their polarization. In the latter part of this talk, we report our activities on micro/nano photonic devices toward optical quantum information processing, microsphere resonators coupled with tapered fibres.

7611-16, Session 4

Tailored state preparation for solid-state quantum memory

E. A. Goldschmidt, Joint Quantum Institute (United States); S. E. Beavan, The Australian National Univ. (Australia); J. Fan, S. V. Polyakov, Joint Quantum Institute (United States); A. L. Migdall, National Institute of Standards and Technology (United States)

We report progress using spectral hole-burning in a rare-earth ion-doped crystal (Pr3+:Y2SiO5) to prepare an ensemble of rare-earth ions with a spectral distribution optimized for use in a Duan-Lukin-Cirac-Zoller-type (DLCZ) quantum-repeater scheme. Rare-earth ion-doped crystals hold significant promise for quantum information applications because of their demonstrated seconds-scale coherence times. However, large inhomogeneous broadening of the optical transitions in these samples requires the use of spectral hole-burning techniques to prepare ensembles with appropriate spectral features for such applications. We develop a model of spectral hole-burning in rare-earth ion-doped crystals which includes the effects of the finite spectral width of the optical field used for hole-burning as well as effects of the propagation of the hole-burning field through an optically thick ensemble. We use this model to computationally optimize the parameters of our state preparation scheme for the DLCZ protocol, including the intensity and pulsing parameters of the hole-burning field. We experimentally realize our state preparation scheme to generate spectrally narrow absorbing features on a background emptied of absorbers. We also use spectral hole-burning techniques to experimentally implement narrow-band spectral filtering to separate optical fields with frequencies that differ by only a few MHz. We discuss our computational and experimental progress and our plans for further work.

7611-17, Session 4

Maximum coherence in optical transitions in rare earth ion-activated solids

A. K. Rebane II, R. K. Mohan, C. W. Thiel, Montana State Univ. (United States)

Using quantum properties of electromagnetic radiation holds promise for future information technology, provided that suitable materials capable of capturing and efficiently maintaining the coherence information can be found or developed. We investigate crystalline materials containing resonantly absorbing rare earth ions from the viewpoint of maximizing the coupling between the optical field and the quantum system, which occurs in the limit of purely radiative decay of the excited state.

7611-34, Poster Session

Tapered fiber coupling to microspheres at cryogenic temperature

H. Takashima, Hokkaido Univ. (Japan) and The Institute of Scientific and Industrial Research (Japan); K. Toubaru, The Institute of Scientific and Industrial Research (Japan); M. Fujiwara, Hokkaido Univ. (Japan) and The Institute of Scientific and Industrial Research (Japan); H. Fujiwara, K. Sasaki, Hokkaido Univ. (Japan); S. Takeuchi, Hokkaido Univ. (Japan) and The Institute of Scientific and Industrial Research (Japan)

Fiber-coupled microspherical resonators coupled with single-light emitters having a narrow homogenous line width have attracted attention recently as one of the most promising cavity systems for solid-state quantum information devices, such as single photon sources and quantum phase gates. In order to maintain a long coherence time of the single light emitter, low temperature environment is required for such an experiment. We, therefore, develop a liquid helium flow cryostat system and demonstrate the coupling between the tapered fibers and the microspheres at cryogenic temperature.

The experiments were demonstrated as follows. A microsphere with a stem was attached to a three-dimensional piezoelectric stage and coupled to the tapered fibers in a large sample chamber (20 cm diameter) of the cryostat. Thanks to this large space, the tapered fibers can be installed in the cryostat without bending. To cool these samples, low pressure helium gas is filled into the sample chamber. In order to probe the coupling between the tapered fiber and the microsphere, tunable single-frequency diode lasers were used and scanned around the resonant peaks of the microspheres.

We measured the dependence of the transmittance spectrum with changing the gap distance between the microsphere and the tapered fiber near 1562.14 nm and at 10 K, and observed the change of the coupling condition of resonant dips from under-coupling to over-coupling. Moreover, we succeeded in the observation of the resonant dips near 638 nm at 8 K.

7611-20, Session 5

Fast optically driven spin qubit gates in an InAs quantum dot

E. D. Kim, Univ. of Michigan (United States) and Stanford Univ. (United States); K. Smirl, X. Xu, B. Sun, P. R. Berman, D. G. Steel, Univ. of Michigan (United States); A. S. Bracker, D. G. Gammon, Naval Research Lab. (United States); L. J. Sham, Univ. of California, San Diego (United States)

Self-assembled quantum dots (QDs) containing a single electron are a highly attractive solid state system for the development of a practical quantum computing architecture. The spins of QD confined electrons have been shown to possess both a long lifetime and a long coherence time and may also be controlled optically, offering the prospect of ultrafast qubit gate operations. Here, we present experimentally realized electron spin qubit gates in a single self-assembled InAs QD using a combination of picosecond optical pulses, spin precession about an external DC magnetic field and optically generated geometric phases. The optical pulses serve to rotate the electron spin about the optical axis, z, while the magnetic field, applied along x, leads to spin precession about x. These two types of rotations may be combined to construct arbitrary unitary operations on the electron spin. In addition, we show that a narrow-bandwidth continuous wave (CW) optical field tuned to one of the optical transitions in the QD may be used to drive a net rotation of the electron spin about the magnetic field axis by the effect of geometric phases imparted to the optically driven electron spin state. The ability to generate these geometric phases with optical pulses would in principle enable the development of arbitrary ultrafast optical spin qubit gates.

7611-21, Session 5

Ultrafast optical spin echo for electron spins in semiconductors

S. M. Clark, Stanford Univ. (United States); K. C. Fu, Hewlett-Packard Labs (United States); Q. Zhang, T. D. Ladd, Stanford Univ. (United States) and National Institute of Informatics (Japan); C. R. Stanley, Univ. of Glasgow (United Kingdom); Y. Yamamoto, Stanford Univ. (United States) and National Institute of Informatics (Japan)

Spin-based quantum computing and magnetic resonance techniques rely on the ability to measure the coherence time T2 of a spin system. We report on the experimental implementation of all-optical spin echo to determine the T2 time of a semiconductor electron-spin system. We use three ultrafast optical pulses to rotate spins an arbitrary angle and measure an echo signal as the time between pulses is lengthened. Unlike previous spin-echo techniques using microwaves, ultrafast optical pulses allow clean T2 measurements of systems with dephasing times (T2*) fast in comparison to the time scale for microwave control. This demonstration provides a step toward ultrafast optical dynamic decoupling of spin-based qubits.

7611-22, Session 5

Ultrafast optical spin echo of a single electron spin in a quantum dot

K. De Greve, D. L. Press, Stanford Univ. (United States); T. Ladd, Stanford Univ. (United States) and National Institute of Informatics (Japan); B. Friess, Julius-Maximilians-Univ. Würzburg (Germany); P. McMahon, Julius-Maximilians-Univ. Würzburg (United States); C. Schneider, M. Kamp, S. Hoefling, A. W. B. Forchel, Julius-Maximilians-Univ. Würzburg (Germany); Y. Yamamoto, Stanford Univ. (United States) and National Institute of Informatics (Japan)

We report on the implementation of a Hahn echo on a single electron spin confined in a quantum dot, through the application of ultrafast, detuned optical rotation pulses ($\pi/2$-π-$\pi/2$-sequence). Without intermediate π-pulse, a 2-pulse Ramsey interference experiment is subject to dephasing in a time-ensemble measurement due to variations in the nuclear spin environment (T_2^*-effect, ns-timescale). Interposing a Hahn echo pulse (π) overcomes this dephasing, and the the decay of the resulting interference fringes as a function of the delay time between the pulses allows to measure the electron spin decoherence time T_2. We measure a T_2-time of 3 µs, which together with all-optical single spin rotation times of 30 ps, would allow for 10^5 single qubit gate operations before decoherence. We further discuss the prospects for extending these experiments to spins with different nuclear spin environments, such as hole-spins in quantum dots or electron spins bound to fluorine impurities in ZnSe.

7611-23, Session 5

Optical manipulation of quantum dot excitons strongly coupled to photonic crystal cavities

J. Vuckovic, Stanford Univ. (United States); A. Faraon, HP Labs. (United States); A. Majumdar, C. Lin, Stanford Univ. (United States); D. R. Englund, Columbia Univ. (United States)

7611-24, Session 5

Optically probing and controlling two coupled quantum dots

D. G. Gammon, Naval Research Lab. (United States)

A semiconductor quantum dot is like an artificial solid state “atom”. Two dots separated by a thin tunneling barrier form a “molecule”. Moreover, the spin of a single electron in a quantum dot provides a quantum memory - one that can be controlled and measured optically. We present our recent results on coupling two spins in a self-assembled InAs/GaAs quantum dot molecule.

7611-25, Session 6

Direct measurement of quantum dot spin dynamics using resonance fluorescence

M. Atature, Univ. of Cambridge (United Kingdom)

Self-assembled semiconductor quantum dots (QDs) have atom-like properties such as discrete energy levels coupled by optical transitions and their coherence properties can be revealed in quantum-optics experiments. Further, the availability of these transitions are governed by spin-dependent optical selection rules. This opens a channel to control and detect a single spin in a quantum dot via lasers. However, QDs can also interact strongly with a spin (nuclei) and/or a charge (electrons) reservoir of the solid-state environment leading to a rich source of interaction mechanisms. Consequently, identifying the regimes of these mechanisms is crucial for achieving a level of control in solid-state-based systems similar to that of atoms. A highlight of recent progress on all-optical control of quantum dot spins will be provided.

7611-26, Session 6

Coherent control of quantum emitters in cavities

C. Shih, A. Muller, E. B. Flagg, The Univ. of Texas at Austin (United States); D. G. Deppe, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States); G. J. Salamo, Univ. of Arkansas (United States)

Semiconductor nanostructures such as quantum dots (QDs) have offered unique opportunities to investigate sophisticated quantum optical effects in a solid-state system. These include quantum interference, Rabi oscillations, as well as photon antibunching, that were previously only observable in isolated atoms or ions. In addition, QDs can be readily integrated into optical microcavities, making them attractive for a number of applications, particularly quantum information processing and high efficiency quantum light sources. In spite of these tremendous progresses, one area that was little explored was coherently control of such solid-state quantum emitters in the cavities. The main technical hurdle lies in the difficulties in eliminating the laser scattering background. By using a sample structure entailing embedding QDs in a planar Fabry-Perot cavity and by using an orthogonal excitation geometry, we have achieved a nearly complete elimination of laser scattering background. This in turns allows us to show resonantly controlled light emissions of quantum dots in the cavity including (a) Nearly ideal fidelity of Rabi flopping using pulse control, (b) direct observation of Mollow triplets in frequency domain, and (c) simultaneously measured first-order and second order photon-photon correlations.

Return to Contents

7611-27, Session 6

Integrated photonic crystal networks with coupled quantum dots

A. Faraon, A. Majumdar, Stanford Univ. (United States); D. R. Englund, Harvard Univ. (United States); Z. Lin, J. Vuckovic, Stanford Univ. (United States)

Single InAs quantum dots can be used to control the transmission function of photonic crystal cavities, as we have already shown for systems that operate both in strong and weak coupling regime. Here we present our most recent work on devices where the cavity is connected in a micron-scale optical network via multiple photonic crystal waveguides terminated with input and output optical couplers. This architecture allows for multiple signal and control beams to be coupled simultaneously in the cavity via distinct ports. The devices are equipped with two input ports where the waveguides are terminated with input grating-couplers that allow for coupling into the waveguide from an out-of-plane direction. A third waveguide coupled to the cavity is terminated with a different kind of grating out-coupler that allows for improved directional scattering of the light transmitted through the cavity. We have already shown in previous experiments with a single cavity with coupled quantum dots, that this system acts as a highly nonlinear medium that enables all optical switching at powers down to the single photon level. In our most recent experiments we show that this switching can be done in integrated structures, as needed for optical signal processing devices for both classical and quantum information science.

7611-28, Session 6

Optimal pulse to generate non-classical photon states via photon blockade

A. Majumdar, A. Faraon, J. Vuckovic, Stanford Univ. (United States)

The single photon character of nonclassical states of light that can be generated using photon blockade is analyzed for time domain operation. There are a few advantages of using photon blockade to generate single photons in a semiconductor system. First, the produced single photons are indistinguishable and jitter-free. Secondly, the collection efficiency of the photons is very high due to the presence of the cavity. Also, one does not need a multi-level atomic system in contrast to the schemes based on atom-optics. It is shown that using photon blockade and an optimal pulse-area, we can achieve 85% single photon population, with multi-photon population of just 8%. We showed that the single photon population oscillates with the pulse-area. This non-classical state generated by photon blockade performs better than a weak coherent pulse, when applied to BB84 quantum cryptography protocol.

7611-29, Session 7

Quantum metrology with cold atoms

M. A. Kasevich, Stanford Univ. (United States)

7611-30, Session 7

Optimal quantum measurements for optical phase

H. Lee, Louisiana State Univ. (United States)

7611-31, Session 7

Imaging by means of quantum nonlinear optics

R. W. Boyd, Univ. of Rochester (United States)

7611-32, Session 7

Entanglement-boosted bright-source interferometry

W. N. Plick, P. M. Anisimov, J. P. Dowling, Hearne Institute for Theoretical Physics (United States)

We present a new scheme for optical interferometry. It has the potential to reach far below the standard quantum limit (SQL) on phase sensitivity. This new proposal avoids the pitfalls of other schemes. It requires no complicated detection protocol, relying on simple intensity measurement. Furthermore, traditional bright coherent sources may be employed. Instead of relying solely on exotic resources such as entangled light or bose-einstein condensates our setup takes as its input coherent light and ``boosts" it with entangled photons from optical parametric amplifiers. The result is a hybrid device which posses the advantages of both squeezed and coherent interferometry, namely, high intensities and sub-SQL scaling. Perhaps most strikingly, this scheme relies on no unknown components and is constructible with current technology.

7611-33, Session 7

Sub-Rayleigh quantum imaging

L. Maccone, Massachusetts Institute of Technology (United States)

Any imaging apparatus cannot produce perfect images: its resolution is limited by the Rayleigh diffraction bound, a consequence of its finite spatial extension. We show various N-photon strategies that allow to resolve details that are smaller than this bound. These methods are loss resistant, since they can employ classical light in each mode. Our results may be of importance in many imaging applications: microscopy, telescopy, lithography, metrology, etc.

7611-35, Session 7

Single photon detection system based on superconducting nanowires for quantum communication

L. Zhang, L. Kang, J. Chen, W. Xu, P. Wu, Nanjing Univ. (China)

A single photon detection system based on superconducting nanowire is described. To make the detector itself, NbN film 4 nm thick is deposited on MgO(100) substrate over an area of 10×10   m2 and patterned into meander line. A single mode fiber is used to couple the signal to the detector. At 4.2 K the maximum system efficiencies are 4.1% at 1310 nm and 2.1% at 1550 nm respectively, while for a dark count rate of 1 Hz, the system efficiencies are 0.6% at 1310 nm and 0.2% at 1550 nm respectively. Two cooling schemes have been developed, one is to dip the detector in liquid helium while the another is to use a close-cycled refrigerator. Field tests indicate that the system is reliable, stable and easy to operate. Higher efficiencies and lower dark count rates can be obtained at lower temperatures.

Conference 7612: Advances in Slow and Fast Light III

Monday-Tuesday 25-26 January 2010 • Part of Proceedings of SPIE Vol. 7612

Advances in Slow and Fast Light III

7612-01, Session 1

EIT-based slow and fast light in an all-fiber system

F. A. Benabid, Univ. of Bath (United Kingdom)

No abstract available.

7612-02, Session 1

All-optical SBS avalanche detector

M. J. Steiner, U.S. Naval Research Lab. (United States)

No abstract available.

7612-03, Session 1

Optical fiber microcoil delay line

M. Sumetsky, OFS (United States)

No abstract available.

7612-04, Session 1

Slow light propagation using optical nanofibers

K. Hakuta, The Univ. of Electro-Communications (Japan)

No abstract available.

7612-05, Session 1

Slow light applications of forward stimulated Brillouin scattering

D. J. Gauthier, Duke Univ. (United States)

No abstract available.

7612-06, Session 1

Spatial and temporal evolution of transient stimulated-Brillouin-scattering slow-light pulse in an optical fiber

L. Ren, Xi'an Institute of Optics and Precision Mechanics (China); Y. Tomita, The Univ. of Electro-Communications (Japan)

Recently, slow-light technology via stimulated Brillouin scattering (SBS) in an optical fiber has attracted a lot of attention owing to its low pump threshold, flexible spectrum tailoring capacity, and good compatibility with existing telecommunication systems. In this paper we present a general theoretical model for analyzing the dynamic behavior of the nonlinear interactions of the transient SBS process based on the three-wave coupled-amplitude equations for the pump, Stokes and acoustic waves. Spatial and temporal evolution of a generating slow-light pulse with the duration of sub-nanosecond can be numerically calculated because our model includes the second-order derivative of the acoustic field. We introduce how this two-boundary initial problem could be efficiently solved. And we conclude that the physical origin of the pulse broadening and distortion can be explained in terms of the temporal decay of the induced acoustic field. Moreover, this theoretical model is applicable to both narrowband and broadband pump cases.

7612-07, Session 2

Electromagnetically-induced transparency and slow and fast light in a room-temperature vapor of 4He*

R. Ghosh, Jawaharlal Nehru Univ. (India); F. Goldfarb, F. Bretenaker, Univ. Paris-Sud 11 (France); J. Ghosh, Jawaharlal Nehru Univ. (India)

No abstract available.

7612-08, Session 2

Recent developments in the study of slow and fast light in a vapor

R. Walsworth, Harvard-Smithsonian Ctr. for Astrophysics (United States); Y. Xiao, Fudan Univ. (China)

No abstract available.

7612-10, Session 2

Slow light in Cesium vapor: pulse delay measurements and predicted delay

M. D. Anderson, G. P. Perram, Air Force Institute of Technology (United States)

Recently there has been increased interest in slow light for applications in optical communications, signal processing, and optical switching. Among the various slow light schemes which allow for control of pulse propagation and tunable delay of optical signals, a fundamental example occurs in the region near optical resonances. We are using the doublet structure of the cesium D2 line to produce tunable optical delays of approaching 50 ns. Group velocity is controlled by varying vapor pressure and/or temperature. Delay measurements are reported across the full cesium D2 spectrum and delay predictions are compared to experimental results.

Delay measurements and computer model predicted delays are reported across the full Cesium D2 spectrum (+/- 20GHz). Setup used a modulated 10ns pulse with Cs cell temperatures ranging from 70-120 deg C.

7612-11, Session 3

Coupled resonator gyroscopes: what works and what does not

M. J. F. Digonnet, M. A. Terrel, S. Fan, Stanford Univ. (United States)

No abstract available.

7612-12, Session 3

Symmetry induced modal dispersion in CROWs

J. Scheuer, Tel Aviv Univ. (Israel)

No abstract available.

7612-13, Session 3

Prospect for development of pulsed CPT Raman-Ramsey clock using atomic vapor

G. S. Pati, Northwestern Univ. (United States); F. K. Fatemi, M. Bashkansky, U.S. Naval Research Lab. (United States); S. M. Shahriar, Northwestern Univ. (United States)

No abstract available.

7612-14, Session 3

Simulated investigation of high-sensitive slow light interferometer

Y. Zhang, Y. Cai, C. Yang, Harbin Institute of Technology (China); Y. Zhang, Harbin Normal Univ. (China); B. Dang, P. Yuan, S. Qiang, Harbin Institute of Technology (China)

We showed that the addition of slow light medium could enhance the spectral sensitivity of interferometer effectively by numerical simulation. And the sensitivity is proportional to the group refractive index of slow light medium. We proposed a requirement for the laser source in slow light interfromenter, including its bandwidth, scanning step when designing the slow light interfrometer. According to the material dispersion characteristics, we selected GaAs as slow light material for the interfrometer.

The K-K relationship shows that there is a large group index in a severe absorption area. GaAs material has a fast variation nearby =900nm which means a larger group index. At =895nm its refractive index and group refractive one are 3.7 and 5.2 respectively, and at =910nm they are 3.57 and 4.8 respectively. The difference between the group and refractive indices is significant. Although the group index at 890nm is larger, the transmittance is low which brings great difficult to the detection. Multi beam interference theory indicates that the interference stripes is influenced by the surface roughness, absorption and the wedge angle. Because of the existence of the absorption and this small wedge angle the imaging quality cannot be got by increasing the index alone. Considering the dispersive property of GaAs, the region between 895nm~915nm is a effective window.

The sensitivity can be enhanced as five times as theoretical result. The study on the slow light interference can not only enhance the spectral sensitivity but also is a convincing proof of the slow light mechanism.

7612-15, Session 4

Slow and stopped images

J. C. Howell, Univ. of Rochester (United States)

No abstract available.

7612-16, Session 4

New applications of slow and fast light

R. W. Boyd, Univ. of Rochester (United States)

No abstract available.

7612-17, Session 4

Superluminal laser: properties and applications

H. Yum, Texas A&M Univ. (United States) and Northwestern Univ. (United States); Y. Wang, Northwestern Univ. (United States); P. R. Hemmer, Texas A&M Univ. (United States); S. M. Shahriar, Northwestern Univ. (United States)

No abstract available.

7612-18, Session 5

Nonanalytical points and the speed of information in a fast light medium

W. F. Silva, M. A. R. C. Alencar, D. Pereira Caetano, J. M. Hickmann, Optics and Materials Group (Brazil)

The increasing demand for faster and broader communications systems have motivated the research on novel schemes for the development of photonic devices. Recently, there has been a huge interest to exploit the phenomena of fast and slow light propagation aiming communications applications. However, this applied research is intimately connected to a fundamental question of physics: what is the information velocity on these systems? In this work, it is proposed a new way to model information mathematically and physically, associating it with unpredictable changes of optical pulses. These pulses are described by a compact support function containing well behaved non analytical points which are associated to information. The information speed is investigated numerically for this pulse propagation through a fast light medium. This medium is modeled as a two level system that presents anomalous dispersion. The propagation was calculated using the frequency domain Fourier or the time domain convolution methods. In both cases the results are the same. It was observed that although the pulse group velocity can be larger than the speed of light in vacuum when the pulse propagates through a medium, the non analytical point velocities are limited by the velocity of light c. Another interesting feature observed for longer propagation is a steepening effect and eventually an optical shock, because the peak of the pulse moves at a group velocity faster than c and the non analytical point moves at c. Our results indicate that this approach is suitable for the investigation of the information velocity in fast or slow light medium.

7612-19, Session 5

Why slow light and fast light are different

J. B. Khurgin, The Johns Hopkins Univ. (United States)

No abstract available.

7612-20, Session 5

Non-linear interactions in electromagnetically induced transparency and related pump-probe optical phenomena in moving atomic systems

V. L. Jacobs, U.S. Naval Research Lab. (United States)

No abstract available.

7612-21, Session 6

Understanding the rich physics of light propagation in slow photonic crystal waveguides

T. F. Krauss, Univ. of St. Andrews (United Kingdom)

No abstract available.

7612-22, Session 6

Coupled cavities and band-edge slow-light in periodic waveguides

A. A. Sukhorukov, The Australian National Univ. (Australia)

No abstract available.

7612-23, Session 6

On-chip studies of slow and fast light

M. F. Lipson, Cornell Univ. (United States)

No abstract available.

7612-24, Session 6

Fast optical correlator via thermal delay tuning in photonic crystal coupled waveguide

N. Ishikura, J. Adachi, T. Baba, Yokohama National Univ. (Japan) and JST-CREST (Japan)

We demonstrate fast optical correlator based on tunable slow light in photonic crystal coupled waveguide (PCCW). We have studied wideband dispersion-free slow light and its tunability in chirped PCCW on SOI substrate. The tunable delay was obtained for picosecond optical pulses by sloping device temperature using laser heating. The widest tuning range is now over 100 ps. In this paper, we propose to use it for the correlator. Because correlators now available employ the movement of mirrors for time-domain scanning, their response speed is of 10 Hz order. We replaced this with the tunable PCCW of 280 microns length. The thermo-optic effect by the laser heating is expected to have a speed of kHz order, which is more suitable for fast data mapping than the mechanical scanning. In this experiment, we tested it for acquiring cross-correlation traces of 1 ps wide optical pulse by modulating the laser with a linear signal of 10 Hz - 100 kHz frequency. We successfully observed the trace of the pulse up to 10 kHz. It is 100 - 1000 times faster than the mechanical one. The pulse shape was gradually deformed when the speed was over 10 kHz, suggesting the thermal response of this device. Due to nonlinear dependence of the delay on heating power, the scanning range was limited to 3.5 ps. But it can be extended to several 10 ps by modifying the modulation signal so that the nonlinear dependence is compensated.

7612-25, Session 7

High-Q passive and active microresonators for dispersion and delay line applications

Y. Dumeige, S. Trébaol, P. Féron, Ecole Nationale Supérieure des Sciences Appliquées et de Technologie (France)

No abstract available.

7612-26, Session 7

Tuning of microring resonators

S. Mookherjea, Univ. of California, San Diego (United States)

No abstract available.

7612-27, Session 7

Slow and fast light propagation in bulk semiconductors: spectral averaging and pulse distortion effects

R. H. Binder, B. Gu, N. Kwong, College of Optical Sciences, The Univ. of Arizona (United States)

No abstract available.

7612-28, Session 7

Nonlinear distortion and spurious-free dynamic range of a tunable delay line based on slow light in SOA

P. Berger, Thales Research & Technology (France) and Laboratoire Aimé Cotton (France); J. Bourderionnet, Thales Research & Technology (France); M. Alouini, Institut de Physique de Rennes (France) and Thales Research & Technology (France); D. Dolfi, Thales Research & Technology (France); F. Bretenaker, Laboratoire Aimé Cotton (France)

Slow light based tunable lines have been intensively studied over the past years for microwave photonics applications. The main focus has been to understand and modelize the underlying phenomena, and to increase the delays and/or the bandwidth of the effect. Among the different slow and fast light architectures, coherent population oscillations (CPOs) in a Semiconductor Optical Amplifier (SOA) offer attractive operational advantages in terms of compactness, integrability and possible parallelism, as well as a continuous tunability of the delay through the injected current. This technology is therefore a promising approach for integration in radar systems.

One of the key parameter of a microwave photonics link for radar applications is the spurious-free dynamic range (SFDR). It represents the operational dynamic range of the link, i.e. the usefull range of RF powers, at a given frequency, for which all spurious signals at harmonic and intermodulation frequencies are below the noise level at the output of the link.

We will present a predictive model to determine the harmonic and intermodulation distortion generation, which takes into account the spatial evolution of the saturation parameters along the SOA's length. The third order intermodulation distortions (IMD3) are then computed over the frequency range of interest for radar applications (up to 20GHz), and for various injected currents. The corresponding SFDR is derived, and finally, we will discuss the influence of the amount of initial distortion on IMD3 generation and SFDR and give some preliminary experimental assessments.

7612-29, Session 8

Control of group velocity in metamaterials

M. Orenstein, G. Rosenblatt, P. Ginzburg, Technion-Israel Institute of Technology (Israel)

No abstract available.

7612-30, Session 8

Recent developments in the study of slow light in complex photonic materials

O. Hess, Univ. of Surrey (United Kingdom)

No abstract available.

7612-31, Session 8

Silicon photonics and silicon plasmonics for slow light applications

U. Levi, The Hebrew Univ. of Jerusalem (Israel)

No abstract available.

7612-32, Session 9

Modulation of single photons

C. Chuu, C. Belthangady, G. Yin, S. E. Harris, Stanford Univ. (United States)

No abstract available.

7612-33, Session 9

Disorder-immune slow light with topological electromagnetic modes

Z. H. Wang, Massachusetts Institute of Technology (United States)

No abstract available.

7612-34, Session 9

Raman amplification in light-stopping systems

M. L. Povinelli, Stanford Univ. (United States)

No abstract available.

7612-35, Session 9

Recent advances in slow and fast light for applications in microwave photonics

J. Mørk, W. Xue, Y. Chen, S. Blaaberg, Technical Univ. of Denmark (Denmark); S. Sales, J. Capmany, Univ. Politécnica de Valencia (Spain)

No abstract available.

7612-36, Session 9

Pulse propagation in two-photon resonance media

A. K. Rebane II, Montana State Univ. (United States)

No abstract available.

Conference 7613: Complex Light and Optical Forces IV

Wednesday-Thursday 27-28 January 2010 • Part of Proceedings of SPIE Vol. 7613
Complex Light and Optical Forces IV

7613-01, Session 1

Generation of structured beams in large-Fresnel number degenerate cavities and beam transformation with orbital angular momentum

T. Lu, National Taiwan Normal Univ. (Taiwan); Y. Lin, Y. Chen, K. Huang, National Chiao Tung Univ. (Taiwan)

We employ a large-Fresnel-number laser system to demonstrate the exotic three-dimensional (3D) optical coherent waves localized on Lissajous parametric surfaces with Lissajous transverse patterns. The coherent structured beams are verified to be composed of degenerate Hermite-Gaussian modes with different longitudinal indices resulted from longitudinal-transverse coupling in degenerate cavities. More strikingly, experimental results reveal that the mode locking of the 3D coherent states forms a nearly complete Devil's staircase with the hierarchical ordering. The experimental structured beams are stable and reproducible, and there is a good agreement between numerical and experimental results.

As well known, the Hermite-Gaussian modes can be converted into Laguerre-Gaussian modes possessing well-defined orbital angular momentum by use of a pair of cylindrical lens. This finding leads to wide applications and provides deep insights for studying optical angular momentum. In this work, we make use of cylindrical lens to transform the Lissajous structured beams superposed of degenerate Hermite-Gaussian modes into the composition of degenerate Laguerre-Gaussian modes. These degenerate Laguerre-Gaussian modes form the intriguing trochoidal structured beam possessing optical orbital angular momentum. The magnitude of orbital angular momentum depends on the mean value of the order of Hermite-Gaussain modes before transformation by cylindrical lens. We further demonstrate that the orbital angular momentum of the trochoidal structured beam can be facilely manipulated.

7613-02, Session 1

Selective excitation of high-order laser modes and its application to vortex array laser beams generation

S. Chu, National Cheng Kung Univ. (Taiwan); K. Otsuka, Tokai Univ. (Japan)

This study reports a scheme to create vortex array laser beams by superposing some kinds of high-order laser modes, on its rotated replicas. An interferometer configuration was used to convert these high-order laser modes to vortex array laser beams containing multi vortexes aligned nearly in square manner. For the generation of such kind vortex array laser beams, this study reports systematic approaches to the selective excitation of high-order laser modes in end-pumped solid-state lasers with a designed laser resonators and the asymmetric pumping. The resulting vortex array laser beams can be applied to optical tweezers and atom traps in the form of two-dimensional arrays, or to study the transfer of angular momentum to micro particles or atoms (Bose-Einstein condensate).

7613-03, Session 1

Optical twists in both phase and amplitude profile

V. R. Daria, The Australian National Univ. (Australia); D. Palima, P. J. L. Rodrigo, J. Gluckstad, Technical Univ. of Denmark (Denmark)

The orbital angular momentum (OAM) of optical fields with phase singularities has been instrumental in creating super-fluid vortex modes in Bose-Einstein condensates, rotating cold atoms and revolving microscopic particles. Here, we describe a novel diffracting beam with OAM but with a helical profile in both phase and amplitude components of the beam. This is different from Laguerre-Gaussian (LG) beams where only the phase component has a helical profile, which introduces a phase singularity at the centre and produces a dark region surrounded by a ring-shaped light pattern. For LG-beams, the ring radius is proportional to the degree of helicity or topological charge of the beam. Our beam is initially characterized with an apodized helical phase front at the outskirts and linearly scaled towards no phase singularity at the centre of the beam. At the focus, we show that our beam forms an intensity distribution that can be accurately described as an "optical twister". Unlike LG beams, it has minimal changes in radius but with a scalable OAM. Furthermore, we characterize the OAM in terms of its capacity to introduce spiral motion on particles trapped along its orbit. We also show that our "optical twister" maintains a high concentration of photons at the focus even as the topological charge is increased. Such beams can be applied to fundamental studies of light and atoms such as in quantum entanglement of the OAM, toroidal traps for cold atoms and for optical manipulation of microscopic particles.

7613-04, Session 1

Stokes polarimetry of a hybrid vector polarization beam from a spun optical fiber

G. Milione, H. I. Sztul, R. R. Alfano, The City College of New York (United States); D. A. Nolan, X. Chen, J. Koh, Corning Inc. (United States)

Hybrid vector polarization (HVP) beams are a special case of cylindrical vector beams (CVB). The polarization of a HVP beam around the beam axis is cylindrically symmetric, similar to other CVBs, but also has a periodically varying state of elliptical, circular and linear polarization over the donut intensity profile. We will discuss the generation of a HVP beam at the output of a few mode, spun elliptical core, optical fiber by coupling an off-axis TEM00 fundamental laser mode at the input. The fiber output's polarization state is analyzed using the experimental method of Stokes polarimetry. The four Stokes parameters are directly related to the geometrical angle and ellipticity of an elliptical polarization state. Each Stokes parameter of the fiber output's polarization state is experimentally reconstructed from measurements with a CCD camera of the beam's intensity distribution passing through different combinations of a polarizer and a quarter wave plate. From the measured Stokes parameters, we numerically calculate the geometrical angle and ellipticity of each local polarization state in the beams transverse two-dimensional plain. The spatial distribution of all local polarization ellipses over the intensity profile is mapped and discussed.

Return to Contents

7613-05, Session 2

Optical singularities induced in a nematic-cell doped by carbon nanotubes

V. V. Ponevchinsky, Institute of Physics (Ukraine); A. N. Goncharuk, F. D. Ovcharenko Institute of Biocolloidal Chemistry (Ukraine); V. Vasil'ev, Institute of Physics (Ukraine); N. Lebovka, F. D. Ovcharenko Institute of Biocolloidal Chemistry (Ukraine); M. S. Soskin, Institute of Physics (Ukraine)

Liquid crystals (LCs) doped by carbon nanotubes display unique properties and have attracted attention due to possible applications [1]. The multi-walled carbon nanotubes (MWCNT) with 20÷30 nm diameter d, aspect ratio L/d ≈ 300 ÷ 1000 and 0.005-0.05 wt % were put into nematic 5CB cell with thickness of 20 mkm. They are arranged spontaneously into an irregular system of aggregates with occasional 3D network and areas of clean LC between them. The optical singularities were absent in the neat LC media. Pairs of optical vortices (OV) appear in a speckle field generated by scattering in of a He-Ne unfocussed laser beam a MWCNT irregular 3D network. Due to our knowledge, this was the first observation of optical singularities initiated by CNT system in a LC cell. OV pairs nucleate and annihilate when ac 10 kHz 0÷10 V electric field is applied across the LC cell. Electrical conductivity of LC/CNT composites demonstrates the tunneling, percolation-like and multiple-connected mechanisms of electrical conductivity behavior. An individual MWCNT is surrounded by a few micrometers thick transition cladding of 5CB molecules with 2nm long axis planar orientation on its surface. Namely it together with randomness of CNT structure originate speckle field with optical singularities.

[1] Jan P.V. Lagerwall and Giusy Scalia Carbon nanotubes in liquid crystals // J. Mater. Chem. - 2008. V. -18. - P. 2890-2898.

7613-06, Session 2

Generic dark hollow beams using negative cones chemically etched in fiber tips

N. K. Viswanathan, G. M. Philip, Univ. of Hyderabad (India)

We report here the generation and characteristics of dark hollow beams (DHBs), especially beams with cylindrical intensity distribution, helical wavefront and phase singularity, using negative cones chemically etched in the tip of optical fibers. Selective excitation of the different guided modes in optical fibers with different V-numbers ranging from 2.405 (single-mode) to 5.69 (multi-mode) etched to different cone dimensions are used to generate in a controllable way a variety of feature-rich DHBs. Negative cones are etched via selective chemical etching process which due to the different core and cladding dopants and dopant concentration results in different etch rates and hence different cone angles and cone depths. Input laser beam guided through the optical fiber diffracts and refracts at the tip resulting in the generation of Laguerre-Gaussian (LG), higher-order Bessel-Gaussian (BG), doughnut hollow and localized hollow beams. For example, overlap in the radiation coming out of the fiber core and cladding at different angles due to different apparent numerical aperture (NA) of the etched fiber tip results in a ring intensity distribution in the output plane. Positioning the ring intensity pattern in the front focal plane of a bi-convex lens results in Bessel intensity distribution whose characteristics are compared with that measured using positive cones etched in the fiber tip. Under certain excitation conditions we also observe DHBs with helical wavefront and phase dislocations embedded in the output beams whose characteristics will also be reported.

7613-07, Session 2

Orbital angular momentum experiments with broadband few cycle pulses

A. N. Richter, M. Bock, Max-Born-Institut für Nichtlineare Optik und Kurzzeitspektroskopie (Germany); J. Jahns, FernUniv. in Hagen (Germany); R. Grunwald, Max-Born-Institut für Nichtlineare Optik und Kurzzeitspektroskopie (Germany)

Bessel-Gauss beams and Laguerre-Gauss beams are well known to carry a certain orbital angular momentum of per photon. Optical vortices in highly intense femtosecond laser pulses are expected to lead towards a variety of specific new applications like momentum selective spectroscopy, nonlinear excitation and material interaction as well as ultrafast quantum information processing. In our experiments, diffractive spiral phase elements were used to generate Bessel-Gauss and Laguerre-Gauss beams with topological charges of =1 and =2. The propagation behaviour and spatio-spectral distribution of a Ti:sapphire laser oscillator beam was investigated under cw and mode-locked conditions. Experimental results are compared with data from analytical and numerical modeling. In addition to helical beam generation with fixed phase patterns, adaptive optical approaches based on liquid-crystal-on-silicon spatial light modulators (LCOS-SLMs) were investigated. For manipulating sub-20-fs pulses, a high-definition microdisplay with a phase step of p for the centre wavelength of 800 nm with excellent temporal transfer was applied as programmable beam shaper. Time-integrated intensity patterns were detected with a CCD matrix camera. The contrast resulting from spectral interference was analyzed in order to quantitatively describe the system perfomance. By further temporal phase measurements with LX-SPIDER technique and spectral mapping with a scanning fiber-based spectrometer, more detailed information about the spatio-temporal characteristics of the helical wavepackets was obtained. Future studies will include the generation of arrays of pulsed vortex beams.

7613-08, Session 3

The electrodynamic mechanisms of optical binding

D. L. Andrews, Univ. of East Anglia Norwich (United Kingdom)

The convenient term 'optical binding' encapsulates a variety of phenomena whereby light can exert a modifying influence on inter-particle forces. The mutual attraction that the 'binding' description suggests is not universal; both attractive and repulsive forces, as well as torques can be generated, according to the particle morphology and optical geometry. Generally, such forces and torques propel particles towards local sites of potential energy minimum, forming the stable structures that have been observed in numerous experimental studies. The underlying mechanisms by means of which such effects are produced have admitted various theoretical interpretations. The most widely invoked explanations include collective scattering, dynamically induced dipole coupling, optically-dressed Casimir-Polder interactions, and virtual photon coupling. By appeal to the framework that led to the first predictions of the effect, based on quantum electrodynamics, it can be demonstrated that each of these apparently distinct representations reflects a different facet of the same fundamental mechanism, leading in each case to the same equations of motion. Further analysis, based on the same framework, also reveals the potential operation of another mechanism, associated with dipolar response to local dc fields that result from optical rectification. This secondary mechanism can engender shifts in the positions of the potential energy minima for optical binding. The effects of particle size and multi-particle interactions can be addressed in a theoretical representation that is especially well suited for modelling applications, including the generation of potential energy landscapes.

7613-09, Session 3

Non-conservative forces in optical tweezers and Brownian vortexes

B. Sun, A. Y. Grosberg, D. G. Grier, New York Univ. (United States)

Mechanical equilibrium at zero temperature does not necessarily imply thermodynamic equilibrium at finite temperature for a particle confined by a static, but non-conservative force field. Instead, the diffusing particle can enter into a steady state characterized by toroidal circulation in the probability flux, which we call a Brownian vortex. The circulatory bias in the particle's thermally-driven trajectory is not simply a deterministic response to the solenoidal component of the force, but rather reflects an interplay between advection and diffusion in which thermal fluctuations extract work from the non-conservative force field. As an example of this previously unrecognized class of stochastic heat engines, we consider a colloidal sphere diffusing in a conventional optical tweezer. Molecular dynamics simulation using force field calculated through Lorentz-Mie theory is compared with experiment observation of a colloidal trajectory using digital holographic microsopy. We demonstrate that non-conservative optical forces bias the particle's fluctuations into toroidal vortexes whose circulation can reverse direction with temperature or laser power.

7613-10, Session 3

Fast and precise measurements of particle charge with optical trapping electrophoresis

F. Beunis, Univ. Gent (Belgium) and ICFO - Instituto de Ciencias Fotónicas (Spain); D. Petrov, ICFO - Instituto de Ciencias Fotónicas (Spain); B. Verboven, F. Strubbe, K. Neyts, Univ. Gent (Belgium)

Optical tweezers have been used extensively to measure the mechanical, chemical, optical and visco-elastic properties of colloidal solutions, biological cells and even single molecules. However, in view of the capability to measure small forces on single particles in an optical trap, surprisingly little research using optical tweezers has been carried out on the electrical properties of these materials. We subject micron-sized, optically trapped colloidal particles in different liquids to a sinusoidally varying electric field, and measure their resulting movement. From this movement, we calculate the electrophoretic mobility and charge (or, more generally, zeta-potential) of the particle in the liquid. The nature of the liquid (in particular its dielectric constant and ionic strength) determines how the electric fields can be generated in it, and we will show how the technique can be adapted for different kinds of liquid. The use of high frequencies (well above the corner frequency of the optical tweezers) allows us to measure the electrical charge on colloidal particles with an accuracy of the order of an electron charge at a speed up to a hundred measurements per second. This technique can be used, for example, to provide valuable information about the processes resulting in a charge on colloidal particles in nonpolar liquids, of which little is understood.

7613-11, Session 3

Spiral imaging of a sphere

D. Petrov, N. Rahuel, L. Torner, ICFO - Institut de Ciencias Fotónicas (Spain)

We study experimentally the Mie scattering of a focused Laguerre-Gaussian (LG) beam by a micron-size sphere using the concept of the spiraling imaging, i.e. exploring the state of orbital angular momentum of the scattered light. In our experiments we change the range of parameters so that both the paraxial regime (when the spin and orbital contributions of the incident beam can be manipulated separately) and the non-paraxial regime have been achieved. The technique consists in illuminating by a Gaussian beam polarized linearly or circularly of a blazed computer-generated hologram that converts the incident beam into a LG beam with the topological charge +1. This beam is focused then by a microscope lens with NA 0.25 or 1.3 on a dielectric sphere of a given radius and refractive index. The state of orbital angular momentum of the total transmitted beam (i.e. its spectrum of spiral modes) is analyzed by a second blazed hologram that splits the incoming beam into several diffraction orders. The field distribution of each diffraction order is analyzed when the sphere moves through the focus of the incident beam. One of the goals of the study is to characterize the spatial resolution that can be achieved by using a specific spiral mode of the transmitted beam as a probe. Unlike other canonical objects exploited previously by the spiral imaging technique, the sphere obeys the symmetry elements similar to those of the incident beam which provides a stronger coupling between the spin and orbital angular momentum.

7613-12, Session 3

NanoTracker: force-sensing optical tweezers for quantitative single-molecule nanomanipulation

H. Eggert, J. van Mameren, A. Wozniak, T. Jaehnke, JPK Instruments AG (Germany)

In the past decade, experiments involving the manipulation and observation of nanostructures with light using optical tweezers methodology have developed from proof-of-principle experiments to an established quantitative technique in fields ranging from (bio)physics to cell biology. With optical tweezers, microscopically small objects can be held and manipulated. At the same time, the forces exerted on the trapped objects can be accurately measured.

With the Prism-Award winning NanoTracker a platform for performing experiments using specimen from single molecules to whole cells is available. With two time-continuous traps, it allows the controlled trapping and accurate tracking of nanoparticles, suspended either in a microfluidic multichannel flow chamber or even in a temperature-controlled open Petri dish. With its 3D detection system, particle displacements in the trap can be recorded with nanometer precision. Moreover, dynamic forces acting on the particle can be measured with better than picoNewton resolution on a microsecond time-scale.

Here, we discuss design features of and measurements done with the NanoTracker platform. In particular, we show how one of the hallmarks of single-molecule biophysics, the overstretching transition of DNA, can be studied in a versatile manner and used for protein-DNA interaction mechanics. Moreover, on the lower side of the force range the other benchmark single-molecule biophysics, kinesin's 8-nm steps and stall forces, are shown to be measurable.

With the NanoTracker, optical tweezers finally transcend from the labs of self-building scientists who helped the technique mature, to a turn-key system able to serve a much wider community of researchers in the life sciences.

7613-13, Session 4

Observation of linear, nonlinear, and singular behavior of the Pancharatnam-Berry phase

T. D. Visser, Delft Univ. of Technology (Netherlands); T. van Dijk, H. F. Schouten, Vrije Univ. Amsterdam (Netherlands)

In 1984 Berry pointed out that a quantum system whose parameters are cyclically altered does not return to its original state but acquires, in addition to the usual dynamic phase, a so-called geometric phase.

It was later realized that such a phase is actually quite common, and occurs in situations ranging from Foucault's pendulum to the Aharonov-Bohm effect.

Also the polarization phenomena described by Pancharatnam represent one of its manifestations.

The polarization properties of a monochromatic light beam can be represented by a point on the Poincare sphere.

When, with the help of optical elements such as polarizers and retarders, the polarization state is made to trace out a closed contour on the sphere, the beam acquires a geometric phase. This Pancharatnam-Berry phase, as it is nowadays called, is equal to half the solid angle of the contour subtended at the origin of the sphere.

In this work we show that such a geometric relation also exists for the so-called Pancharatnam connection, i.e., the criterion according to which two beams with different polarization states are in phase. This relation can be extended to arbitrary (i.e., non-closed) paths on the Poincare sphere.

In fact, we find that the Pancharatnam-Berry phase is a special case of this relation.

We also show that the geometric phase for non-closed paths can depend in a linear or in a nonlinear fashion on the orientation of the optical elements, and sometimes this dependence is singular.

Experimental results that confirm these three types of behavior are presented. The observed singular behavior may be applied in optical switching.

7613-14, Session 4

Geometric phases in astigmatic paraxial modes of all orders

S. J. M. Habraken, G. Nienhuis, Leiden Univ. (Netherlands)

The astigmatic modes of paraxial light beams are characterized by a well-defined set of parameters. This set specifies bosonic ladder operators that connect the modes of various orders, in analogy to the ladder operators connecting harmonic-oscillator wave function. The variation of the ladder operators under propagation is described by the ray matrix of the astigmatic optical system.

We study the underlying parameter space and the geometric phase that arises from it. This phase can be viewed as the flux of a gauge field through an enclosed area in parameter space. We discuss the physical significance of this magnetic analogy. The well-known Gouy effect for isotropic modes is identified as a special case. More general cases of the geometric phase arise for cyclic transformations of astigmatic modes of any order.

Recently, the geometric phase arising from a cyclic transformation of photon polarization (the Pancharatnam phase) has been used experimentally to probe and and study entangled two-photon states. In analogy, our present work could be applied in the domain of two-photon states with quantum entanglement in their spatial degrees of freedom.

7613-15, Session 4

New polarization singularities of partially coherent light beams

M. S. Soskin, Institute of Physics (Ukraine); P. V. Polyanskii, Yuriy Fedkovych Chernivtsi National Univ. (Ukraine)

It is shown that for an incoherent superposition of the orthogonally polarized laser beams the polarization singularities of a new type arise at transversal cross-section of a paraxial combined beam instead of common singularities, such as amplitude zeroes or optical vortices inherent to scalar fields, and polarization singularities such as points and lines inherent to completely coherent vector fields. There are contours along which the degree of polarization equals zero and the state of polarization is undetermined (singular), and isolated points where the degree of polarization equals unity and the state of polarization is determined by the non-vanishing component of a combined beam. Optical vortices of the orthogonally polarized component lie under points. points differ essentially from points of singular optics of coherent fields by absence of topological charge and certain morphology of neighborhood (S, M, L). Crossing of line is accompanied by step-like change of polarization state onto orthogonal one (sign principle). and singularities are represented at the whole Stokes space, namely at and inside of the Poincare sphere. The conditions of topological stability of and singularities are discussed, as well as the peculiarities of the spatial distribution of the degree of polarization in the closest vicinity of such singularities. First experimental examples of reconstruction of the combined beam's vector skeleton formed by and singularities as the extrema of the complex degree of polarization are given.

7613-31, Poster Session

Optimisation of sub-micron optical waveguides for propulsion of nanoparticles and nanowires

O. G. Hellesø, Univ. of Tromsø (Norway); D. Neel, Institut d'Electronique Fondamentale (France); S. Gétin, Lab. d'Electronique de Technologie de l'Information (France); B. S. Ahluwalia, Univ. of Tromsø (Norway)

Optical waveguides have the possibility to combine optical trapping in the evanescent field with other optical and micro-fluidics functions. Waveguides with a high refractive index can tightly confine the optical field and thus create an evanescent field with a high intensity. Such waveguides with sub-micron thickness have proved useful for optical trapping and propulsion of nanoparticles and nanowires. In this paper we do 2-D simulations in order to optimise the waveguide cross-section for maximum intensity in the evanescent field of the waveguide. We also do 3-D simulation of the optical forces on nanoparticles and nanowires using the finite element method (FEM). Some experimental results are presented, on optical propulsion using such waveguides. In particular, we have used the waveguides to transport semiconductor nanowires and gold nanoparticles.

7613-33, Poster Session

Creating optical vortex modes with a single cylinder lens

H. Sridhar, M. G. Cohen, J. W. Noe, Stony Brook Univ. (United States)

Optical-vortex (Laguerre-Gauss) modes can be created by introducing a pi/2 phase shift between orthogonal components of Hermite-Gauss (HG) modes. The converter design introduced by M.W. Beijersbergen et al. [Optics Commun. 96, p. 123, 1993] achieves this phase shift by means of two parallel cylinder lenses preceded by a spherical matching lens. We have observed that high-quality mode conversions can easily be achieved with a single cylinder lens, and have applied this method to an optical vortex tweezers with good results. We have modeled the conversion process analytically and will discuss the advantages and limitations of this simplified converter.

7613-16, Session 5

Spin-orbit interactions of light

K. Y. Bliokh, National Univ. of Ireland, Galway (Ireland)

Spin and orbital degrees of freedom of light are independent of each other as the wave propagates freely in vacuum. However, they become coupled by various perturbations of the medium, such as inhomogeneity, anisotropy, or non-linearity. This produces spin-orbit coupling within the Maxwell equations, which leads to the spin-to-orbital angular momentum conversion and spin-dependent transport of light (spin Hall effect). The transport effects are typically small (proportional to the wavelength) and negligible in classical optics, but they might be crucial for operating light at nano-scales - e.g., in photonic and plasmonic system. I will give an overview of recent theoretical and experimental studies of fine spin-induced phenomena upon the light propagation and scattering in inhomogeneous media. The spin-orbit interactions are characterized by a fundamental duality of dynamical (particle) and geometrical (wave) aspects. On the one hand, the spin-orbit coupling can be attributed to the Coriolis effect and angular momentum dynamics. On the other hand, it is described in terms of the Berry phases and interference of partial plane waves in the wave packet. We anticipate that, akin to electron spintronics, spin-induced wavelength-scale phenomena in the evolution of light will form a promising avenue in nano-optics.

7613-17, Session 5

Propagation of a hybrid vector polarization beam in a uniaxial crystal

G. Milione, H. I. Sztul, R. R. Alfano, The City College of New York (United States)

Propagation of a hybrid vector polarization (HVP) beam in a uniaxial birefringent quartz crystal was experimentally investigated at different angles to the optic axis. We use a combination of radial polarizing device and quarter wave plate to tailor a linearly polarized gaussian beam into the desired HVP beam. The HVP beam can be theoretically expressed as a superposition of two orthogonal linearly polarized Laguerre-Gaussian (LG) modes of opposite topological charge, l=-1 and l=+1. Using a double-slit interference method we examine the helical phase structure of both orthogonal LG components individually and verify their predicted topological charge. When propagating through the crystal, the HVP beam decomposes into these two orthogonal components traveling along the ordinary and extraordinary rays separately creating a spatial phase difference between them. The phase and polarization structure of the HVP beam after propagation through the crystal is investigated. Orienting the transmission axis of a liner polarizer between the orthogonally polarized LG10 and LG-10 components shows a fork fringe pattern arising from their interference.

7613-18, Session 5

Rotational frequency shift in cylindrical vector beam due to skew rays in few-mode optical fibers

N. K. Viswanathan, K. V. Inavalli, Univ. of Hyderabad (India)

We report here rotational frequency shifts, also known as rotational Doppler effect (RDE), observed in helically-phased cylindrical vector beam generated by propagating the fundamental (TEM00) laser mode at an angle in a few-mode optical fiber. Cylindrical vector optical vortex beams were first generated by directly transforming polarized Gaussian input beam launched at an angle to the fiber axis [N.K. Viswanathan and V.V.G.K. Inavalli, Opt. Lett., 34, 1189, 2009]. The input beam launch conditions (tilt angle and offset) with respect to the fiber axis allows us to precisely control the fraction of the total power guided in the fundamental mode (HE11) and the first-order annular waveguide modes (TM01, TE01, HE21). By combining the reference (Gaussian) and signal (annular) modes into a single beam in a horizontally-held short-length of few-mode fiber we construct a vectorial optical vortex one-beam interferometer for the first time to the best of our knowledge. In the proposed scheme the output beam with a shifted vortex in its cross-section rotates around the beam axis, resulting in the rotation of the zero-intensity point in the output radiation field, as a function of the input Gaussian beam polarization and the analyzer rotation. Explanation of the direct generation of cylindrical vector vortex beams in a short-length of few-mode optical fiber using the vector wave equation leads us to understanding the measured rotational frequency shifts.

7613-19, Session 5

Singular trajectories space-time domain topology of developing speckle field

V. Vasil'ev, M. S. Soskin, Institute of Physics (Ukraine)

The work is devoted to establishment of real-time topological dynamics of the generic developing paraxial elliptic speckle field generated and driven by the system 'laser beam + photorefractive crystal LiNbO3: Fe. Dynamics of optical field polarization in fixed beam cross-section was measured by the elaborated quick-action real-time Stokes-polarimetry and analyzed in 3D space-time domain [1]. The closed loops and open lines singular trajectories [2] correspond to direct and chain topological reactions in real-time topological dynamics [1, 3]. Their topological and statistical properties are investigated in details.

[1] V. Vasil'ev, M. Soskin Topological and morphological transformations of developing singular paraxial vector light fields // Optics Communications. - 2008. V. 281,   22. - P. 5527-5540.

[2] F. Flossmann, K. O`Holleran, M. R. Dennis, M. J. Padgett Polarization singularities in 2D and 3D speckle fields // Phys. Rev. Lett. - 2008. V. 100. - P. 203902-1 - 203902-4.

[3] V. Vasil'ev, V. Ponevchinsky, and M. Soskin Chain topological reactions in developing random light fields // Proceedings of SPIE. - 2009. V. 7227. - P. 72270A.

7613-20, Session 6

Quantum imaging and orbital angular momentum

J. Leach, B. Jack, J. Romero, S. Franke-Arnold, Univ. of Glasgow (United Kingdom); A. Jha, R. W. Boyd, Univ. of Rochester (United States); S. M. Barnett, Univ. of Strathclyde (United Kingdom); M. Ritsch-Marte, Medizinische Univ. Innsbruck (Austria); M. Padgett, Univ. of Glasgow (United Kingdom)

Entanglement is the phenomenon that can link quantum systems no matter what their physical separation. Using entangled photons, we demonstrate the contrast enhancement of images within a ghost-imaging system by use of non-local phase filters and present results for the Einstein-Podolsky-Rosen paradox for angle and orbital angular momentum states of light. We obtain edge-enhanced images as a direct consequence of the quantum correlations in the orbital angular momentum of the down-converted photon pairs. For phase objects, with differently orientated edges, we show a violation of a Bell-type inequality, thereby unambiguously revealing the quantum nature of our ghost-imaging arrangement.

7613-21, Session 6

Extending optical entanglement into higher dimensions

C. C. Harb, The Univ. of New South Wales (Australia); J. Janousek, K. Wagner, H. A. Bachor, The Australian National Univ. (Australia)

Optical entanglement is a key requirement for many quantum communication protocols. Conventionally, entanglement is formed between two distinct beams, with the quantum correlation measurements being performed at separate locations. Such setups can be complicated, requiring the repeated combination of complex resources, a task that becomes increasingly difficult as the number of entangled information channels, or modes, increases. We show entanglement between two spatial modes within one beam. Our technique is particularly elegant and a major advance towards practical systems with minimum complexity. We demonstrate three major experimental achievements: (i) only one source is required to produce squeezed light in two orthogonal spatial modes, (ii) the entanglement is formed through lenses and beam rotation, without the need of a beam splitter and (iii) the quantum correlations are measured directly and simultaneously using one multi pixel, quadrant detector. The latest experimental results showing significant entanglement between two orthogonal spatial modes will be presented.

7613-22, Session 6

Helical-mode interference of photons and biphotons

E. J. Galvez, L. E. Coyle, E. Johnson, B. Reschovsky, Colgate Univ. (United States)

We study the spatial correlations of heralded photons and biphotons when they are put in a superposition zero and first-order helical modes. Heralded photons and biphotons are produced by parametric down-conversion and are sent through a Mach-Zehnder interferometer that has a spiral phase plate in one of its arms. Detection of the light after the interferometer is done with single-photon detectors preceded by rotatable masks. In the case of heralded photons we observe results that are consistent with an asymmetric probability pattern that rotates as a function of the interferometer phase. This is consistent with the classical results of interference of light beams in helical. They constitute a direct measurement of the helical mode of single photons. Studies with biphotons are ongoing, but are expected to give non-classical modes, where the spatial mode shared by the two correlated photons is different from the mode of the individual photons. These constitute a new type of quantum-optical singularities. At the conference we will present our single-photon results and an update to our experiments with biphotons.

7613-23, Session 7

Off-axis binding and induced circulation in counter-propagating beam traps

G. D. Love, J. M. Taylor, Durham Univ. (United Kingdom)

Optically bound arrays of microparticles in counter-propagating laser traps are typically constrained to the beam axis. Here we report on binding where the particles are displaced from the beam axis, and also describe circulatory motion of the bound arrays around the beam axis. We show both experimental results and a Mie scattering simulation, and discuss the physical basis for the effects.

7613-24, Session 7

Geometrical configurations in optical binding

L. C. Davila Romero, D. L. Andrews, Univ. of East Anglia Norwich (United Kingdom)

Optical binding is a phenomenon that is exhibited by micro-and nano-particle systems, suitably irradiated with off-resonance laser light. Recent quantum electrodynamical studies on optically induced inter-particle potential energy surfaces have revealed unexpected features of considerable intricacy. When several particles are present, the effect commonly results in the formation of varied geometrical assemblies. The exploitation of these features presents a host of opportunities for the optical fabrication of nanoscale structures, based on the fine control of a variety of attractive and repulsive forces, and the torques that operate on particle pairs. This paper reports the results of recent quantum electrodynamical studies on the energy landscapes for systems of three and more particles; the analysis of local minima allows determination of the energetically most favorable positions. Promising results are exhibited for the optical fabrication of assemblies of molecules, nanoparticles, microparticles, and colloidal multi-particle arrays. The comprehension of mechanism that is emerging should help determine the fine principles of multi-particle optical assembly. As such, the development of theory represents a rigorous and general formulation paving the way towards a fuller comprehension of nanoparticle assembly based on optical binding.

7613-25, Session 7

Optical forces in biophotonics: transfection and cell sorting

W. A. Ertmer, Leibniz Univ. Hannover (Germany); H. Meyer, R. Lorbeer, G. Bergmann, H. Lubatschowski, Laser Zentrum Hannover e.V. (Germany); H. M. Escoboar, I. Nolte, StiftungTierärztliche Hochschule Hannover (Germany); A. Heisterkamp, Laser Zentrum Hannover e.V. (Germany)

Lately, several groups successfully used ultrashort laser pulses to selectively permeabilize the membrane of living cells to achieve transport of foreign molecules, like DNA, into the cells. For this, the high field intensities of tightly focused laser pulses are used to induce multiphoton absorption and the creation of a small scale optical breakdown at the membrane of the target cell. Afterwards, DNA or other foreign molecules are able to diffuse into the cell and achieve, for example, transfection of living cells. However, the cell throughput of this method is low, as, due to tight focusing. We present a technique to achieve fs-laser transfection in living cells at higher throughput by implementing optical traps into microfluidic chips. For this, a trapping laser beam, is coupled into a microscope setup and combined with a Ti:Sa fs-laser beam to achieve simultaneous trapping and optical perforation.

7613-26, Session 7

Integrated platform based on high-refractive index contrast waveguide for optical guiding and sorting

B. S. Ahluwalia, O. G. Hellesø, Univ. of Tromsø (Norway); A. Z. Subramanian, J. S. Wilkinson, Univ. of Southampton (United Kingdom); J. Chen, X. Chen, Vestfold Univ. College (Norway)

The high-refractive index contrast (Δn ~0.65 as compared to silicon oxide) of Tantalum Pentoxide ($Ta2O5$) waveguides allows strong confinement of light in waveguides of sub-micron thickness (200 nm). This generates enhanced intensity in the evanescent field, which we have employed for efficient propelling of micro-particles. Feasibility of opto-fluidics sorting of different sized micro-particles based on their varying optical propulsion velocity is reported. Optical propulsion of fixed red blood cells (RBC) with velocity higher than previously obtained is also reported. We have further compared the optical propulsion velocity of RBC in isotonic solution (0,25M sucrose) and water.

7613-27, Session 8

A new twist on three-dimensional light fields

R. Piestun, Univ. of Colorado at Boulder (United States)

The synthesis of light fields in three dimensions is creating a revolution in areas such as optical tweezers, microscopy, and microfabrication. We review the origins of 3D synthesis and present space, Fourier, and modal domain methods. These methods were originally used to demonstrate arrays of nondiffracting beams, dashed, dark, rotating, and generalized self-imaging fields. Hence, generating arbitrary 3D light distributions subject to fundamental wave equation constraints was possible. Current focus is in engineering point spread functions to achieve 3D superresolution via photoactivation - localization microscopy. An information theory analysis shows the benefit of a double-helix point spread function, which delivers higher Fisher information than classical clear apertures. Recent experiments in single molecule imaging show an improvement in resolution of one order of magnitude over the classical Rayleigh limit.

7613-28, Session 8

Velocity of optical Airy beams

H. I. Sztul, G. Milione, R. R. Alfano, The City College of New York (United States)

Optical Airy beams have gained much attention recently due to their accelerating and non-diffractive behavior. We analytically and numerically analyze and discuss the wave velocities of the Airy solution to the wave equation and show that the phase velocity is varying spatially as the beam propagates along its curved trajectory. We show a non-constant phase velocities as the Airy beam propagates through Air. The phase velocity of the Airy beam is compared to that of a plane wave and helical wave to further understand the dynamics of this accelerating wave.

Our previous analysis showed the optical Airy beam has a spatially varying linear and angular momentum. With the current analysis of the velocities, a more complete picture of this new class of solution to the wave equation will be discussed. This will be especially useful in analyzing the propagation of Airy beams both through Air and optical materials.

7613-29, Session 8

Collinear non-diffracting beams: classification and properties

B. S. Ahluwalia, Univ. of Tromsø (Norway); W. M. Lee, Univ. of St. Andrews (United Kingdom)

Over the past decade, there has been considerable interest in the class of non-diffracting light beams known as Bessel beams. Bessel beams have had a number of applications, for instance, in second harmonic generation, as novel optical tweezers, cell sorting and as atom light guides. Coherent addition of two or more higher order Bessel light beams (non-diffracting beams) with different azimuthal phase variation can generate fascinating light beams that exhibit azimuthal modulated intensity pattern at the outer rings whilst retaining its central topological charge. Under a given set of conditions, a range of azimuthal modulated intensity non-diffracting beams (‘collinear-propagating’) can be obtained. In this paper, we explore the ‘collinear-propagating’ Bessel beams of different azimuthal phase variations that can generate a range of azimuthally modulated light fields and elucidate the properties of such non-diffracting beams as well as discussing its dynamics in free space propagation.

7613-30, Session 8

Noise-reduction for fringe analysis using the empirical-mode decomposition with the generalized analysis model

C. Lee, W. Su, C. Lee, National Sun Yat-Sen Univ. (Taiwan)

Phase-extraction from fringe patterns is an inevitable procedure in many applications, such as interferometry, Moiré analysis, and profilometry using structured light illumination. Errors to phase-extraction always occur when the signal-to-noise ratio is weak. In this paper, we use the empirical mode decomposition (EMD) with a generalized analysis model to reduce the white noise from a fringe pattern. It is found that phases can be extracted with high accuracy once noise-reduction is performed with this model.

Conference 7614: Laser Refrigeration of Solids III

Thursday 28 January 2010 • Part of Proceedings of SPIE Vol. 7614

Laser Refrigeration of Solids III

7614-14, Poster Session

Light-down versus light-up conversion in radiative cooling of semiconductors

V. K. Malyutenko, V. Lashkaryov Institute of Semiconductor Physics (Ukraine)

General problem in optoelectronic devices is that they degrade when operated even in moderate power mode; keeping them cooled is a challenge. Conventional thermoelectric coolers that provide heat transfer are not the best solution as they need additional room, electric bias, and direct contact with cooled object. Radiative cooling in semiconductors that provides net cooling has received a great deal of attention due to its potential as efficient way for manipulating a device temperature using remote energy source. In this report we discuss pros and cons of two approaches in radiative cooling of semiconductors. First approach is based on the light up-conversion in direct bandgap materials through the interband luminescence when the energy of the escaping blue-shifted photon exceeds that for the pumped laser photon by ~kT value; it is not realized yet. Second approach makes use the light down-conversion through releasing the energy from indirect/direct bandgap materials in the form of multiple intraband red-shifted photons per single pumped photon through thermal emission. In contrast, we give details of the first observation of net radiative cooling by down-conversion in bulk Si by >3K starting from 470 K. We also define what parameters have to be met in order to achieve deeper cooling

7614-01, Session 1

Laser cooling with real and virtual transitions: comparative analysis

J. B. Khurgin, The Johns Hopkins Univ. (United States)

Laser cooling of solids can be accomplished by up-conversion of radiation using different mechanisms - photoluminescence, Raman, or Brillouin scattering. Photoluminescence involves consecutive real processes in while stimulated scattering involves instant virtual transitions in which optical or acoustical phonons are being absorbed. The latter mechanism is used in laser cooling of micro-mechanical structures. In this talk I will show that all the laser cooling schemes follow the same general principles and show that each of them has its niche where it has advantages over other schemes.

7614-02, Session 1

Optical refrigeration breaks the Peltier barrier: cooling Yb:YLF to 155K

D. Seletskiy, S. Melgaard, M. Sheik-Bahae, The Univ. of New Mexico (United States); S. Bigotta, A. Di Lieto, M. Tonelli, Univ. di Pisa (Italy); R. Epstein, Los Alamos National Lab. (United States)

We have attained 154 degrees of cooling from ambient using a Yb-doped YLF crystal. This establishes a new record for laser cooling of solids and puts the technology in the cryogenic temperature regime. Absolute temperature and heat lift surpass that of thermoelectric coolers, making this the first implementation of an all solid state optical cryocooler.

7614-03, Session 1

Crystal-field effects in fluoride crystals for optical refrigeration

M. P. Hehlen, Los Alamos National Lab. (United States)

Laser cooling of fluoride crystals doped with ytterbium (Yb) has made tremendous progress in the past year, and Yb-doped YLiF4 now outperforms multi-stage thermo-electric coolers. The laser-cooling performance of these materials is a direct result of crystal-field interactions at the Yb site in the crystal. I will review the material chemistry and crystallography of fluoride crystals and discuss the effect of crystal field symmetry and strength on the Yb^{3+} ground state splitting and transition strengths.

7614-04, Session 2

Lasing without heat generation

S. R. Bowman, U.S. Naval Research Lab. (United States); S. P. O'Connor, N. Condon, S. Biswal, A. Rosenberg, Naval Research Laboratory (United States)

Novel high power ytterbium YAG lasers are described. These lasers incorporate the principle of anti-Stokes fluorescence cooling to reduce or eliminate detrimental heating. Lasers with net heating and net cooling are demonstrated. By balancing the spontaneous and stimulated emission, we have reduced the net thermal loading to below 0.01% of the laser's average output power. Design, testing, and analysis are reported for lasers up to 500W average power. Issues and limitations of this approach are discussed.

7614-05, Session 2

High-power fiber lasers with integrated rare-earth optical cooler

G. Nemova, R. Kashyap, Ecole Polytechnique de Montréal (Canada)

High-power lasers (traditional solid-state and Raman lasers) suffer from heat generated by the quantum defect, which deteriorates their performance. The radiation-balanced technique was proposed to solve the problem in the case of solid-state lasers [1] and the intrinsic heat-mitigation technique, which relies on coherent anti-Stokes Raman scattering (CARS), was proposed to solve the problem of heat generation in the high power Raman laser [2]. Unfortunately radiated energy increases only linearly with the length of the laser medium in both schemes. We propose a radically new approach to solve the problem of heat generation in lasers. We have considered athermal fiber lasers, where rare-earth (RE) based refrigeration sources are incorporated in the body of the devices. This new technique, which has been developed for traditional solid-state and Raman lasers, ensures the exponential growth of radiation along the laser medium and provides radiation-balanced operation. The performance of RE refrigeration sources is based on radiation cooling of solids with anti-Stokes fluorescence proposed by Pringsheim in 1929 [3] and experimentally observed in solid materials in 1995 by Epstein's research team [4]. In our two lasers pump schemes, the heat generated by the quantum defect is compensated for by laser cooling from anti-Stokes fluorescence of Yb^{3+} ions doped in ZBLANP glass.

1. S. R. Bowman, IEEE J. Quantum Electron. 35, 115 (1999).

2. N. Vermeulen, C. Debaes, P. Muys & H. Thienpont, Phys. Rev. Lett. 99, 093903 (2007).

3. P. Pringsheim, Z. Phys. 57, 739 (1929).

4. R.I. Epstein, M.I. Buchwald, B.C. Edwards, T.R. Gosnell, C.E. Mungan, Nature (London) 377, 500 (1995).

7614-06, Session 2

Spectroscopy of Yb-doped YLF crystals for laser cooling

S. Melgaard, D. Seletskiy, M. Sheik-Bahae, The Univ. of New Mexico (United States); S. Bigotta, A. Di Lieto, M. Tonelli, Univ. di Pisa (Italy); R. Epstein, Los Alamos National Lab. (United States)

Spectroscopic characterization of YLF crystal doped with Yb reveals the performance potential of this material in laser cooling applications. Temperature-dependent spectra allow us to estimate the minimum achievable temperature and the parasitic background absorption.

7614-07, Session 2

Laser cooling in erbium-based solids

Z. U. Hasan, Z. Qiu, Temple Univ. (United States); I. Khan, Temple University (United States)

Laser cooling at 1.5 micron has been demonstrated with low cooling efficiencies and attainable temperatures less than 1 degree Celcius below the ambient temperature by two groups. It is an important range of spectrum where lasers developed for communications can be used as the pump source for inducing the Anti-Stokes Emission from solids. Such lasers are available either as Erbium based lasers or semi-conductor diode lasers. High efficiency laser cooling in this range will potentially miniaturize the cooling devices. The status of laser refrigeration in Erbium based solids will be reviewed.

7614-08, Session 3

Laser cooling of a semiconductor load using a Yb:YLF optical refrigerator

D. Seletskiy, S. Melgaard, M. Sheik-Bahae, The Univ. of New Mexico (United States); S. Bigotta, A. Di Lieto, M. Tonelli, Univ. di Pisa (Italy)

A Yb-YLF laser cooler has been operated with a GaAs optical device as a thermal load. A GaAs/GaInP double heterostructure is placed in thermal contact with the crystal and is cooled by an amount 110 degrees below the ambient. This demonstrates the feasibility laser cooling technology in a practical application, I.e. cooling a sensor close to the cryogenic temperature regime using an all solid-state device. The absolute temperature and heat lift make laser cooling competitive with thermo-electric coolers.

7614-09, Session 3

Local internal and bulk optical cooling in Nd-doped crystals and nanocrystalline powders

A. J. Garcia-Adeva, R. Balda, M. Al Saleh, J. Fernandez, Univ. del País Vasco (Spain)

We present the first experimental demonstration of local internal and bulk optical cooling in samples of Nd-doped KPb_2Cl_5 crystals and Nd-doped KPb_2Cl_5 nanocrystalline powders. Local internal anti-Stokes laser cooling in crystals of KPb_2Cl_5 doped with 1% Nd^3+ was probed by using collinear photothermal deflection spectroscopy in the 800-900 nm spectral range (around the barycenter of the 4F3/2 electronic transition of the Nd^3+ ions). The transition from heating to cooling clearly shows up in the photothermal deflection spectra as a 180º phase change around 855 nm. The efficiency of this cooling process was found to be around 0.82%. In order to study the possibility of optical bulk cooling occurring in nanocrystalline powder samples, various crystals were grounded into fine powders with typical grain size distributions spanning from 1 to 3 microns. The bulk optical cooling capability of these powders and some crystalline samples was investigated by using an infrared thermal camera. The time evolution of the thermal field in the samples upon excitation with femtosecond laser pulses was recorded along runs of various durations. Once reached the stationary regime, the temperature of the sample (both the average temperature and the temperature at various local spots) steadily decreases. We also investigated the possibility of controlling the dynamics of the optical cooling process by adequately tuning the excitation wavelength. It is found that by changing this parameter, it is possible to increase the temperature drop in the sample (up to 2 °C in certain cases) in a controlled and reproducible way.

7614-10, Session 3

Progress in laser cooling of semiconductors

C. Wang, C. Li, M. Hasselbeck, M. Sheik-Bahae, The Univ. of New Mexico (United States)

The state of current research in laser cooling of semiconductors is reviewed. Emphasis is placed on measurement of external quantum efficiency in GaAs heterostuctures, which embodies two critical parameters: non-radiative recombination and luminescence extraction efficiency. New experimental results will be presented that characterize device operation as a function of temperature and laser excitation power. The crucial importance of parasitic background absorption is discussed.

7614-11, Session 3

Practical devices for semiconductor luminescent refrigeration

S. Wu, Arizona State Univ. (United States); S. Yu, Univ. of Arkansas (United States); S. R. Johnson, D. Ding, Y. Zhang, Arizona State Univ. (United States)

Vibration free semiconductor luminescent refrigerators have the potential to operate at low temperature and can be monolithically integrated with other semiconductor devices, such as, infrared sensors for space applications. However, two necessary but very challenging conditions have to be met to achieve cooling using semiconductors: namely, near unity internal quantum efficiency and extraction efficiency. This work focuses on molecular beam epitaxy grown GaAs based light emitters with InGaAs quantum well active regions and AlGaAs barriers for carrier confinement. In order to achieve high internal quantum efficiency, the AlGaAs barriers are grown at 670 °C using Sb as a surfactant to minimize the formation of material defects near the active region. To achieve high extraction efficiency, a GaAs hemisphere with a ZnO anti-reflection coating is fabricated on the back side of the device, which has a calculated extraction efficiency close to unity. The fabrication process requires nine photolithography steps using eight different mask sets. The completed devices are probed optically and electrically and the efficiencies are measured using an integration sphere calibrated at the emission line of the device. Thermal isolation is achieved by suspending the device from the GaAs substrate using four narrow polyimide supporting arms. Additional experiments and results will be presented.

7614-12, Session 4

Theory of time-resolved photo-luminescence and carrier lifetime measurements in GaAs/GaInP heterostructures

G. Rupper, N. Kwong, R. H. Binder, College of Optical Sciences, The Univ. of Arizona (United States)

Recently, interest in optical refrigeration of semiconductors, which is based on photo-luminescence up-conversion, has drawn extensive attention both theoretically and experimentally. Theoretical descriptions often treat spatially homogeneous semiconductors, because of their conceptual simplicity. In typical experiments, however, semiconductors are usually heterostructures designed to reduce non-radiative recombination at the sample's surface. In particular, GaAs/GaInP structures have been used in experiments. In these structures, the GaAs layers are usually unintentionally p-doped, while the surface layers of GaInP are n-doped. Recent measurements of the non-radiative recombiation lifetime yielded values in the desirable inverse microsecond regime, and it is believed that the non-radiative recombination processes occur mainly at the heterostructure interfaces and its surfaces. For this reason, it is important to know the spatial density distribution. Furthermore, photo-luminescence and carrier lifetime measurements are not spatially resolved, and therefore it is desirable to have a theory that can simulate lifetime measurements using the spatially varying density profile as an input. We have developed such a theory, using the simplifying assumption of quasi-thermal equilibrium (at each time during the photo-luminescence decay process). Using this theory, we are able to relate measurable (i.e. spatially averaged) lifetime measurements to the underlying non-radiative decay processes that, in our simulations, occur predominantly at the GaAs/GaInP interface. From this, we find that spatial inhomogeneities in the carrier density, which are most pronounced at low optical excitation powers, can have appreciable effects on the lifetime measurements.

7614-13, Session 4

Characterization of GaAs double-heterostructures grown by phosphorous MBE

C. Li, C. Wang, M. Hasselbeck, M. Sheik-Bahae, K. J. Malloy, The Univ. of New Mexico (United States)

Growth of GaAs double heterostructures by molecular beam epitaxy is attractive because it may lead to dramatically reduced parasitic background absorption. Parasitic absorption is believed to be the primary impediment to the realization of net laser cooling in a GaAs device. The need for GaInP surface passivation layers and phosphorous in particular has resulted in devices grown exclusively by the MOCVD process. We have implemented an MBE reactor with a phosphorous capability and have grown GaAs/GaInP double heterostructures for laser cooling. A series of systematic experiments to characterize these devices is described.

7614-15, Session 4

A thermophotonic heat pump

J. Oksanen, J. Tulkki, Helsinki Univ. of Technology (Finland)

One of the main challenges in demonstrating electroluminescent cooling is the low extraction efficiency of semiconductor LEDs. Another challenge for developing efficient electroluminescent cooling applications is the very low internal quantum efficiency of the small band gap semiconductors (ideally E_{g}sim kT) which otherwise would be most efficient in converting carrier heat to light energy.

We propose a new approach to electroluminescent cooling in which the emitted photons are intentionally absorbed within the same semiconductor crystal they were originally emitted in and in which the requirements of demonstrating and making use of electroluminescent cooling are significantly relaxed compared to conventional structures. The resulting device, the thermophotonic heat pump (THP), is a new solid state heat pump that uses light as the working fluid. It shares the advantages of thermoelectric devices like small size, reliability and the lack of environmentally harmful fluids or gases.

The THP is formed of two large area light emitting diodes enclosed in a semiconductor material with an effectively homogeneous refractive index. One of of the diodes operates as a conventional light emitting diode and the other diode operates as a photovoltaic cell.

Ideally the THP structure allows heat transfer at the Carnot efficiency.

According to our simulations the THP has also in practice potential to demonstrate a significantly higher coefficient of performance (COP) than thermoelectric devices.

Conference 7615: Vertical-Cavity Surface-Emitting Lasers XIV

Wednesday-Thursday 27-28 January 2010 • Part of Proceedings of SPIE Vol. 7615

Vertical-Cavity Surface-Emitting Lasers XIV

7615-01, Session 1

Experimental demonstration of low-jitter performance and high-reliable 1060nm VCSEL arrays for 10Gx12ch optical interconnection

K. Takaki, The Furukawa Electric Co., Ltd. (Japan); N. Iwai, The Furukawa Electric Co., ltd. (Japan); S. Kamiya, The Furukawa Electric Co., Ltd. (Japan); H. Shimizu, The Furukawa Electric co., ltd. (Japan); K. Hiraiwa, S. Imai, Y. Kawakita, T. Kageyama, The Furukawa Electric Co., Ltd. (Japan); T. Ishikawa, The Furukawa Electric co., ltd. (Japan); N. Tsukiji, A. Kasukawa, The Furukawa Electric Co., Ltd. (Japan)

Due to the recent demand for increased data rate and reliability as light sources for ultra high bit rate optical interconnection under non-hermetic, high current density and high temperature, 1060nm VCSELs and their arrays have been investigated to make sure their potential superiority in performance.

No systematic studies on 1060nm high speed VCSELs have been reported in terms with reliability so far to our best knowledge. In this work, a systematic and intensive study on reliability has been performed for our 1060nm VCSELs consist of double intra-cavity and oxide confined structure with over 70ps eye opening width at 10Gbps and 1E-12 BER in Ib=3mA. Aging tests for 3467pcs discrete non-hermetic VCSEL chips were performed under 20kA/cm2, 70degC to 120degC and up to 5736 hours, which is equivalent to over 10million device hours in normal operating condition. We found one degraded device due to the electro-migration of the metal interconnecting layer, resulting in 81Fits (C.L.=90%) under Ea=0.35eV and no current accelerated factor. Also, their degradation of threshold current after 3,000 hours operation was less than 0.1mA under high stress condition of 40kA/cm2 and 120degC, which corresponds to more than hundreds year operation. It should be noted that no remarkable change in both threshold current and output power was observed until their lifetime even at extremely high temperature and current density condition, which ensure the stable 10Gbps operation over lifetime.

It is experimentally proved that 1060nm VCSELs have great potentiality in the future large green data traffic system.

7615-02, Session 1

Manufacturability of 850nm data communication VCSELs in high volume

T. E. Sale, G. Koh, J. Tan, J. Hwang, R. Nabiev, Avago Technologies Singapore (Singapore); L. Giovane, R. Murty, Avago Technologies Ltd. (United States); C. Chen, Avago Technologies Singapore (Singapore)

Frequently quoted advantages of VCSELs over other optical sources include wafer scale fabrication and testing, low cost, ease of fabricating arrays and ease of fibre coupling. In order to capitalize on these advantages it has been necessary to bring VCSEL products to a level of maturity so that there is both a sufficient product demand and robust fabrication methodology in order to make high volume manufacture and the associated economies of scale viable. Avago Technologies produces a range of single channel and parallel optical link products incorporating 850nm band VCSEL sources operating at up to 10Gb/s per channel. Fundamental to the viability of these products is the performance of VCSEL device. Factors including link budgets, driver design, assembly tolerances, environmental factors and reliability place tight and often conflicting demands on the VCSEL specification which must balance with the variability of device parameters resulting from the device fabrication process and the resulting yield and cost implications. This paper will explore some of the important factors which need to be controlled to ensure manufacturability of VCSEL devices. These factors include process definition and control for epitaxy, etching, lithography etc, wafer level testing procedures, data analysis techniques and reliability testing. A robust device design in combination with sensible system specifications helps to make the most of the manufacturing process.

7615-03, Session 1

Emcore VCSEL failure mechanism and resolution

C. Lei, N. Li, C. Xie, R. F. Carson, X. Sun, W. Luo, L. Zhao, EMCORE Corp. (United States)

Extensive VCSEL reliability improvement work was carried out at Emcore in the past year with significant results. In this talk, we will present failure mechanism, method and effectiveness of wafer and die screening, approaches to eliminate the failure mechanism and results of improved reliability.

7615-04, Session 2

High-speed low current density 850 nm VCSELs

A. G. Larsson, P. Westbergh, J. S. Gustavsson, A. Haglund, Chalmers Univ. of Technology (Sweden)

The design of an oxide confined 850 nm VCSEL has been engineered for high speed operation at low current density. Strained InGaAs/AlGaAs QWs, with a careful choice of In and Al contents based on rigorous band structure and gain calculations, are used to increase differential gain and reduce transparency carrier density. Various measures are implemented for reducing capacitance, resistance and thermal impedance. Modulation bandwidths > 20 GHz at 25°C and > 15 GHz at 85°C were obtained, limited primarily by parasitics. Transmission up to 32 Gbit/s over multimode fiber was successfully demonstrated with the VCSEL biased at a current density of ~10 kA/cm2.

7615-05, Session 2

Emerging VCSEL technologies at Finisar

J. A. Tatum, D. Gazula, J. K. Guenter, R. H. Johnson, G. D. Landry, A. N. MacInnes, G. Park, K. Wade, Finisar Corp. (United States)

Finisar continues to invest in VCSEL development activity. In this paper we will discuss recent results on high speed VCSELs targeted for the emerging 16GFC (Fibre Channel) standard as well as the now forming 25Gbps PCI express standard. Significant challenges in designing for reliability and speed have been overcome to demonstrate VCSELs with bandwidth in excess of 30Gbps. Practical packaging considerations will also be described. VCSELs used in high power and single mode applications will also be presented.

7615-06, Session 2

120 Gbps VCSEL arrays: fabrication and quality aspects

M. Grabherr, S. Intemann, L. R. Borowski, R. King, D. Wiedenmann, R. Jaeger, Philips Technologie GmbH U-L-M Photonics (Germany)

Linear 12 channel VCSEL arrays offer 120 Gbps aggregate bandwidth and are deployed in the Active Optical Cables, one of the fastest growing market for VCSELs.

Main criteria for the VCSEL array component are homogeneity, yield, and reliablity. We highlight details of the fabrication process and results on quality aspects. Excellent on wafer homogeneity and oustanding array homogeneity are achieved by control of epitaxy and wet oxidation process.

Long term stability and spontaneous failure rates based on a significant number of field installations are reported.

7615-07, Session 2

Optimizing 10Gbps VCSEL for real-world laser driver in parallel optical transceiver

C. Xie, N. Li, C. Lei, W. Luo, X. Sun, EMCORE Corp. (United States)

Recent VCSEL drivers for high data rate parallel transceivers are designed to DC couple to the VCSELs. These drivers normally include no back termination to save power. Due to mechanical restrictions, the wire bond between the driver's output and the laser is usually quite long. Such laser drivers in a transceiver can cause excessive optical eye distortions (overshoot, pattern dependent jitter, etc.) to a VCSEL which performs well when driven by a 50Ohm source. Therefore more careful design optimizations (of the VCSEL's intrinsic behavior and its parasites) are needed for such applications. In most cases, this is the only way to achieve good transceiver performance for a given VCSEL driver IC. In this talk, we present Emcore's recent effort to optimize the 850nm 10G VCSEL array for the real world laser drivers used in parallel transceivers and active cables.

7615-08, Session 3

VCSEL-based Faraday rotation spectroscopy at 762nm for battery-powered trace molecular oxygen detection

S. G. So, G. Wysocki, Princeton Univ. (United States)

Faraday Rotation Spectroscopy (FRS) is a polarization based spectroscopic technique which can provide high sensitivity concentration measurements of paramagnetic trace gases and free radicals. We have developed sensor systems which require only 0.2W to perform TDLAS (tunable diode laser absorption spectroscopy), and can additionally be duty cycled, enabling wireless sensor networks of laser-based trace gas sensors. Ultra low power capability at similar detection levels can be achieved with vertical cavity surface emitting lasers (VCSEL) versus other diode laser based sensor systems that require power dissipation in the 2-5W range. We adapted our integrated TDLAS electronics (laser current driver, temperature control, data acquisition, detector preamplifier, lock-in amplifier, wireless data transfer) for this work to use FRS techniques in order to more compactly and robustly quantify molecular oxygen (O2) using a 762.3nm VCSEL in the A band. Using a modulated magnetic field, we demonstrate fundamental shot noise dominated performance, achieving 8.8×10-7 /Hz½ absorption coefficient performance and resulting in a minimum detection limit of 220 ppmv in 1 second of O2 in a 15cm path. At longer paths and integration times, such a sensor will enable oxygen measurements at biotic respiration levels (<1ppmv) to measure CO2 - O2 exchange for mapping natural fluxes of greenhouse gases. We will also describe a permanent magnet solution which can allow FRS measurements at the same total power consumption as TDLAS (0.3W), removing the requirement for a 30W+ magnetic field driver. Opportunities for improvement of detection limits by increasing various system performance parameters will also be described.

7615-09, Session 3

Polymer-coated vertical-cavity surface-emitting laser diode vapor sensor

T. Ansbæk, C. H. Nielsen, N. B. Larsen, S. Dohn, A. Boisen, I. Chung, D. Larsson, K. Yvind, Technical Univ. of Denmark (Denmark)

We report theoretical and experimental results on a new vapor sensor for monitoring volatile organic compounds. The sensor provides the advantage of a small form-factor, mechanical stability and low cost when combined with a monolithically integrated photodiode detector. The sensor comprises a sensing polymer layer on the facet of a vertical surface emitting laser (VCSEL) diode. The analyte sorption is transduced to the electrical domain through modulation of the detected output power of the VCSEL as the optical thickness of the sensor coating changes. The output power modulation was detected using a silicon photodiode. The analyte-polymer system chosen for investigation was that of acetone vapor sorption in polystyrene. The polystyrene was deposited by the solvent-free technique of plasma polymerization onto a commercially available single-mode 850 nm VCSEL. The coated VCSEL and an un-coated VCSEL were connected to a laser driver and placed in a chamber with electrical connections. The experiments were done at room temperature and the chamber pressure was maintained at 800 mbar. In the first experiment the lowest relative acetone concentration detected was 25000 ppm which we expect can be improved by dealing with signal drift and noise. The sensor response time is estimated to be on the magnitude of 100 seconds making this a promising technique for odor monitoring systems within numerous fields such as medical diagnosis and environmental monitoring.

7615-10, Session 3

Non-mechanical beam steering of high-speed VCSEL arrays

J. Joseph, R. Safaisini, Colorado State Univ. (United States); G. T. Dang, Army Research Lab. (United States); K. L. Lear, Colorado State Univ. (United States)

The high resonance frequency, circular beam profile, and monolithic 2-D array formation of VCSELs make them important light sources for applications such as LIDAR requiring both high modulation frequency and significant output powers. One of the main challenges in realizing high speed, high power VCSEL arrays is managing the heat generated in the junction. High modulation frequency (>8 GHz) arrays with over 100 mW output power with effective heatsinking has already been published. [1]

In this paper, we report the demonstration of non-mechanical beam steering of high speed VCSEL arrays. 980 nm oxide-confined VCSELs were fabricated using MBE growth of AlGaAs n- and p-type distributed Bragg reflectors (DBRs) with InGaAs active region on a n-type substrate. Up to 24 separate VCSEL arrays can be independently switched to sweep the beam across the illumination area. Each array can generate ~100 psec pulse widths providing high resolution for imaging detectors. Non-mechanical beam steering of laser pulses is ideal for LIDAR applications to eliminate the need for a flash pulse at much higher power.

Three array designs with variety of total areas were fabricated with 97, 137, and 278 elements. The corresponding mesa diameters were 24, 14 and 10 µm with pitches of 52, 40 and 26 µm. The relative output power, speed, and thermal performance of each array design will be reported.

[1] R. Safaisini, J. R. Joseph, G. Dang, and K. L. Lear, “Scalable high-power, high-speed CW VCSEL arrays,” Electronics Letters, vol. 45, no. 8, pp. 414-415, April 9, 2009.

7615-11, Session 3

Position sensing using integrated VCSEL/PIN microsystem

A. V. Giannopolous, A. M. Kasten, N. Hardy, T. Jefvert, K. D. Choquette, Univ. of Illinois at Urbana-Champaign (United States)

Compact, non-contact, and low operating power sensors are desirable for position sensing applications. Vertical cavity surface emitting lasers integrated monolithically with PIN photodetectors have been designed and fabricated for optical position sensing. This compound semiconductor component has in turn been hybridly integrated onto a Si-platform to form a microsystem. Using a metallic grating as a position gauge, the sensor microsystem can measure differences in reflected power from the grating as it travels parallel to the sensors. This measurement technique allows for a high spatial resolution. Calculations indicate that such a device can detect spatial changes on the order of the wavelength of light emitted from the laser. Measurements from the work described here show the potential to use VCSEL/PIN chips to determine position with an accuracy of sub-micron resolution.

7615-12, Session 3

Fabrication of an integrated 670nm VCSEL-based sensor for miniaturized fluorescence sensing

T. D. O’Sullivan, Stanford Univ. (United States); E. A. Munro, Univ. of Toronto (Canada); J. S. Harris, Jr., Stanford Univ. (United States); O. Levi, Univ. of Toronto (Canada)

Integrated optical semiconductor devices are a promising technology for both lab-on-a-chip and molecular imaging applications. Previous integrated sensor efforts focused on near-IR wavelengths. Yet, some biomedical applications require sensors at visible/red wavelengths due to the accessibility of fluorescent dyes and proteins, deep tissue penetration, and the potential for fluorescence multiplexing.

We designed and fabricated a monolithically integrated sensor on GaAs incorporating 670nm VCSELs and PIN photodetectors. We discuss the design tradeoffs necessary to achieve high power VCSELs and low dark current PIN photodetectors. Specifically, lasers that were processed individually from the same integrated epitaxy achieved 2.6mW output power at room temperature (RT), while separate detectors exhibit RT dark current less than 3pA/mm2 (100mV bias). The integration yielded a slight reduction in performance, causing dark current to increase to 26pA/mm2 and a laser power reduction to 0.5mW. We are optimizing the integrated device process flow to overcome these issues.

Because overall device sensitivity is limited by efficacy of the detector to reject the laser background, it is less sensitive to the integration challenges. Microstructure fabrication prevents spontaneous emission from impinging directly on the photodetector. A fluorescence emission filter suitable for transmitting Cy5.5 fluorescent dye emission is bonded to the photodetector mesas. Alternatively, we evaluate the integration of a thin-film dielectric emission filter stack. Miniature packaging makes the sensor suitable for portable diagnostic assays and in vivo rodent studies. We are presently characterizing the integrated sensor for use in both types of studies; we expect performance to approach that of previous hybrid sensors that yielded 10nM in vitro sensitivity.

7615-13, Session 4

High power VCSELs for miniature optical sensors

J. Geske, Aerius Photonics, LLC (United States)

Recent advances in Vertical-cavity Surface-emitting Laser (VCSEL) efficiency and packaging have opened up alternative applications for VCSELs that leverage their inherent advantages over light emitting diodes and edge-emitting lasers, such as low-divergence symmetric emission, wavelength stability, and inherent 2-D array fabrication. Improvements in reproducible highly efficient VCSELs have allowed VCSELs to be considered for high power and high brightness applications. In this talk, Aerius will discuss recent advances with Aerius’ VCSELs and application of these VCSELs to miniature optical sensors such as rangefinders and illuminators.

7615-14, Session 4

High-brightness pump sources using 2D VCSEL arrays

J. Seurin, G. Xu, Q. Wang, B. Guo, R. Van Leeuwen, A. Miglo, P. Pradhan, J. D. Wynn, V. Khalfin, C. Ghosh, Princeton Optronics, Inc. (United States)

Many applications require laser pump sources with high output power (tens to hundreds of Watts) in the smallest spot, with the smallest divergence. Such high-brightness pump sources typically use edge-emitting semiconductor lasers. However, it is also possible to use high-power two-dimensional vertical-cavity surface-emitting laser (VCSEL) arrays for this purpose. Using a single 2D VCSEL array chip combined with a matching micro-lens array we have recently demonstrated more than 1MW/cm^2-sr of brightness at 976nm. Such VCSEL-based pump sources can be made into fiber-coupled modules (typically 100 to 400 micron core-diameter fiber) for fiber-laser pumping, or they can be made into a simpler and less expensive sub-assembly (without the fiber-pigtail) for direct end-pumping of solid-state rod lasers. These novel high-brightness pump sources exhibit some well-known intrinsic VCSEL performance features such as wavelength stability, narrow spectrum, and good reliability, even for high-temperature operation.

7615-15, Session 4

Advanced characterization techniques for high-power VCSELs

H. Moench, J. Kolb, P. Pekarski, U. Schulz, Philips Research (Germany); M. Miller, Philips Technologie GmbH U-L-M Photonics (Germany); A. Valster, Philips Lighting B.V. (Netherlands); S. Gronenborn, Philips Extreme UV GmbH (Germany)

High power bottom emitting and oxide confined VCSELs with large diameter (30-150µm) emitt multiple transversal modes which change with induced current and device temperature. Furthermore measurements as a function of current are affected by underlying temperature changes due to the relatively high heat load of the device. Therefore standard characterization techniques as LIV curves and spectroscopic measurements cannot be applied as straightforward as for low power devices.

This work describes an understanding of the emission of high power VCSELs incl. changes in the emission of transversal modes. These modes can be understood as Fourier modes which perfectly describes the emission into different angles at various wavelengths as a function of temperature.

Improved characterization techniques are proposed which enable the correct measurement of intrinsic device temperature and a correction method for measurements at various currents. Short pulse techniques

and measurements at various heat sink temperatures give the necessary set of information which can be used to calculate back to the behaviour at constant temperature and therefore give meaningful LIV curves from which loss mechanisms can be discussed. In addition guidelines for the thermal design of high power VCSELs can be derived.

In order to better understand limiting effects on slope efficiency the internal quantum efficiency of the QWs is independently measured using a novel cut back method of in plane emitting devices. The optical losses are determined by measurements with various amounts of optical feedback into the VCSELs.

7615-16, Session 4

High-power low-noise VCSEL seed laser for fiber laser applications

B. Guo, Q. Wang, B. Xu, R. van Leeuwen, J. Seurin, G. Xu, C. Ghosh, Princeton Optronics, Inc. (United States)

The properties of high-power and low-noise seed lasers are key for high performance master oscillator-power amplifier (MOPA) fiber-lasers. We have successfully demonstrated high-power and low-noise seed lasers using our VCSEL technology. We used an external-cavity configuration with optimum cavity design for single-mode control. The external-cavity VCSEL achieved high-power single-mode pulsed operation with good mode quality that allowed it to be efficiently coupled into a single-mode PM or non-PM fiber. Using high-speed driving electronics, optical pulse widths of 12ns and shorter were obtained with repetition rates of up to 1 MHz. The optical output peak power obtained is over 10 W.

We have also demonstrated a CW version of this high-power VCSEL seed laser achieving single transverse and longitudinal mode with an output power of greater than 0.5 W. The high-power external cavity VCSELs were operated in single longitudinal mode demonstrating narrow spectral line-width of 200kHz, and having very low RIN of -155dB at 1MHz, which was even lower at higher frequencies.

7615-17, Session 4

Dynamics of the angular emission spectrum of broad-area VCSELs

S. Gronenborn, RWTH Aachen (Germany); H. Moench, Philips Research (Germany); M. Miller, P. Gerlach, Philips Technologie GmbH U-L-M Photonics (Germany); P. Loosen, Fraunhofer-Institut für Lasertechnik (Germany)

High power VCSELs can be realized by scaling up the active area of bottom-emitting devices. This results in a large Fresnel number of the laser cavity. The laser beam cannot be described with Gauss modes in a simple way anymore, but is best described in terms of tilted plane waves, called Fourier modes.

The beam quality and mode spectra depending on the applied current and the temperature of the VCSEL are investigated. Two-dimensional measurements of the near and the far field are combined with power and spectral measurement to characterize the VCSEL. Polarization and Fourier filtering are used to examine the spatially-dependent emission in detail. A rich dynamic in the angular emission profile for large-area VCSELs is discovered and can be explained by considering the backreflections from the imperfect AR-coating on the substrate and thermal effects. A theoretical model was developed to simulate the dynamics of the angular emission. The calculated angular and spectral profiles match the experimental observations very well over the whole parameter range.

The influence of the active area is studied for diameters of the oxide aperture from 20 up to 300 µm. For smaller diameters diffraction effects become more dominant, the Fresnel number is reduced and the emission spectrum gets closer to the Gauss mode description. The dynamic is changed as the influence of the backreflections becomes weaker.

For larger diameters the current-dependence is reverted which can also be explained by the model if one considers the three-dimensional temperature profile.

7615-18, Session 5

High-index-contrast subwavelength grating VCSEL

P. Gilet, N. Olivier, P. Grosse, K. Gilbert, A. Chelnokov, Lab. d'Electronique de Technologie de l'Information (France); I. Chung, J. Mork, Technical Univ. of Denmark (Denmark)

In this article, we report our results on 980nm high-index-contrast subwavelength grating (HCG) VCSELs for optical interconnection applications. In our structure, a thin undoped HCG layer replaces a thick p-type Bragg mirror. The HCG mirror can feasibly achieve polarization-selective reflectivities close to 100%. The investigated structure consists of a HCG mirror with an underneath /4-thick oxide gap, four p-type GaAlAs/GaAs pairs for current spreading, three InGaAs/GaAs quantum wells, and an n-type GaAlAs/GaAs Bragg mirror. The HCG structure was defined by e-beam lithography and dry etching. A Ti/Pt/Au p-type contact ring was deposited on top of the four-pair current spreading layers and was thermally annealed during a selective wet oxidation process. The current oxide aperture and the oxide gap underneath the HCG were simultaneously formed by the selective wet oxidation process. The HCG was so designed that the reflected mode recovers Gaussian shape after passing through the /4-thick oxide gap which is thinner than other designs reported in the literature. Sub-milliamp threshold current was achieved, and single-transverse-mode and single-polarization emission was maintained over all injection currents. This shows that the HCG mirror with a thin oxide gap works well as a polarization-selective mirror. An hero device exhibited maximum singlemode output power of more than 4 mW at room temperature and 1 mw at 70°C, which are the highest value ever reported from the HCG structures. These results build a bridge between a standard VCSEL and a hybrid laser on silicon, making them of potential use for the realization of silicon photonics.

7615-19, Session 5

80nm-tunable high-index-contrast subwavelength grating long-wavelength VCSEL: proposal and numerical simulations

I. Chung, J. Moerk, Technical Univ. of Denmark (Denmark); A. Sirbu, Ecole Polytechnique Fédérale de Lausanne (Switzerland); V. Iakovlev, Beam Express S.A. (Switzerland); A. Mereuta, A. Caliman, K. Elyahou, Ecole Polytechnique Fédérale de Lausanne (Switzerland)

A widely-tunable long wavelength vertical-cavity surface-emitting laser structure employing a MEMS-tunable high-index-contrast subwavelength grating (HCG) and an extended cavity is suggested and numerically investigated. The device structure consists of a GaAs HCG, a 970-nm-thick air gap, an antireflection oxide layer, five InAlGaAs/InP quantum wells with a regrown tunnel junction, and an undoped AlGaAs/GaAs bottom DBR. The reliability of this epi structure with an AlGaAs/GaAs top DBR has been experimentally proven, demonstrating 8 mW single-mode emission at 0ºC. The HCG structure and antireflection layer can be realized by e-beam lithography and wet oxidation of the high aluminium content layer after the wafer bonding. Vectorial simulations based on the modal expansion method and the finite-difference time-domain method, were used to investigate the tuning characteristics and single mode properties. As the air gap thickness underneath the HCG was varied by ±250nm, the lasing wavelength was found to tune linearly by more than 80 nm. The 250-nm mechanical actuation can be obtained using piezoelectric or electrostatic forces. The 80-nm tuning range is very large compared to the 2.5-nm tuning range reported in the literature, and results from making the air gap part of the optical cavity. This is achieved by inserting an antireflection layer below the air gap and by not adopting

partial top DBR layers for current spreading. The single mode operation was maintained throughout the tuning range, thanks to the selective pumping of the fundamental mode and the moderate mode selection by the HCG itself.

7615-20, Session 5

Thermal resistance reduction in 670nm vertical-cavity surface-emitting lasers

R. Safaisini, Colorado State Univ. (United States); K. Johnson, Vixar (United States); K. Lear, Colorado State Univ. (United States)

One of the many challenges in realizing improved red VCSELs is the higher thermal resistance of the ternary alloys required in the active region and mirrors. The resultant high junction temperatures decrease output power, roll-over current, resonant frequency, and reliability. Epitaxial modifications to reduce thermal resistance have been reported previously [1]. Others, described in this paper, are the minimization of semiconductor material outside the active region and surrounding the mesas in high thermal conductivity material such as copper.

We report on the first investigation of the effect of mesa plated sidewall heatsinks on the performance of red oxide-confined VCSELs. Single mode visible (670 nm) VCSELs with side-mode suppression ratio (SMSR)>20 dB were fabricated with an AlGaInP active region and AlGaAs distributed Bragg reflectors (DBRs). Copper is electroplated on and around VCSELs with different mesa diameters with a variety of overlap sizes in order to analyze the impact of mesa heatsinks as well as investigating the dominant direction of heat flow in the active region and mirror structures.

Results showed that plated heatsinks, on average, more than doubled the maximum output power due to better heat transfer in the structure. This analysis also indicates a reduction in laser threshold current after plating. A trend of reduction in thermal impedance for some devices has also been observed with increasing the plating overlap size.

[1] Klein Johnson, Mary Hibbs-Brenner, and Matt Dummer, "Modal and Thermal Characteristics of 670 nm VCSELs," SPIE Photonics West, 2009.

7615-21, Session 5

Photonic crystal single mode red VCSELS

A. M. Kasten, L. Naden, K. D. Choquette, Univ. of Illinois at Urbana-Champaign (United States); K. Johnson, M. Hibbs Brenner, Vixar (United States)

A photonic crystal etched into the top VCSEL facet can produce index guided single mode emission with high side mode suppression. Previous efforts have demonstrated single mode infrared VCSELs. We describe photonic crystal VCSELs for cavity confinement combined with ion implantation for electrical confinement within 670 nm red VCSELs. The fabrication of the photonic crystal pattern is based on a self-aligned optical lithography process. We report single mode VCSELs with output power greater than 1 W and 28 dB side-mode suppression ration at 674 nm. The photonic crystal VCSEL threshold current is reduced to 1 mA as compared to 2.5 mA for a similar ion implanted VCSEL.

7615-22, Session 6

High-speed 850nm oxide confined VCSELs for DATACOM applications

A. Mutig, Technische Univ. Berlin (Germany); S. S. Blokhin, A. A. Nadtochiy, Ioffe Physico-Technical Institute (Russian Federation); G. Fiol, Technische Univ. Berlin (Germany); J. A. Lott, V. A. Shchukin, N. N. Ledenstov, VI Systems GmbH (Germany); D. Bimberg, Technische Univ. Berlin (Germany)

VCSELs are broadly used as low cost reliable light sources for high speed data communication in LAN/SAN and in optical cables for computer and consumer applications. Rapid increase of the serial transmission speed and the limitations of copper wire-based links at bit rates >10 Gbit/s and distances >1 m extend the application field of fiber-optic interconnects to progressively shorter distances. The wavelength of 850 nm is standard for LAN/SAN applications over OM3 and OM4 multimode fiber and will continue playing important role in future standards. Here we present the results obtained on 850 nm oxide-confined VCSELs operating at bit rates up to 40 Gbit/s under direct modulation at current densities ~10 kA/cm^2 which are low enough for device reliability. The key device parameters: resonance frequency, damping and parasitic cut-off frequency were defined for devices with oxide-confined apertures of different diameters. Small signal modulation bandwidths and resonant frequencies up to ~22 GHz were measured. Electrical parasitic cut-off frequency of 24-28 GHz limited the high speed operation at the highest optical modulation speeds. We believe that with moderate effort in further reduction of electrical parasitics current modulated VCSELs can reach 30GHz optical modulation bandwidth and operate reliably even above 40 Gb/s.

7615-23, Session 6

High-speed VCSELs beyond 10 Gb/s development at Emcore

N. Li, C. Xie, C. Lei, X. Sun, W. Luo, EMCORE Corp. (United States); D. Kuchta, C. L. Schow, F. E. Doany, IBM Thomas J. Watson Research Ctr. (United States)

In this talk, we will present recent developments of beyond 10 Gb/s serial operation 850 nm vertical-cavity surface-emitting lasers (VCSELs) based on 10 Gb/s GenX design platform released to mass production in 2007. They have been developed to provide a solution not only to meet stringent 10 Gb/s IEEE & Fiber Channel specifications in 2007 but also for emerging demands of 17 Gb/s Fiber Channel serial and 100 Gb/s (4x25 Gb/s or 5x20 Gb/s) parallel applications in local and storage area networks (LANs and SANs). The paper covers optimized GenX VCSEL device designs, manufacturing processes, DC and AC characteristics, equivalent circuit models, recommended operating conditions, as well as preliminary reliability studies. We have successfully demonstrated low 25°C threshold current of 0.65 mA with ~7.5 um GenX VCSELs can be modulated up to 25 Gb/s with open eyes at 6 mA bias. For the same design, open eyes of 20 Gb/s can be achieved as low as 4 mA at 25°C and 8 mA at 70°C with higher extinguished ratio. More details of performance improvement will be presented.

7615-24, Session 6

High-speed 980nm VCSELs with integrated distributed losses for mode control

A. N. Al-Omari, Yarmouk Univ. (Jordan); K. L. Lear, Colorado State Univ. (United States)

High speed, single fundamental mode, oxide-confined, polyimide planarized 980nm vertical cavity surface emitting lasers (VCSELs) with a multi-oxide layer (MOL) structure to increase oxide aperture diameter and maintain single-mode operation are fabricated and characterized. VCSELs with an 8um active diameter and 16 mode suppression layers maintained single transverse mode operation under continuous wave (CW) condition with a side-mode suppression ratio (SMSR) of more than 32dB at current densities up to 20 times threshold, which is five times higher than the previously reported value for devices with three mode suppression layers, and exhibited a 3-dB modulation frequency bandwidth up to 13GHz at a current density of only 10kA/cm^2. The threshold current and voltage were as low as 260uA and 1.45V, respectively.

7615-25, Session 6

Dynamics of 1.55 µm buried tunnel junction VCSELs under optical injection around threshold

A. J. Daly, B. J. Roycroft, Tyndall National Institute (Ireland); F. H. Peters, Univ. College Cork (Ireland); M. Ortsiefer, Vertilas GmbH (Germany); B. Corbett, Tyndall National Institute (Ireland)

An investigation into the carrier and spectral dynamics of a 1.55 µm Buried Tunnel Junction (BTJ) VCSEL was carried out by examining the emission spectra under high resolution and the voltage across the junction as polarisation resolved light from a tunable laser source was injected into the cavity. The VCSEL combines an epitaxial InGaAlAs distributed Bragg reflector with a Si/CaF_2 dielectric reflector and an oval shaped BTJ leading to a predominantly single transverse polarisation mode and laser linewidths as low as 20 MHz. Around lasing threshold and injecting into the primary mode, the voltage required to maintain the current drops due to stimulated emission and a consequent reduction in the carrier density. Locking behaviour associated with this characteristic is measured with increased input power. Voltage drops as large as 6 mV are measured. Above threshold, injection locking is measured in addition to features associated with the relaxation oscillations of the carriers. The paper will present the polarisation, temperature and current dependence of the changes in the optical and voltage spectra of the BTJ-VCSEL. Optical injection can be used as a way to increase the VCSEL modulation bandwidth

Conference 7616: Novel In-Plane Semiconductor Lasers IX

Monday-Thursday 25-28 January 2010 • Part of Proceedings of SPIE Vol. 7616

Novel In-Plane Semiconductor Lasers IX

7616-01, Session 1

Unique lasing mechanism of localized dispersive nanostructures in InAs/InGaAlAs quantum dash-broad interband laser

C. Tan, Lehigh Univ. (United States); H. S. Djie, JDS Uniphase Corp. (United States); C. Tan, The Univ. of Sheffield (United Kingdom); B. Ooi, Lehigh Univ. (United States)

The authors report the nanowires-like and nanodots-like lasing behaviors in addition to multiwavelength interband transitions from InAs/InAlGaAs quantum dash (Qdash) lasers in the range of ~1550 nm. The presence of lasing actions simultaneously from two different dash ensembles, after postgrowth intermixing for crystalline quality improvement, indicate the absence of optical phonon emission due to the small variation in quantized interband transition energies. This effect is reproducible and shows strongly different lasing characteristics from the counterpart of quantum dot and quantum wire lasers. Furthermore, the small energy spacing of only 20 nm (at center lasing wavelength of ~1550 nm) and the subsequent quenching of higher energy transition states at higher bias level in Qdash lasers suggest the absence of excited-state transition in highly inhomogeneous self-assembled Qdash structures. However, the appearance of a second lasing line in a certain range of high injection level, which is due to the presence of different sizes of dash assembles, corresponds to the transition from smaller size of Qdash ensembles in the same planarly active medium. This unique transition mechanism will affect the carrier dynamics, relaxation process in particular and further indicates localized finite carrier lifetime in all sizes of Qdash ensembles. These phenomena will lead to important consequences for the ground-state lasing efficiency and frequency modulation response of Qdash devices. In addition, these imply that proper manipulation of the Qdash ensembles will result in localized nanolasers from individual ensemble and thus contributing towards enormously large envelope lasing coverage from semiconductor devices.

7616-02, Session 1

Temperature and threshold characteristics of quantum dot laser diodes

D. G. Deppe, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States)

Quantum dot laser diodes have advanced to the point that there may now be commercial applications in optical data transmission. One of the most immediate and important could be for 1.3 µm lasers in access networks such as fiber to the home or business. The opportunity is to reduce the optical transceiver cost using the novel physics of quantum dot laser diodes over planar quantum wells. In addition, the quantum dot laser diodes are showing novel performance in mode-locking, internal loss, and ability to operate with low dissipated power density, which could make the new devices important for silicon photonics wavelength division multiplexing, and integrated photonics that can use the novel mode-locking behavior of high stability.

The physics of the quantum dot laser diode will be discussed relevant to these applications to develop physical models for the devices. The specifics of the electronic structure in terms of both electron and hole levels will be presented, and how these influence the threshold and modulation characteristics. Nonequilibrium transport occurs because of inhomomogeneous broadening, and can lead to negative To at temperatures close to room temperature. The more commonly observed negative To below room temperature is identified with the temperature dependence of the laser diode transparency current, and closely spaced hole levels. Inhomogeneous broadening due to dot size nonuniformity may also explain the modulation speed limitations, and reduced feedback sensitivity.

7616-03, Session 1

High-power 1060-nm quantum dot laser with improved characteristic temperature by tunneling injection

E. Pavelescu, C. Gilfert, J. P. Reithmaier, Univ. Kassel (Germany)

The lack of green high power devices imposed new concepts to be investigated for display applications. A possible approach is frequency doubling of near infrared 1060 nm high power semiconductor lasers. Besides beam quality, the application of frequency doubling for green light generation is especially demanding regarding output power and temperature stability. Up to now quantum well lasers dominate the high-power semiconductor lasers available in this wavelength region. Lasers using self-assembled quantum dots as gain material have been proved suitable for high power applications due to their distinct advantages over quantum well lasers in terms of reduced threshold current density and temperature sensibility. Despite significant progress in the fabrication of QD lasers, the predicted ultrahigh temperature stability of operation has fallen far short of expectation. This is mainly caused by the presence of a wetting layer, which hosts a large density of states acting as a carrier reservoir and restricting the population of the lower energy dot states.

A solution to these problems is to use a tunneling injection structure, whereby the charge carriers are introduced into the lower dot states by tunneling from an adjacent injector quantum well. High-power 1060 nm quantum dot laser material was developed with tunnel injection quantum well active zones. The new type of laser material showed an improved internal efficiency (85 %) and allowed output power in excess of 4 W (limited by the current source) with a high characteristic temperature (194 K in the 2-80 oC range) for 100 µm broad area lasers.

7616-04, Session 1

Random population of InAs/GaAs quantum dots

I. P. O'Driscoll, M. Hutchings, P. M. Smowton, P. Blood, Cardiff Univ. (United Kingdom)

The processes which control the occupation of quantum dot (QD) states have a major influence on the temperature dependence of threshold current and the modulation speed of QD dot lasers. Using variable stripe length measurements we have investigated the occupation of dot states of different energy as a function of temperature using structures which have a bimodal size distribution which allows us to distinguish emission from two groups of dots ("large" and "small") with different energy states located in different dots, and emission from ground and excited states in the same size group being of different energy but located in the same dot.

Between 200K and 80K spontaneous emission from higher states on the small dots increases relative to the emission at lower energy from larger dots which indicates a transition to non-thermal population. At 80 K and 20 K, we observe a linear relation between the emission of the ground states of the small and large dots as a function of current, even though they are many (kT) apart and the slope indicates that states of different energy are populated with the same probability. From measured gain spectra we find a local minimum at 180K in the radiative threshold current density as a function of temperature which is due to an increase in recombination from higher lying states of the small dots as the temperature is reduced. The computed threshold current for thermal occupation at 300K and random population at 20K is in good agreement with these results.

Return to Contents

7616-05, Session 1

Dual-state lasing and the case against the phonon bottleneck

P. Spencer, E. Clarke, R. Murray, Imperial College London (United Kingdom); M. Majid, D. T. D. Childs, R. A. Hogg, The Univ. of Sheffield (United Kingdom)

The behaviour of quantum dot (QD) lasers is not yet fully understood; partly this is because these devices do not conform to the ideal of a homogeneous gain medium and the novel electronic structure leads to dual state lasing. Differences in the behaviour of bulk, quantum well and quantum dot (QD) diodes are evident from their IV characteristics and much useful information can be derived from modulation measurements of the -I2 d2V/dI2 response (figure 1 - not seen here) [1]. Here we apply an equivalent circuit model of the QD diode, separating the diode-like (thermal) and QD-like (athermal) I-V components. Combining this with optical mode profile measurements, we can identify changes at the laser thresholds which are caused by filamentation of the light emission and current distribution. Our results confirm that dual-state lasing (figure 2 - not seen here) is fundamentally a multi-mode phenomenon [1, 2], in contradiction to previous phonon bottleneck models [3, 4].

1. Spencer et al., Electron. Lett. 43, 574 (2007)

2. Houlihan & Kelleher; Opt. Comm. 281, 1156 (2008)

3. Markus et al., Appl. Phys. Lett. 82, 1818 (2003)

4. Viktorov et al., Appl. Phys. Lett. 87, 053113 (2005)

7616-06, Session 2

Pulse characteristics of passively mode-locked quantum dot lasers

L. F. Lester, The Univ. of New Mexico (United States); D. J. Kane, Mesa Photonics, LLC (United States); N. G. Usechak, Air Force Research Lab. (United States); C. Lin, Y. Li, The Univ. of New Mexico (United States); Y. Xin, IBM Corp. (United States); V. I. Kovanis, Air Force Research Lab. (United States)

Interest in quantum dot mode-locked lasers (QDMLLs) has grown in recent years since their first demonstration in 2001 as applications for optical time domain multiplexing, arbitrary waveform generation, two-photon sources, and optical clocking are anticipated. Ultrafast pulses from QDMLLs have been reported as short as 390 fs using intensity autocorrelation techniques, but so far detailed characterization examining the pulse shape, duration, chirp, and degree of coherence spiking in these lasers has not been absent. We describe direct frequency-resolved optical gating (FROG) measurements on a QDMLL operating at a repetition rate of 5 GHz with typically 5-10 ps pulses. Since commercially available FROG devices lack the sensitivity required to measure the output pulses from QDMLLs, we built a unique, ultra-sensitive second-harmonic-generation FROG system. Good pulse retrievals were obtained from an 8.2-mm cavity length QDMLL that has a 1.1-mm long saturable absorber at average powers up to about 5-10 mW. FROG traces at higher average powers contained coherence spikes. These features are well known in intensity autocorrelations and are usually caused by laser instabilities, which are always “coherent” at zero time delay, causing a large and fictitiously narrow peak to occur. Unlike intensity autocorrelation, however, FROG is not susceptible to confusing these coherence spikes with the actual pulse width of the laser. In addition, the data showed a clear pulse asymmetry corresponding to a fast rise and slow fall time that has not been reported before. The mostly linear chirp in the pulses indicates that recompressing the output can produce sub-picosecond pulses.

7616-07, Session 2

Improved performance of GaAsSb/GaAs SQW lasers

N. Hossain, S. R. Jin, S. J. Sweeney, Univ. of Surrey (United Kingdom); S. Q. Yu, S. R. Johnson, D. Ding, Y. Zhang, Arizona State Univ. (United States)

Improvements in MBE grown 1.3µm GaAsSb/GaAs single QW lasers are reported to aid in the design and optimization of low cost GaAsSb/GaAs-based edge-emitting lasers and VCSELs for potential applications in optical fiber communication systems. At room temperature (RT), the devices show a low threshold current density (Jth) of 253 Acm-2, a transparent current density (Jtr) of 98 Acm-2, an internal quantum efficiency (i) of 71% and an optical loss (¬i) of 18 cm-1. The important recombination mechanisms of the lasers are investigated by measuring both facet and spontaneous emission spectra in the temperature range of 12-300K. The results show that defect related recombination in these devices is negligible and the primary non-radiative recombination has a stronger dependence on the carrier density than the radiative current. The device operates up to 80 0C and has a characteristic temperature (T0) = 51K near RT. The temperature dependence of the radiative current density is much weaker than Jth, which indicates that the non-radiative process increases superlinearly with increasing temperature. From the measured Jth and its radiative component we found that non-radiative processes are dominant at RT in these lasers and contribute to ~84% of the threshold current. Additional theoretical and experimental investigations to identify the specific non-radiative processes in this material, the detailed device structure and the possibility to exploit this material for the production of 1.3 µm VCSELs will be discussed further at the conference.

7616-10, Session 2

A platform for GaAs opto-electronic integrated circuits based on GaAs/AlGaAs regrowth upon patterned InGaP

K. M. Groom, D. T. D. Childs, P. D. L. Greenwood, B. J. Stevens, J. S. Roberts, M. Hugues, M. Hopkinson, R. A. Hogg, The Univ. of Sheffield (United Kingdom)

We present novel approaches for fabrication of GaAs-based self-aligned lasers, superluminescent diodes (SLDs), and distributed feedback lasers, which can be extended for realisation of a toolkit for GaAs-based opto-electronic integrated circuits (OEICs). Our self-aligned stripe, formed using one regrowth step utilizes an n-doped InGaP current blocking and index guiding layer, and is applied to 980nm and strain-balanced 1050nm-emitting quantum wells (QWs) and to 1.3µm emitting quantum dots (QDs). No AlGaAs is exposed at any stage during the fabrication and regrowth processes, and long wavelength QDs, which are very sensitive to post-growth heat treatment, demonstrate no blue-shift in emission despite the relatively high MOVPE regrowth temperature employed (690ºC). Single lateral mode performance will be discussed and compared with standard ridge lasers processed from identical material, and realisation of near-symmetric far-field profiles will be discussed. Our structure is compatible with incorporation of an unpumped and laterally unguided window-structured back facet for realisation of ultra-low facet reflectivity [R ~10(-7)] for complete suppression of lasing, provided at the interface between the stripe region and the window region, formed monolithically and with only one overgrowth. This represents the first demonstration of a window structure formed within any self-aligned stripe and, when applied to width-chirped QWs has allowed attainment of high power SLDs with greater than 100nm bandwidth at 1050nm.

Realization of a toolkit for GaAs-based OEICs is now possible, being compatible with active/passive integration methods and sampled InGaP/GaAs gratings fabrication. DFB lasers utilising high-index-contrast GaAs/InGaP gratings have been demonstrated and will also be discussed.

7616-11, Session 2

The potential of Bismide alloys for efficient near- and mid-infrared semiconductor lasers

S. J. Sweeney, Univ. of Surrey (United Kingdom)

In spite of their importance in optical communications systems, InP-based semiconductor lasers operating in the 1.3-1.6um range suffer from high threshold currents and a large sensitivity to temperature, requiring the use of energy-demanding temperature stabilisation electronics. The cause of this behaviour has been the subject of considerable debate. Previous works have shown that Auger recombination processes (e.g. CHSH) and inter-valence band absorption involving transitions to the spin split-off (SO) band dominate the threshold current of InP-based lasers around room temperature. Further work has shown that antimonide-based lasers operating between 2 and 3um have lower threshold currents and a reduced sensitivity to temperature. This is due to the large spin-orbit splitting in antimonide-alloys (such that the SO splitting is larger than the band gap) which suppresses such losses. While conventional GaAs and InP-based alloys provide band gaps suitable for laser emission in the near-IR, the valence band structure enables such losses to persist. The SO-splitting is strongly dependent on the group V element atomic number and Bismuth is the largest stable group V element. Hence, Bismuth containing alloys (e.g. GaAsBi/GaAs) offer a large SO-splitting. Also, due to valence band anti-crossing, as observed in GaAsBi, the incorporation of Bismuth offers the potential of narrow gap III-V semicondutors with large spin-orbit splitting. For Bi fractions ~10% we show that a preferential band structure may be formed offering lasing in the telecoms band (and beyond) whilst suppressing the losses which dominate conventional InP and GaAs based lasers, offering the potential for efficient, uncooled sources.

7616-66, Session 2

Diode lasers emitting above 3 um at room temperature with more than hundred of mW of continuous wave output power

L. Shterengas, G. Kipshidze, T. Hosoda, G. Tsvid, G. Belenky, Stony Brook Univ. (United States)

Until recently the very idea of diode lasers operating in continuous wave (CW) at room temperature (RT) with wavelength near 3 μm was thought to be questionable. This pessimism originated in the well known fundamental increase of the nonradiative Auger recombination and of free carrier absorption with wavelength. The associated carrier and photon losses were considered likely to prevent the mid-infrared diode lasers from reaching CW lasing at RT.

Today, CW RT operation of the diode lasers emitting above 3 μm is a reality. Clearly, this experimental fact casts doubt on the validity of the aforementioned old argument. Moreover narrow bandgap nature of the active region not only brings disadvantages but also can provide significant benefits. The advantage of using narrow bandgap material for generation of optical gain originates in the proportionality between electron density of states and bandgap. Hence, mid-infrared diode lasers can have much lower transparency and, possibly, lower threshold carrier concentrations as compared to their near-infrared counterparts.

In this work we report on recent month's progress in design and development of the GaSb-based Type-I diode lasers. The contemporary devices generate hundreds of mW of output power up to 3.3 μm. The experimental values of the CW threshold current densities are below 500 A/cm2 for 3.3 μm emitters while 3 μm emitting lasers demonstrate only 200 A/cm2. The operating voltages are near 1.5 V at maximum output power levels. The realistic prospects to improve the output power further and to extend the device operating wavelength will be presented.

7616-12, Session 3

Progress on compact ultrafast quantum dot based lasers

E. U. Rafailov, M. Cataluna, Univ. of Dundee (United Kingdom)

In this paper we review the recent progress on the development of novel quantum-dot structures and laser devices. The investigation of novel regimes of ultrashort pulse generation in quantum-dot edge-emitting lasers will be presented. We will illustrate how new functionalities have been opened up, such as dual-wavelength mode-locking and enhanced tunability, through the exploitation of the excited-state transitions in the quantum dots as an additional degree of freedom in these ultrafast lasers. Progress on novel design rules for quantum-dot based vertical external cavity lasers and SESAMs are also considered.

7616-13, Session 3

Double-interval harmonic mode-locking technique for diverse waveform generation

Y. Li, F. L. Chiragh, C. Lin, The Univ. of New Mexico (United States); Y. Xin, IBM Corp. (United States); L. F. Lester, The Univ. of New Mexico (United States)

Compared to the traditional two-section quantum-dot passively mode-locked lasers (QDMLLs), reconfigurable multi-section QDMLLs are more beneficial for diverse waveform generation since they can demonstrate higher order harmonics of a laser's fundamental repetition rate simply by placing the saturable absorber section at different locations within the laser cavity. However, as the preferred repetition rate increases, it becomes increasingly difficult to pattern the absorber small enough such that it can be easily biased and unambiguously positioned to stimulate the desired harmonic. The double-interval technique is advantageous because it easily achieves harmonics that would otherwise be problematic using the traditional, single absorber method. The double interval technique refers to using two saturable absorbers that stimulate different harmonics in order to achieve a multiple of the two. In this work, a 6.75-mm long reconfigurable QDMLL that consists of twenty-seven 250-micron sections was fabricated. The 2nd, 3rd, and 5th harmonics of laser's fundamental frequency were realized by applying a single absorber in the laser cavity. Through the double interval technique, mode-locking at the 6th and 10th harmonics are demonstrated by combining two lower order harmonics of the laser's repetition rate. A 60 GHz repetition rate is achieved at the 10th harmonic of the laser device. Higher repetition rates are expected using a shorter device that has a higher fundamental frequency.

7616-14, Session 3

Pulse picking from 4GHz pulse trains generated by mode locking of 1cm-long monolithic 1060nm DBR lasers

A. Klehr, A. Liero, Ferdinand-Braun-Institut für Höchstfrequenztechnik (Germany); T. Hoffmann, Ferdinand-Braun-Institut für Höchstfrequenztechnik (Germany); S. Schwertfeger, H. Wenzel, G. Erbert, W. Heinrich, G. Tränkle, Ferdinand-Braun-Institut für Höchstfrequenztechnik (Germany)

For applications as micromachining, material processing, fluorescence spectroscopy, biomedical application and nonlinear optics femtosecond or picosecond pulses with repetition rates in the kHz and MHz range are needed. Mode locking in lasers is a well known technique to generate such short pulses. The repetition rate of the pulses emitted from these devices depends on the total cavity length and is usually in the GHz or high MHz range. To reduce the repetition rate pulse pickers are used to selectively pick off pulses.

We present experimental results from a new hybrid arrangement consisting of a 1cm long monolithic 4-section DBR master oscillator and an ultra fast pulse picker element driven by a high frequency GaN high-electron mobility transistor with low capacitances and high current density. The master oscillator generates 4GHz pulse trains with a pulse width of 10ps by mode locking. Selective pulse picking with a free choice of the repetition rate is reached with a two section tapered element consisting of a 1000µm ridge waveguide section and a 3000µm long tapered section. The RW section is driven by the HF transistor with short current pulses by which the absorption of the RW section can be modulated. An injected optical pulse can pass the RW section in case of transparency and will be amplified in the tapered section. Detailed investigations of pulse picking with this new pulse picker arrangement will be presented.

7616-15, Session 3

Linewidth enhancement factor and dynamical response of an injection-locked quantum dot Fabry-Perot laser at 1310nm

M. C. Pochet, N. A. Naderi, The Univ. of New Mexico (United States); N. B. Terry, V. I. Kovanis, Air Force Research Lab. (United States); L. F. Lester, The Univ. of New Mexico (United States)

This work investigates the linewidth enhancement factor (alpha-factor) and dynamical response under optical injection of an InAs/InGaAs Quantum Dot Fabry-Perot laser. Using the injection-locking technique, the above threshold alpha-factor of the device is measured to be 0.6, an uncharacteristically small value, at bias currents close to threshold. A strong dependence of the alpha-factor on the photon density is shown as its measured value is found to increase with the bias current and/or the injected photon density. Such finding demonstrates that the alpha-factor can be manipulated for the purpose of modifying the modulation response or chirp behavior under injection-locked conditions. The below threshold alpha-factor is also measured using the Hakki-Paoli technique for comparison purposes. The measured alpha-factor values are then used to simulate the dynamical response (i.e. stable locking, Period-1, Period-2, or chaos) in the context of single mode rate equations under zero-detuned injection conditions for external injected power ratios ranging from -6.5dB to +26dB. Legacy literature has shown that optically injected diode lasers typically follow the period doubling route into a chaotic region as the injection level and/or optical detuning are varied. Theoretical predications show that only a small region of Period-1behavior will be observed for this optically-injected Quantum Dot device at bias currents close to threshold, driven largely by the low alpha-factor. Experimental results showed that under zero-detuned optically injected conditions, only unlocked and stable locking behaviors are observed. Such findings suggest that a Quantum-Dot device can be employed in an injection-locked configuration for photonic tunable clock applications.

7616-16, Session 4

Progress of blue and green InGaN laser diodes

S. Lutgen, A. Avramescu, T. Lermer, D. Queren, J. Müller, A. Breidenassel, U. Strauss, OSRAM Opto Semiconductors GmbH (Germany)

Mobile laser projection is of great commercial interest. Today, a key parameter in embedded mobile applications is the wall plug efficiency. We report improvements of the performance of blue InGaN laser in view of efficiency and life time. Furthermore, we present pioneering studies on long wavelengths InGaN laser diodes. The technological challenge is to achieve InGaN-quantum wells with sufficiently high material quality for lasing. We investigate the density of non radiative defects in dependence on In-concentrations of the light emitting InGaN quantum wells. Electro-optical measurements confirm that low defect densities are essential for stimulated emission. Laser operation at 516nm with more than 50mW output power in pulse operation is demonstrated.

7616-17, Session 4

Lasing of semipolar InGaN/GaN(11bar{2}2) heterostructures grown on m-plane sapphire substrates

A. Strittmatter, M. Teepe, Z. H. Yang, C. L. Chua, J. Northrup, N. M. Johnson, Palo Alto Research Center, Inc. (United States); V. A. Ivantsov, A. Syrkin, L. Shapovalov, A. S. Usikov, Technologies and Devices International, Inc. (United States); R. G. W. Brown, Ostendo Technologies, Inc. (United States)

Results will be presented demonstrating optically pumped lasing from InGaN/GaN MQW heterostructures grown by MOCVD on semi-polar GaN(11.2) and compared to results on c-plane reference structures. The semi-polar GaN layers were 10 to 20 m thick and grown by HVPE on sapphire substrates. Theoretical simulations demonstrated vanishing internal electric fields in semi-polar InGaN/GaN(11.2) heterostructures. For verification, double quantum well InGaN/GaN heterostructures with lower AlGaN cladding layers suitable for optical pumping experiments were developed. Optical experiments under low- and high excitation conditions provided evidence for the theoretical results. First, the room-temperature photoluminescence (low-excitation density) of semi-polar InGaN/GaN heterostructures emitting at 500 nm was only a factor of 2-3 less in intensity than comparable structures emitting at 400 nm as opposite to similar c-plane structures which showed an intensity reduction of a factor of ten. As a result, the PL intensity of the semi-polar heterostructures outperforms the c-plane reference structure at 500 nm wavelength despite a lower crystalline quality of the GaN template. Second, the optically pumped lasing achieved on the semi-polar InGaN/GaN structures at wavelengths from 400 nm up to 500 nm consistently occurs with no blue-shift with respect to the low-excitation photoluminescence spectrum. In contrast, lasing on the c-plane heterostructures exhibits a monotonically increasing blue-shift with regard to the photoluminescence spectrum with increased emission wavelength. For instance, in structures with the PL spectrum centered at 480 nm the lasing is blue shifted by 20 nm. These results demonstrate the potential of semi-polar GaN(11.2)/sapphire templates for achieving true green laser diodes.

The research at PARC was performed under the DARPA VIGIL Program, managed by Michael Haney.

7616-18, Session 4

Nitride-based laser diodes with InAlN cladding layers

N. Grandjean, A. Castiglia, E. Feltin, G. Cosendey, A. Altoukhov, J. Carlin, R. Butté, Ecole Polytechnique Fédérale de Lausanne (Switzerland)

We report on laser diodes (LDs) that include Al0.83In0.17N alloy as bottom cladding layer. Al0.83In0.17N layers are equivalent, in terms of refractive index, to AlGaN layers with an Al content of 46% and, at the same time, are lattice matched (LM) to GaN. The index contrast to GaN exceeds 8% for such a LM AlInN layer in the 400-420 nm wavelength range whereas this value is limited to ~ 2% when using an AlGaN layer with an Al content of 7%. Increasing the Al-content would lead to a higher refractive index contrast between the waveguide region and the claddings and therefore to a better mode confinement. However, such an increase eventually leads to cracking of the AlGaN claddings due to the tensile strain that builds up during growth. Modeling of laser structures demonstrates that AlInN alloy could act as a perfect optical blocking layer avoiding mode leakage in the substrate.

InGaN/GaN multiple quantum well (MQW) based LDs including an Al0.83In0.17N cladding layer have been grown on freestanding GaN substrates by metal organic vapor phase epitaxy. Emission properties are compared to our state of the art LDs, which exhibit current threshold of 3 kA/cm2 and a differential quantum efficiency of 0.5 W/A (per facet - uncoated) under cw operation. Finally, the impact of the AlInN

cladding on the I-V characteristics and the farfield distribution pattern are presented.

7616-19, Session 4

Nonpolar and semipolar InGaN beyond blue region and its device appication

H. Ohta, J. S. Speck, S. P. DenBaars, S. Nakamura, Univ. of California, Santa Barbara (United States)

This paper is an invited paper (contacted by prof. Michael Kneissl).

7616-20, Session 5

Quantum cascade lasers: an enabling technology for mid-infrared photonics (Keynote Presentation)

F. Capasso, Harvard Univ. (United States)

The Quantum Cascade Laser (QCL) has emerged as the laser of choice for photonics in the mid-IR, particularly in the molecular fingerprint region (= 4 to15 µm), comprising the two atmospheric windows, due to: (1) its very large wavelength coverage, including broadband lasing, by control of layer thickness that allows tailoring of QCL performance for many applications;1 (2) standard semiconductor processing with epitaxial layers grown by commercial growth platforms (MBE, MOVPE) used in photonics at telecom wavelengths and in high-speed electronics;2 (3) high power operation;1,2 (4) excellent temperature performance due to the high T0.1,2 These characteristics descend from its operating principle which frees it from “band-gap slavery”: unipolar lasing between confined electron quantum states . Among QCL’s important uses are: (1) single mode broadly tunable lasers with   100 mW peak power and tens of mW of cw power at room temperature (RT) for chemical sensing and trace-gas analysis at parts per billion in volume in areas such as: pollution monitoring including greenhouse gas emissions, security and law enforcement applications, combustion diagnostics and breath analysis; industrial process control, scientific instrumentation for atmospheric chemistry;3 (2) compact, chip-scale, broadband spectrometers with performance comparable to state-of-the-art Fourier-Transform-Infrared spectrometers;4 (3) cw RT devices with Watt-level power for infrared countermeasures.5 QCL commercialization will be discussed.6 .

1. F. Capasso et al. Physics Today, 55, 34-38, 2002.

2. M. Troccoli et al. Journal of Lightwave Technology 26, 3534-3554 (2008).

3. G. Wysocki et al. Appl. Phys. B 92, 305-311 (2008).

4. B. Lee at al. Photonics Spectra, May 2008.

5. A. Lyakh et al. Appl. Phys. Lett 92, 111110 (2008).

6. http://www.researchandmarkets.com/reports/1055867/worldwide_nanotechnology_mid_ir_sensor_market

7616-21, Session 5

Quantum cascade lasers: ab initio design and circuit resonators

J. Faist, ETH Zürich (Switzerland)

The quantum cascade laser (QCL) has demonstrated operation over an extremely wide wavelength range extending from the mid-infrared at 2.9µm to the Terahertz at 360µm. These achievements require the design of very complicated sequences of layers with Angstrom accuracy.

We demonstrate that the combination of a density-matrix based simulation software with good control of the epitaxy enables a true “quantum engineering” of structures based on ab-initio modeling. Extremely wide gain bandwidth QCL chips were designed and grown, enabling external cavity tuning from 7.8 to 11.8 µm wavelength from the same chip. Application of such devices are for spectroscopy of molecules in a solid or liquid matrix that display very broad absorption lines.

In the Terahertz, MBE-grown structures have demonstrated record low frequency operation, down to 1.2THz. Taking advantage of the tight confinement provided by the metal-metal waveguide, we also have explored microcavities as well as photonic crystal quantum cascade lasers based on these very low frequency materials. These cavities enable us to explore the coupling between transport and photon emission in the regime of very subwavelength emitters, as the ratio of volume over lambda cube is much below unity. Particularly interesting are cavities presenting strong analogy with LC circuits where the Purcell factor can be much larger than unity.

7616-22, Session 5

An aluminum-free mid-infrared quantum cascade laser

G. Strasser, Technische Univ. Wien (Austria) and Univ. at Buffalo (United States); M. Nobile, H. Detz, A. M. Andrews, P. Klang, W. Schrenk, Technische Univ. Wien (Austria)

We report about a novel material system, InGaAs/GaAsSb lattice matched to InP, suitable for intersubband devices like quantum cascade lasers (QCLs). The material system utilizes InGaAs wells and GaAsSb barriers to confine electrons with a conduction band offset of 360 meV, comparable to GaAs/AlGaAs. In contrary to all existing QC lasers this material system is completely free of aluminum, resulting in a low effective electron mass in the barrier material. A detailed study on ISB absorption in InGaAs/GaAsSb multiple quantum wells (well widths ranging from 4.5 nm to 12 nm) show pronounced and narrow ISB absorption at room temperature in a broad wavelength range (5.8 - 11.6 micron). We will report about two kinds of interssubband devices: QWIPs and QCLs. InGaAs/GaAsSb QWIPs operating at a wavelength of 5.5 micrometers have been fabricated. The first QC lasers emit at a wavelength of approximately 11 micron with a threshold current density of 1.7 kA/cm2 and a maximum optical output power of 20 mW at 78K. Novel designs show better performance and the best performance will be discussed at the conference. THz QCLs have not been realized yet, but there is no physical reason why this should not be possible.

7616-23, Session 5

Suppression of carrier leakage in 4.8 µm emitting quantum cascade lasers

D. Botez, J. Shin, L. J. Mawst, Univ. of Wisconsin-Madison (United States); I. Vurgaftman, J. R. Meyer, U.S. Naval Research Lab. (United States)

Conventional quantum-cascade (QC) lasers emitting in the 4.5-5.5 µm wavelength range and designed for high-power operation suffer from significant carrier leakage from their active regions to the continuum, as evidenced by low values (i.e., ~ 140 K) for the characteristic temperature coefficients, T0 and T1, of their threshold current and slope efficiency, respectively. As a result their maximum CW wallplug efficiencies at room temperature (RT) reach values of only ~ 10 %.

By taking advantage of the flexibility of MOCVD crystal growth and an advanced 8-band k p code we have designed and demonstrated QC-lasers structures for which the injected carriers are tightly confined to the active region such that record T0 and T1 values (i.e., 278 K and 285 K) are achieved up to 90 oC heatsink temperature. Tight carrier confinement is achieved in two ways: 1) creating deep quantum wells and tall barriers in the active region (AR) ; and 2) tapering, towards the AR, the conduction band edge of both the injector and extractor regions. In turn injected electrons that are thermally excited to the upper AR energy levels cannot escape to the continuum via scattering to the upper and lower minibands of the extractor region. This is achieved at no penalty in threshold-current density. The record-high T0 and T1 values indicate that we are approaching temperature dependences determined mainly by optical-phonon scattering. They should significantly improve CW operation (e.g., doubling the RT CW wallplug efficiency) and make possible the realization of intersubband quantum-box lasers

7616-24, Session 6

Tunable and high-temperature THz quantum-cascade lasers

Q. Hu, Massachusetts Institute of Technology (United States)

The terahertz frequency range (1-10 THz) has long remained undeveloped, mainly due to the lack of compact, coherent radiation sources. Semiconductor electronic devices (such as transistors) are limited by the transient time and RC roll-off to below 1 THz. Conventional semiconductor photonic devices (such as bipolar laser diodes) are limited to above 10 THz even using small-gap lead-salt materials. Transitions between subbands in semiconductor quantum wells were suggested as a method to generate long wavelength radiation at customizable frequencies. The recently developed THz quantum-cascade lasers (QCL) hold great promise to bridge the so-called “THz gap” between conventional electronic and photonic devices.

7616-25, Session 6

Physics of terahertz quantum cascade lasers

H. C. Liu, National Research Council Canada (Canada)

In this talk, I will take the example of the 3-well resonant phonon design and consider its device physics. Recent insight using density matrix formalism will be discussed together with existing experimental results. Further possible improvements and new directions will also be discussed.

7616-26, Session 6

Terahertz quantum cascade lasers: current challenges in design and implementations

D. Indjin, P. Harrison, Z. Ikonic, C. A. Evans, L. J. Lever, A. Valavanis, Univ. of Leeds (United Kingdom); N. V. Vukmirovic, Lawrence Berkeley National Lab. (United States); R. W. Kelsall, E. H. Linfield, P. Dean, S. P. Khanna, N. Hinchcliffe, A. G. Davies, Univ. of Leeds (United Kingdom)

THz QCLs have reached a technological maturity since the first time realised in 2002. However, with maximal operating temperature around 180K in pulsed mode and ~ 250K with the help of the strong magnetic field, a number of milestones should be reached in order to improve the device performances before achieving full commercialization. In this talk, we will concentrate on the recent design and modelling issues as well as on current challenges in the growth, fabrication, characterization and application of improved and modified designs. The recent realisations, like electrically tunable heterogeneous cascade QCL, ambipolar dual-frequency QCL, etc will be also discussed. Different aspects of QCL structure modeling, such are the pure rate equation scattering transport model, density matrix and Non-equilibrium Green function approach, 2D and 3D electro-thermal model and inclusion of the depopulation due to the stimulated emission and their usefulness to design of novel structures will be analysed. Also, our experience in direct joint work and day-to-day bi-directional interaction between the design/modelling and growth/fabrication/characterization teams will be shared to the auditorium.

7616-27, Session 6

Gain competition in two-color quantum cascade lasers

C. J. Pflügl, M. Geiser, Harvard Univ. (United States); A. A. Belyanin, Texas A&M Univ. (United States); Q. J. Wang, N. Yu, Harvard Univ. (United States); T. Edamura, H. Kan, Hamamatsu Photonics K.K. (Japan); F. Capasso, Harvard Univ. (United States)

We investigated two-color mid-infrared quantum cascade lasers designed for THZ difference frequency generation. Due to gain competition mid-infrared modes tend to start lase in higher order modes. This leads to unwanted cancellation effects reducing the power of the terahertz radiation by about an order of magnitude. To understand this lateral mode behavior, we developed a model that describes the mutual pump mode interactions. The mid-IR pump mode with the lower lasing threshold reduces population inversion in the substack with the higher threshold due to stimulated emission. Based on these findings we were able to improve the design and avoid undesired lasing in higher lateral modes.

7616-28, Session 7

Thin film III-V edge emitting lasers integrated onto silicon

N. M. Jokerst, S. Palit, Duke Univ. (United States); J. Kirch, G. Tsvid, L. J. Mawst, T. F. Kuech, Univ. of Wisconsin-Madison (United States)

The integration of compound semiconductor edge emitting lasers onto silicon enables the realization of complete optical systems on silicon for chip scale applications. One interesting application for III-V lasers on Si is portable optical sensing for medical, environmental, and security applications. For these applications, the chip scale integration of an entire optical sensing system is a design goal, including an optical source, waveguide interconnect, optical sensors, and optical detection. For system portability, low power consumption and low heat dissipation are essential, which drives high efficiency optical components, interfaces, and interconnections. Processes and tradeoffs for the integration of III-V edge emitting lasers onto Si will be discussed, including laser contact schemes and metal/metal bonding for heat dissipation. Results for contacts (n and p) on the top side of thin film lasers will be presented, as well as results for contacts on both sides of the thin film lasers. Test results for lasers integrated onto Si with other optical components will also be discussed, including waveguides, passive couplers, and photodetectors. Prospects for chip scale integrated sensing systems on Si using these components and sensors will also be presented.

7616-29, Session 7

Compact hybrid Si microring lasers

D. Liang, J. E. Bowers, Univ. of California, Santa Barbara (United States); M. Fiorentino, R. G. Beausoleil, Hewlett-Packard Labs. (United States)

Microring resonator lasers are promising components for photonic integrated circuits due to their small size, single mode lasing behavior and the fact that etched or cleaved facets are not required. In this paper we review the recent progress in developing compact microring lasers on the hybrid silicon platform. A simplified self-aligned process is used to fabricate devices as small as 15 micrometer in diameter. The optically-pumped, continuous wave (cw) devices show low threshold carrier density, comparable to the carrier density to reach material transparency. In the electrically-pumped lasers, the short cavity length leads to the minimum laser threshold less than 5 mA in cw operation. The maximum cw lasing temperature is up to 60 deg.C. Detailed studies in threshold and differential efficiency as a function of ring diameter, coupling coefficient, and bus waveguide width are presented. Surface recombination at the dry-etched exposed interface is investigated qualitatively by studying the current-voltage characteristics. Ring resonator-based figures of merits including good spectral purity and large side-mode suppression ratio are demonstrated. Thermal impedance data is extracted from temperature-dependent spectral measurement. High-speed measured results are presented as well.

The demonstrated compact hybrid ring lasers have low power consumption, small footprint and dynamic performance. They are promising for Si-based optical interconnects and flip-flop applications.

7616-30, Session 7

Monolithic integration of the Ga(NAsP)-laser material lattice matched on (001) Si-substrate

W. Stolz, Philipps-Univ. Marburg (Germany); B. Kunert, NAsP III/V GmbH (Germany); S. Liebich, M. Zimprich, S. Zinnkann, K. Volz, Philipps-Univ. Marburg (Germany)

The novel direct band gap, dilute nitride Ga(NAsP)-material system allows for the first time the monolithic integration of a III/V laser material lattice matched to Si substrate. This lattice-matched approach allows for the first time for a high-quality, low defect density integration of a III/V-laser material potentially leading to long-term stable laser devices on Si-substrate. The broad area laser structures consist of pseudomorphically strained active Ga(NAsP)/(BGa)(AsP) multi-quantum-well heterostructures (MQWHs) embedded in thick doped (BGa)P waveguide layers, grown by a specific low-temperature metal organic vapour phase epitaxy (MOVPE) process on (001) Si-substrate. The optimization of the laser properties focus on improvements in material quality based on MOVPE growth conditions as well as the design parameters such as optimal carrier and light field confinement, doping levels and post-growth annealing treatments. This paper will present and discuss the current status to realise electrical injection laser diodes as a basis for Si-photonics based opto-electronic integrated circuits (OEICs) with novel functionalities.

7616-31, Session 7

Sb-based laser sources grown by molecular beam epitaxy on silicon substrates

J. Rodriguez, L. Cerutti, P. Grech, G. Boissier, G. Narcy, E. Tournie, Univ. Montpellier 2 (France)

The material system comprising GaSb, InAs, AlSb and their related alloys are an impressive toolbox for device designers, as they offer a very large choice of band-gaps and band offsets. Molecular beam epitaxy (MBE) and device processing have been improved quickly over recent years, allowing the fabrication of high performance devices as quantum cascade lasers, mid-infrared edge (MIR) emitting and surface emitting lasers, superlattice infrared photodetectors, but also very high speed / low consumption AlSb/InAs field effect transistors.

Efforts have been made to monolithically grow these devices onto larger and cheaper substrates like GaAs and Si, to improve the yield / decrease the cost of this technology and possibly integrate the devices with CMOS technology.

We recently fabricated a 2.3 µm edge emitting laser grown by MBE on a Si substrate, and demonstrated room-temperature pulsed operation. Lasers emitting at this wavelength are of particular interest for gas sensing. Challenges to further improve the device include the substrate preparation, optimization of the nucleation layer quality, but also the conduction band engineering in order to facilitate the electronic transport at the Si/III-Sb interface.

In this communication, we describe our efforts to address these issues, and discuss our latest results on antimonide-based lasers emitting at different wavelengths and grown on Si substrates.

7616-32, Session 8

High-power spectrally-stable DBR semiconductor lasers designed for pulsing in the nanosecond regime

J. K. O’Daniel, M. Achtenhagen, Photodigm, Inc. (United States)

The basic design considerations for a spectrally-stable DBR semiconductor laser specifically designed for pulsing in the nanosecond regime is presented, along with test results from devices fabricated according to these design parameters. Results show excellent mode selection and spectral stability over an extremely large range of conditions, including temperature ranges of 15-60ºC and peak drive current ranges from threshold to 880mA. These lasers exhibit peak output powers of greater than 500 mW for DBR semiconductor lasers at 976 nm and 1064 nm while remaining spectrally stable. Chirp data shows the chirp can be effectively tuned from approximately 1GHz to greater than 20GHz by varying the pulse width and peak drive current.

7616-33, Session 8

High-power ultralow-noise semiconductor external cavity lasers based on low-confinement optical waveguide gain media

P. W. Juodawlkis, W. Loh, F. J. O’Donnell, M. A. Brattain, J. J. Plant, MIT Lincoln Lab. (United States)

For the past several years, we have been developing a new class of high-power, low-noise semiconductor optical gain medium based on the slab-coupled optical waveguide (SCOW) concept. The key characteristics of the SCOW design are (i) large (> 5 x 5 µm), symmetric, fundamental-transverse-mode operation attained through a combination of coupled-mode filtering and low index-contrast, (ii) very low optical confinement factor (~ 0.3-0.5%), and (iii) low excess-optical loss (i ~ 0.5 cm-1). The large transverse mode and low confinement factor enables SCOW lasers (SCOWLs) and amplifiers (SCOWAs) having Watt-class output power. The low confinement factor also dictates that the waveguide length be very large (0.5-1 cm) to achieve useful gain, which provides the benefits of small ohmic and thermal resistance. In this talk, we review the operating principles and performance of the SCOW gain medium, and detail its use in semiconductor external cavity lasers. Specifically, we describe a 1.55- m packaged, single-frequency SCOW external cavity laser (SCOWECL) having an output power of 0.37 W, an open-loop Gaussian (Lorentzian) spectral linewidth of 35 kHz (1.75 kHz), and relative intensity noise (RIN) less than -162 dB/Hz from 2 MHz to 10 GHz. The SCOWECL consists of a double-pass, curved-channel InGaAlAs quantum-well SCOWA and a narrowband (2.4 GHz) fiber Bragg grating (FBG) external cavity. In the RIN spectrum, we observe no evidence of a relaxation oscillation or residual longitudinal sidemodes, implying a sidemode suppression ratio (SMSR) in excess of 80 dB.

7616-34, Session 8

Ultra-high-power ultra-low RIN up to 20 GHz 1.55 µm DFB AlGaInAsP laser for analog applications

J. Burie, G. Beuchet, M. Mimoun, P. Pagnod-Rossiaux, B. Ligat, J. Bertreux, J. Rousselet, J. Dufour, P. Rougeolle, F. J. Laruelle, 3S PHOTONICS SA (France)

Low levels of intensity noise in semiconductor laser diodes is a key feature for numerous applications including high resolution spectroscopy, fiber-optic sensors, signal distribution in broadband analog communications (CATV), and more generally for microwave photonics systems. In particular, a DFB laser with very low relative intensity noise (RIN) levels from 0.1 to 20 GHz is a key component for radars as it corresponds to the whole frequency bandwidth of interest. Several approaches have been reported but most suffer from the compromise between RIN level and output power level and stability, with RIN level in the range -150 dB.Hz-1 to -155 dB.Hz-1 in this frequency range. We report here results from a new AlGaInAs DFB laser diode developed at 3S PHOTONICS. Excellent device performance is observed across an operating range from the laser threshold up to the thermal roll-over. Pure longitudinal single mode at 1545 nm is obtained over the whole current operating range with side mode suppression ratio higher than 50 dB. The maximum output power reaches up to 140 mW. In these conditions, RIN levels below -160 dB.Hz-1 is obtained in the up to 20 GHz. These are the best results to our knowledge combining such high single mode output power with such low RIN level in the frequency range 0.4-20 GHz.

7616-35, Session 8

High reliability and very low linewidth of 852nm DFB lasers for Cs pumping

C. Cayron, V. Ligeret, P. Resneau, Alcatel-Thales III-V Lab. (France); J. Nagle, S. Bansropun, Thales Research & Technology (France); M. Lecomte, M. Calligaro, O. Parillaud, M. Krakowski, Alcatel-Thales III-V Lab. (France)

The development of techniques such as atom optical pumping, for atomics clocks or precise gyroscopes, requires laser diodes with high power and excellent spectral (narrow linewidth) and spatial qualities together with high reliability.

We have realized a six months ageing test on DFB lasers emitting at 852nm for Cs pumping. We had two different ageing conditions (power and temperature) : 10 DFB lasers were aged at 40°C and 20mW and three DFB lasers at 25°C and 60mW.

The extrapolated lifetimes at 40°C, based on 20mW operating current, of our DFB laser are higher than 500000 hours which confirm the excellent potential of this Al-free technology for long life spatial mission. Furthermore, the evolution of the operating current (initially around 70mA), after six month, is less than 5% (corresponding to 3mA).

We obtain a very good stability of optical spectra : an average variation of the Side Mode Suppression Ratio (SMSR) less than 2dB and a variation of the wavelength less than 0.12nm at ageing temperature (40°C).

Then we measured the linewidth of our aged DFB laser with the delayed self-heterodyne method after the six months ageing: we obtain a very narrow linewidth at 25°C (measurement temperature) around 215kHz (lorentzien fit, white noise) or 330kHz (Gaussian fit, 1/f noise).

7616-36, Session 8

High-power ridge-waveguide DFB-lasers and MOPAs emitting at 1064nm with a vertical far-field angle of 15°

O. Brox, F. Bugge, A. Ginolas, A. Klehr, P. Ressel, H. Wenzel, G. Erbert, Ferdinand-Braun-Institut für Höchstfrequenztechnik (Germany)

We present high-power ridge waveguide DFB-lasers and DFB-MOPAs with high-quality beams optimised for pulsed operation and current modulation.

The vertical structure of the devices comprises an InGaAs/GaAsP double quantum well active region which is embedded asymmetrically in a recently developed 4.8µm broad AlGaAs waveguide region. The upper waveguide layer of the DFB-sections contains a 60nm thick GaAs grating layer, which is patterned with holographic lithography followed by a second epitaxial step. The second order grating results in single-mode longitudinal emission around 1064nm. The fundamental-lateral mode is stabilized with a 4µm broad ridge defined by 5µm wide trenches. Devices with power reflectivities of 0.95 and less than 10^-3 for back and front facet, respectively where mounted p-side up on C-mounts. We measured a threshold current of 35mA and a CW optical output power of almost 400mW at a current of 500mA for 1mm long DFB-lasers. The slope efficiency slightly above threshold is as high as 0.95W/A. For pump currents up to 500mA the fabricated devices emit with FWHM divergences of 10° and 15° for the lateral and vertical direction, respectively. The output beam with an ellipticity of 1:1.5 is well suited for direct coupling into single-mode waveguides.

In the DFB-MOPA, the DFB-laser is monolithically integrated with a 1mm long modulation section and a 2mm long amplifier ridge-waveguide section to boost the output power and to facilitate a modulation of the power while keeping the emission wavelength constant. Details will be presented at the conference.

7616-37, Session 9

Progress in InAs-based quantum cascade lasers

A. N. Baranov, R. Teissier, O. Cathabard, J. Devenson, Univ. Montpellier 2 (France)

Due to the high conduction band offset of 2.1 eV, the InAs/AlSb material system is very attractive for the development of short wavelength quantum cascade lasers (QCL). Using these materials we have demonstrated first QCLs operating below 3 µm. The shortest emission wavelength of the InAs-based QCLs is limited by the direct-indirect valley separation in the quantum wells which is also larger compared with other QCL materials. The carrier leakage into the L-valley can be decreased by using a special design with reduced coupling between active quantum wells. This approach allowed us to realize QCLs emitting close to 2.6 µm.

The wavelength range around 3.3 µm is extremely important for applications based on molecular spectroscopy because of strong absorption of hydrocarbons in this spectral region. We fabricated single frequency distributed feedback InAs/AlSb QCLs for this spectral range operating in pulse mode up to 100°C with RT peak optical powers exceeding 100 mW.

The InAs/AlSb system is also attractive for the development of long wavelength lasers because of the small electron effective mass in InAs resulting in higher QCL gain compared with other materials. We realized InAs/AlSb QCLs emitting near 9 µm and operating in pulse mode up to 400 K. The lasers with Fabry-Perot resonators worked in the continuous wave (cw) regime up to 250 K exhibiting single frequency emission in a large range of operation conditions. The cw optical power of the devices approaches 1 W at liquid nitrogen temperature.

Prospects of InAs-based QCLs will be discussed in the conclusion.

7616-38, Session 9

High performance short wavelength InP-based quantum cascade lasers

J. W. Cockburn, D. Revin, P. Commin, S. Zhang, A. B. Krysa, K. Kennedy, The Univ. of Sheffield (United Kingdom)

There has recently been considerable interest in the development of high performance quantum cascade laser (QCL) sources in the 3-4µm region of the mid IR spectrum, where numerous technological applications exist. Whilst the “traditional” InGaAs/AlInAs QCL materials system is unable to provide high performance operation at wavelengths below about 3.8µm, due to insufficient quantum well depth, alternative systems such as InGaAs/AlAsSb and InAs/AlSb have been used to demonstrate QCL operation at sub-3µm wavelengths. InGaAs/AlAsSb is particularly interesting since it combines very deep quantum wells with lattice-matched compatibility with InP and associated waveguide and device fabrication technology. This presentation will review recent Sheffield work on InGaAs/AlAsSb/InP QCLs, which has led to room temperature operation at wavelengths down to 3µm, and 300K pulsed peak powers of up to 20W in the 3.3-3.7µm range.

7616-39, Session 9

Interface roughness in QCLs: a new insight

J. B. Khurgin, The Johns Hopkins Univ. (United States)

We shall discuss the role played by interface roughness in the QuantumCascade Lasers and show that not only it contributes to the line width and transport characteristics, but that it also can dramatically alter the threshold due to roughness-induced intersubband scattering

7616-40, Session 9

Coherent transport in QCLs: a new theoretical approach

A. Gordon, D. Majer, Optigo Systems, Ltd. (Israel)

A new theoretical method for describing QCLs is presented. The method extends the familiar incoherent rate equations to include coherence. Output power vs. current (LI) and current-voltage (IV) curves are calculated at very modest computational effort. Coherence is shown to play an important role in QCLs.

While standard rate equation models consist of equations of motion (EOMs) for subband populations, our model adds EOMs for coherences, i. e. off diagonal terms in the density matrix. Our extended EOMs are derived from standard ones by imposing three requirements:

1. Expectation values of physical quantities should be independent of the choice of basis.

2. The density matrix should be positive definite.

3. The EOMs should reduce to existing well-established rate-equation models when coherences are omitted.

We show that once these requirements are imposed, very little freedom is left for choosing the EOMs.

A well known drawback of incoherent QCL models is that the LI and IV curves exhibit sharp peaks at the anticrossing of subbands, in contradiction with experiments. The reason for these artifacts is that when anticrossing occurs, incoherent rate equations allow electrons to hop between the anticrossed levels infinitely fast, which is unphysical. We show that the cohernces included in our model prohibit such unphysical hopping. As a result, the LI and IV curves become smooth, similarly to the experimental ones, and exhibit no artifacts at points of anticrossing. The important role of coherence in QCLs is thereby demonstrated.

7616-41, Session 9

Room-temperature surface-emitting distributed-feedback quantum cascade lasers without top cladding layers

A. Bousseksou, J. Coudevylle, G. Xu, R. Colombelli, Institut d'Électronique Fondamentale (France); C. Sirtori, Univ. Paris Diderot (France); G. Beaudoin, G. Patriache, I. Sagnes, Ctr. National de la Recherche Scientifique (France)

We demonstrate surface-emitting distributed-feedback (DFB) quantum cascade (QC) lasers - operating in the mid-infrared - with double-slit 2nd order DFB gratings which are implemented via the sole patterning of the top metallic layer, directly at the top of the active region. The double-slit design allows one to reduce the high plasmonic losses which would be induced by a standard 2nd order grating. The devices operate at room temperature, and the emitted spectra show single mode emission at 7.2 um wavelength. The device far-field consists of an almost single-lobed emission with a low divergence (<1 degree) in the grating direction. This result shows that sub-wavelength patterning of the top metallisation layer of mid-infrared surface-plasmon QC lasers allows one to reduce the losses even for higher-order DFB grating devices.

7616-42, Session 10

Highly power-efficient quantum cascade lasers

P. Q. Liu, A. J. Hoffman, M. D. Escarra, K. J. Franz, Princeton Univ. (United States); J. B. Khurgin, Y. Dikmelik, Johns Hopkins University (United States); X. Wang, J. Fan, AdTech Optics Inc. (United States); C. F. Gmachl, Princeton Univ. (United States)

Quantum Cascade (QC) lasers are mid- and far-infrared light sources based on cascaded intersubband optical transitions and resonant tunneling into population-inverted laser subbands. By the very nature of the laser process, the devices are not naturally highly power-efficient: the cascading process involves non-radiative energy drops, the intersubband transition has a strong non-radiative component, and optical losses are high. Nevertheless, much progress has been made recently in increasing the wall-plug efficiency (WPE). Here, we show how various design strategies are employed to raise the lasers' WPE. In particular, we discuss how "speeding-up" the transit of electrons through the injector regions - based on a new understanding of the inter- and intra-subband scattering processes - increases the WPE. A strongly decreased injection barrier thickness leads to better coupled injector and upper laser subbands, with a splitting of ~20meV for QC lasers with ~4.5um emission wavelength. For pulsed mode operation, one of our best performing lasers has a slope efficiency of ~8W/A, at least ~10.0W peak optical output power, and a peak WPE of 47% at 80K. We tested a considerable number of QC lasers, the majority of which (in the cavity length range from 2.3-3.0mm) has a peak wall-plug efficiency greater than 40% at 80K. A low waveguide loss of ~1.5/cm is extracted from "1/L" measurements, which also helps for achieving high power efficiency. The authors acknowledge the collaboration with Jerry Meyer and his team at the Naval Research Laboratory, Washington, DC. This work is supported in part by MIRTHE (NSF-ERC) and DARPA-EMIL.

7616-43, Session 10

Heat transfer speed and phonon related phenomena in terahertz quantum cascade lasers

G. Scamarcio, M. S. Vitiello, Univ. degli Studi di Bari (Italy)

We report on the measurement of both transverse and in-plane heat transfer speed in GaAs/AlGaAs quantum cascade lasers via time-resolved micro-probe photoluminescence. We found approximately a one order of magnitude reduction in the heat transverse speed with respect to bulk values that we ascribed to the heat interface boundary resistance. We also compared the non equilibrium population of phonons via anti-Stokes Raman scattering in different active region configurations.

7616-44, Session 10

Integrated tunable DBR quantum cascade lasers with ~0.03nm/mA tuning efficiency

L. Cheng, F. Choa, Univ. of Maryland, Baltimore County (United States)

We report the fabrication and testing results of an integrated distributed-Bragg-reflector (DBR) tunable quantum-cascade-laser (QCL). With separated thermal controls on gain and buried grating sections. A wavelength tuning efficiency of ~0.03 nm/mA was obtained without affecting the laser output power. By integrating a passive grating-tuning-section in the waveguide, DBR QCLs have the advantages of small size, light weight, large mode spacing for mode-hop-free tuning compared with that of conventional tunable QCLs using an external tuning grating. The waveguide fabrications of DBR QCLs include (1) grating formed through holography technique, (2) buried grating over growth, and (3) buried-heterostructure regrowth. We then packaged the laser to a mount

that can separately control the temperatures of the gain and the grating sections. To avoid thermal stress, the laser gain section was flip-chip mounted on a copper bar. The grating section is standing 100 μm above a small TE cooler, which is separately mounted on another copper bar but mechanically locked together with the laser mount. The grating section and the TE cooler are thermally coupled with a small chunk of thermal grease to ensure heat conduction is taking place. The preliminary results of wavelength tuning, by adjusting TE cooler current from +600 mA (cooling) to -600 mA (heating), have achieved a maximum wavelength tuning of ~35 nm. This is corresponding to a tuning efficiency of ~0.03 nm/mA. Meanwhile, we are in the process of further improving the tuning efficiency and turning range with better mounting and higher thermal capacity TE coolers.

7616-45, Session 11

Challenges for mid-IR interband cascade lasers

J. R. Meyer, U.S. Naval Research Lab. (United States)

The interband cascade laser (ICL) is now the leading coherent semiconductor source for most wavelengths in the 3-4 micron spectral band. The ICL may be considered a hybrid between the conventional laser diode, in that electron-hole radiative recombination provides the active transitions, and the intersubband-based QCL, in that injected electrons produce an additional photon at each step of a multi-stage staircase. NRL ICLs with type-II “W” active region recently attained the long-standing goal of room-temperature cw operation. External differential quantum efficiencies per stage are as high as 65% at 78 K and 28% at 300 K. Input power densities (product of the voltage and current density) required to reach threshold at 300 K are as low as 1 kW/cm2, which is nearly an order of magnitude lower than the best QCL results. For field operation this could represent a 10-times-longer battery lifetime, even at wavelengths beyond 4 microns where QCLs otherwise perform quite well. More than a dozen already-grown ICL wafers, with emission wavelengths spanning 2.9-4.2 microns, appear capable of above-ambient cw operation once narrow ridges have been processed.

Broad-area devices with 5 active stages display pulsed threshold current densities as low as 400 A/cm2 at T = 300 K, due to a substantial suppression of Auger non-radiative decay. Furthermore, a new ICL design has lowered the internal loss at room temperature to as low as 6 cm-1. These advances, combined with improved narrow-ridge processing, have led to the fabrication of 3.7 micron ICLs that lase at up to 335 K in continuous mode. A 10-micron-wide ridge with high-reflection and anti-reflection facet coatings produced up to 59 mW of cw power at 298 K, and displayed a maximum wall-plug efficiency of 3.4%. Narrow ridges were also patterned with corrugated sidewalls that perform two functions: (1) To suppress higher-order lateral modes by introducing additional loss near the ridge boundaries, (2) To introduce a 4th-order distributed feedback grating that selects a single longitudinal mode. Ridges of this type generated up to 12 mW cw in a single spectral mode (3.63 microns) at 25 °C, and up to 29 mW at 0 °C.

7616-46, Session 11

Room-temperature mid-IR emission from intersubband transitions in InAs quantum dots

D. M. Wasserman, T. Ribaudo, D. Adams, Univ. of Massachusetts Lowell (United States); S. A. Lyon, Princeton Univ. (United States); E. A. Shaner, B. S. Passmore, S. K. Lyo, Sandia National Labs. (United States)

There is significant interest in the mid-infrared spectral range for defense, communication and sensing applications. All of the above applications require efficient, compact, and wavelength flexible sources, and have benefited from the demonstration and subsequent rapid development of the Quantum Cascade Laser (QCL). The use of quantum dots in optoelectronic devices was first suggested over 25 years ago as a means to improve the efficiency and temperature performance of interband lasers. Here we discuss recent work incorporating quantum dots into intersublevel cascade-like emitter devices in an effort to both improve mid-IR source efficiency and create naturally surface emitting sources. We will show the first room temperature emission from such devices and discuss the spectral modification of this emission by means of surface plasmon based top contacts.

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed MArtin Co., for the United States Department of Energy’s National Nuclear Security Administration under contract No. DE-AC04-94AL8500.

7616-47, Session 11

InAs-based plasmon waveguide interband cascade lasers

Z. Tian, Z. Cai, R. Q. Yang, T. Mishima, M. R. Santos, M. B. Johnson, Univ. of Oklahoma (United States); J. F. Klem, Sandia National Labs. (United States)

Interband cascade (IC) lasers take advantage of the broken band-gap alignment in type-II quantum wells to reuse injected electrons in cascade stages for photon generation with high-quantum efficiency. Unlike intraband quantum cascade lasers, IC lasers use interband transitions for photon emission without involving fast phonon scattering, making it possible to significantly lower the threshold current density. Over the past several years, significant progress has been made in developing efficient IC lasers, particularly in the 3-4 microns region. The recent accomplishments include: single-mode distributed feedback IC lasers that operated in continuous wave (cw) mode at thermoelectric cooler temperatures (up to 261 K) near 3.3 microns (selected for a NASA flight mission to Mars); and above room temperature cw operation at 3.75 microns with low power consumption (<0.6 W at threshold at 300 K). These accomplishments demonstrate the great potential of IC lasers as energy-efficient mid-IR light sources. Here, we will report our recent efforts in the development of IC lasers at longer wavelengths (4.2-7.6 microns and beyond) based on InAs substrates and plasmon-waveguide structures. Our initial effort led to cw operation of broad-area IC lasers at temperatures up to 150K and demonstrated the improvement in thermal dissipation by the reduced thermal resistance of a plasmon waveguide structure. We will discuss technical issues that have been encountered and report our latest results.

7616-48, Session 11

Short-pulse high-power operation of GaSb-based diode lasers in the 1.9 to 2.3 μm wavelength range

M. Müller, M. Rattunde, G. Kaufel, J. Schmitz, J. Wagner, Fraunhofer-Institut für Angewandte Festkörperphysik (Germany)

GaSb-based diode lasers are ideally suited to cover the 1.9 to 3.3 μm wavelength range [1 3], providing sufficient output power to serve a wide range of applications such as medical diagnostics and therapy, welding of transparent plastic material as well as low quantum deficit pumping of infrared-emitting solid state lasers. The continuous wave output powers of these devices is thermally limited due self-heating of the device, resulting in a maximum reported optical power of 2 W for broad-area single emitters [3] and 20 W for a linear array of 19 emitters on a 1 cm wide laser bar [4].

We will present a systematic study of the output power limiting effects for GaSb-based diode lasers when operated in the short-pulse high-peak-current regime. Epi-side down mounted broad-area (BA) diode lasers with emitter widths of 90 and 150 μm and epi-side up mounted 6 μm or 16 μm wide ridge waveguide (RW) diode lasers have been compared side-by-side, both types of lasers sharing an identical waveguide structures. Devices were driven by current pulses with varying length (30-200 ns) and maximum peak currents of up to 170 A. Repetition rate was kept sufficiently low (1-2 kHz) to suppress thermal cross-talk between successive laser pulses. The output power was measured temporally resolved, using a calibrated integrating sphere. Time-resolved lasing spectra were recorded with a time resolution of 3 ns using the boxcar technique. In this way, the time-dependence of the active region temperature during laser pulses could be deduced from the known temperature induced shift of the lasing spectrum.

Despite the drastically different performance of the BA and RW-lasers in CW-operation, they were found to behave almost identical in short-pulsed operation (pulse length <50ns): Also under these short-pulse operating conditions all lasers are still limited in output power by self-heating, and the current density at with this thermal-rollover occurs is almost identical for all laser geometries. The measured time and current density dependent temperature raise of the active region could be modeled, assuming an adiabatic heating of the active region by the waste heat generated during the current pulse.

With the heatsink temperature set to 30°C, a maximum single-emitter output power of 22.5 W was recorded at an injection current density of 110 kA/cm2 (50 ns pulse length), and a maximum power density at the output facet of 26.7 MW/cm2 (30 ns pulse length) was achieved, without encountering catastrophic optical mirror damage.

1.L.Sheterengas, G. Belenky, T. Hosada, G. Kipshide S. Suchalkin, Appl. Phys. Lett. 93, 011103 (2008).

2.C. Lin, M. Grau, O.Dier, M.C. Amann, Appl. Phys. Lett. 84, 5088 (2004).

3.M. Rattunde, J. Schmitz, G. Kaufel, M. Kelemen, J. Weber and J. Wagner, Appl. Phys. Lett. 88, 081115 (2006).

4.M. T. Kelemen, J. Gilly, R. Moritz, M. Rattunde, J. Schmitz, and J. Wagner, Proc. SPIE Vol. 6876, 68760E-1 (2008).

7616-49, Session 11

Long-wavelength type-I Lasers on GaSb grown by molecular beam epitaxy

J. A. Gupta, P. J. Barrios, P. Waldron, G. C. Aers, C. Storey, National Research Council Canada (Canada)

The 3-4um wavelength range is very important for atmospheric sensing since many gaseous hydrocarbon species exhibit strong absorption features in this range, free of interferences from water vapor. Tunable diode laser absorption spectroscopy (TDLAS) provides a means for very sensitive detection of such gases by modulating the laser emission wavelength across a region of interest. There are currently three strong candidates for laser sources in this wavelength range: intersubband quantum cascade lasers (QCLs); interband cascade lasers (ICLs); and type-I interband diode lasers. The latter approach has clear advantages due to the simplicity of design and epitaxial growth, although it is more challenging to reach longer wavelengths compared with the other alternatives.

In this work, type-I interband lasers on GaSb were grown by solid-source molecular beam epitaxy (MBE) using 16nm InGaAsSb compressively-strained quantum wells (QWs) with 30nm AlInGaAsSb quinary barriers for improved hole confinement. The 3QW active regions were embedded in standard AlGaAsSb waveguides to limit the thickness of quinary material due to its low growth temperature requirements. In continuous-wave operation, a typical ridge waveguide laser (width 10um, length 1214um) produced 6mW total output power at 20°C with a threshold current of 140mA. The temperature sensitivity of the devices remains a challenge, as evidenced by the dramatically improved performance at 0°C (16mW total output power, threshold current 74mA).

7616-64, Poster Session

Coupled-cavity edge-emitting lasers for optical biosensing applications

R. Thomas, P. M. Smowton, Cardiff Univ. (United Kingdom); H. D. Summers, Swansea Univ. (United Kingdom); G. T. Edwards, Cardiff Univ. (United Kingdom)

Recent advances in micro-fluidics have led to much interest in micro-electrical mechanics systems (MEMS) for biosensing applications. We propose a simple monolithic edge-emitting device where two independently pumped laser sections are coupled via a short external sensing-cavity (~50µm) etched into the wafer plane. Biological cells are then introduced to the optical plane via a micro-fluidic channel passing through the sensing-cavity. Fabry-Perot modes formed in the sensing-cavity act as a frequency band-pass filter to the allowed coupled-cavity modes of the device. The small refractive index and scattering loss perturbation introduced by a passing cell, can therefore, induce large changes to the wavelength and power coupling profile of the sensing-cavity.

The coupled-cavity configuration described above has been modelled using the transfer matrix approach to map the stationary mode solutions of the system as a function of the carrier densities in each of the laser sections. This simple design model shows that by using different length laser sections the mode spacing of the coupled-cavity device can be tuned via the Vernier effect. If the device mode spacing is much smaller than the sensing-cavity mode spacing then the cell will cause the output wavelength to change by discrete mode hops between the allowed modes of coupled-cavity offering a detection range equal to the sensing-cavity mode spacing. However, as the coupled-cavity mode spacing approaches that of the sensing-cavity then more complex behaviour is predicted with the device switching between the modes of the coupled-cavity and those of the individual laser sections.

7616-65, Poster Session

Manipulation of optical modes in quantum dot laser diodes by selective oxidation of high aluminum content AlGaAs layers

G. J. Michell, Cardiff Univ. (United Kingdom); H. D. Summers, Swansea Univ. (United Kingdom); P. M. Smowton, Cardiff Univ. (United Kingdom)

This work reports the effects created by the selective oxidation of high aluminium content AlGaAs layers at the facets of standard 50µm stripe quantum dot lasers. The devices all emit at wavelengths around 1.3µm and are standard 5-stack quantum dot lasers with a single 30nm thick 95% aluminium AlGaAs layer added into the p-side cladding at a distance of 160nm from the active region. In all devices the high aluminium content layers have been oxidised selectively by high temperature steam oxidation so as to divert carriers away from both facets, leaving small unpumped sections at either end.

Such unpumped regions provide a means to reduce the width of the lasing near-field spatial profile. Under equivalent pumping conditions just above threshold oxidised devices showed an approximate 65% reduction in the FWHM of the spatial near-field compared to unoxidised devices of the same cavity length. This effect is attributed to saturable absorber-type behaviour of the unpumped sections, where the absorber saturates first at the location of highest optical intensity, so allowing lasing over a smaller spatial area. A secondary effect of the narrowed near-field is a significant reduction in threshold current. This has been observed in devices with cavity lengths of 1.5mm or longer.

We also describe the temporal and spectral behaviour of the devices, where the combination of self-heating and saturable absorption created by the absorber sections generates saw-toothed wavelength-time profiles.

7616-50, Session 12

Simulation of high-brightness tapered lasers

I. Esquivias, H. Odriozola, J. G. Tijero, L. Burruel, A. Martín-Mínguez, Univ. Politécnica de Madrid (Spain); N. Michel, M. Calligaro, M. Lecomte, O. Parillaud, M. Krakowski, Alcatel-Thales III-V Lab. (France)

Tapered semiconductor lasers have demonstrated both high power and good beam quality, and are of primary interest for those applications demanding high brightness optical sources. The complex non-linear interaction between the optical field and the active material requires accurate numerical simulations to improve the device design and to understand the underlying physics.

In this work we present results on the design and simulation of tapered lasers by means of a Quasi-3D steady-state single-frequency model. The results are compared with experiments on Al-free active region devices emitting at 975 and 1060 nm. The performance of devices based on symmetric and asymmetric epitaxial designs is compared and the influence of the design on the beam properties is analyzed. Tapered lasers with separate electrical contacts in the straight and tapered sections are also presented, and the role of the design parameters on the maximum modulation efficiency is analyzed. An extremely high value of the steady-state modulation efficiency (50 W/A) is experimentally demonstrated.

7616-51, Session 12

Two-sections tapered diode lasers for 1 Gbps free-space optical communications at 1060nm with high modulation efficiency of 17 W/A

N. Michel, M. Calligaro, Y. Robert, M. Lecomte, O. Parillaud, M. Krakowski, Alcatel-Thales III-V Lab. (France); I. Esquivias, H. Odriozala, J. Garcia-Tijero, Univ. Politécnica de Madrid (Spain); O. C. H. Kwok, R. Penty, I. White, Univ. of Cambridge (United Kingdom)

High-brightness tapered diode lasers at 1060 nm are required in display applications,for green light generation by frequency doubling, and for free-space optical communications.

In these applications, a drive current of less than 100 mA is required to be compatible with low-cost commercial drivers. We have developed Al-free active region tapered lasers at 1060 nm. They contain a straight ridge waveguide section of 1 mm length and a 2 mm long tapered section, which has an angle of 6°. In the static regime, both the ridge and tapered sections are biased with CW currents, of 100 mA and 2A, respectively. In this case,the lasers deliver 1W CW, together with a good beam propagation ratio (M2<2). In the dynamic regime, the ridge section is operated with a high-speed current at 1 Gbps,which has a low amplitude of only 35 mA. The current on the tapered section is kept at a constant value of 1.5 A CW. When the ridge current is low (10 mA), the output power is of only 40 mW.

When the ridge current is high (45 mA), the output power increases from 40 mW to 620 mW.This corresponds to a high modulation efficiency of 17 W/A, which is significantly higher than that of single electrode lasers (~ 1 W/A). The optical modulation amplitude of 580 mW, and the high optical extinction ratio of 12 dB are also attractive for free-space optical communications.At the conference, we will also report on the design for high modulation efficiency, and on the packaged source based on the same lasers.

7616-52, Session 12

Catastrophic optical mirror damage in diode lasers monitored during single pulse operation

J. W. Tomm, M. Ziegler, T. Elsaesser, Max-Born-Institut für Nichtlineare Optik und Kurzzeitspektroskopie (Germany); H. E. Larsen, P. M. Petersen, P. E. Andersen, Risø National Lab. (Denmark); U. Zeimer, D. Fendrich, Ferdinand-Braun-Institut für Höchstfrequenztechnik (Germany)

The catastrophic optical mirror damage (COMD) effect is analyzed for 808 nm emitting diode lasers in single-pulse operation. This approach allows for better separating facet degradation from subsequent degradation processes in the bulk. During each single pulse, both nearfield of the laser emission and thermal image of the laser facet are monitored with cameras being sensitive in the respective spectral regions. A temporal resolution of better than 7 µs is achieved. The COMD is unambiguously related to the occurrence of a ‘thermal flash’ detected by thermal imaging. A one-by-one correlation between emission nearfield, ‘thermal flash’, thermal runaway, and structural damage is observed. As a consequence of the single-pulse-excitation technique, the propagation of ‘dark bands’ (as observed in photo- or cathodoluminescence maps in the plane of the active region) from the front facet is halted after the first pulse. Because of the rapidness of the thermal runaway, we propose the described technique for the test of the facet stability and the intentional preparation of early stages of COMD; even for diode lasers that regularly fail by mechanisms other than COMD.

7616-53, Session 12

Comparison of 650 nm tapered lasers with different lateral geometries at output powers up to 1W

B. Sumpf, P. Adamiec, J. Fricke, P. Ressel, H. Wenzel, G. Erbert, G. Tränkle, Ferdinand-Braun-Institut für Höchstfrequenztechnik (Germany)

650 nm tapered laser diodes with nearly diffraction limited beam quality are requested for laser display applications.

In this paper, results for 2 mm long 650 nm tapered lasers diodes with different lateral geometries will be presented. The vertical structure is based on a 5 nm thick InGaP single quantum well embedded in AlGaInP waveguide and n-AlInP and p-AlGaAs cladding layers. The ridge waveguides of lengths LRW = 200 µm, 300 µm, 500 µm, and 750 µm were fabricated using selective etching. The contact window for the tapered section was defined applying ion implantation. Devices with a taper angle of 4° were manufactured. The facets were passivated. The rear side was high reflection coated and the taper side anti reflection coated. The devices were mounted p-side down on CVD-diamond heat spreaders and standard C-mounts.

All devices reached a maximal output power larger than 1 W. They had a threshold current density of about 700 A/cm2 and a slope efficiency of 0.8 W/A. The best conversion efficiency was 20%. The devices with the shortest RW-length LRW = 200 µm had the best beam quality (beam waist width 8 µm, far field angle 8.8°, 85% of the emitted power in central lobe, M2 of 1.3 (1/e2)) at P = 1 W. The beam quality for devices with longer RW-section deteriorates up to M2 = 4.4 for a LRW = 750 µm laser. Possible reasons for this behavior will be discussed.

7616-54, Session 13

High-power high-brightness semiconductor lasers based on novel concepts

D. Bimberg, K. Posilovic, T. Kettler, D. Seidlitz, V. Kalosha, V. A. Shchukin, N. N. Ledentsov, Technische Univ. Berlin (Germany); N. Y. Gordeev, L. Y. Karachinsky, I. I. Novikov, M. V. Maximov, Ioffe Physico-Technical Institute (Russian Federation); D. Schröder, P. Hennig, JENOPTIK Laserdiode GmbH (Germany)

The spectrum of direct applications of high power/brightness semiconductor lasers e.g. for material processing will enormously increase in the future due to their unchallenged energy conversion efficiency. The irrevocable requirement for new applications is a significant increase of power and brightness as compared to present laser concepts. We have developed several alternative conceptual approaches[1] to increase both simultaneously and present here not only proofs of feasibility but already very exciting results. In our first approach we use a broad waveguide with an embedded photonic band crystal acting as a higher order mode filter, allowing us to expand the ground mode across the entire waveguide. A very narrow vertical far field of ~ 7° results. 980 nm single mode lasers on CS mounts show > 2 W, wp ~ 60%, M^2 ~ 1.5, BPP 0.47 mm mrad and a brightness of 6.5 108 Wsr-1cm-2 respectively. Coherent coupling of several such lasers is presented. In another approach we use leaky designs with feedback. The mode leaks from a conventional waveguide into a transparent substrate and reflects back such that one mode builds up, others are suppressed by interference. We demonstrate record vertical far field divergence of 1°.

Reference:

1. Vitaly A. Shchukin et al, Photonics West 2010.

7616-55, Session 13

High-peak-power pulse generation with GHz repetition rate using a Q-switched 1060nm DBR tapered laser

A. Klehr, B. Sumpf, K. Hasler, J. Fricke, A. Liero, T. Hoffmann, G. Erbert, G. Tränkle, Ferdinand-Braun-Institut für Höchstfrequenztechnik (Germany)

For several applications like free-space communications, spectroscopy, optical switching, micromachining and pumping of non-linear optical systems there has been a growing demand for compact high energy picosecond pulse sources. Recent development of semiconductor Q-switched lasers show the capability for high energy short pulse generation with potential advantages of compactness, flexibility, easy fabrication, and simply control.

We present experimental results from a Q-switched three section tapered waveguide diode laser which has a DBR grating incorporated. The tapered laser with an InGaAs triple quantum-well (TQW) active region consisting of a 2000µm long tapered element with an angle of 6°, a 1000µm ridge waveguide (RW) section and a 1000µm long DBR section with a 6th order Bragg grating with a duty cycle of /P > 0.9.

By biasing the tapered section with 4A cw current and GHz sinusoidal modulation of the RW section, short pulses of ~75ps width and a pulse power of 6.3W is reached corresponding to 470pJ pulse energy. The Q-switched pulses are single mode with a central emission wavelength of ~1065nm, a SMSR <40dB, and a FWHM spectral width ≤0.04nm. The pulse train exhibits excellent spectral stability due to the DBR grating incorporated for wavelength control.

Detailed investigations of pulse generation with DBR tapered lasers under different electrical driving conditions will be presented.

7616-56, Session 13

Novel single-mode fiber coupled broadband seed source for pulsed fiber laser systems

E. A. Zibik, B. N. Sverdlov, S. Mohrdiek, J. Troger, S. Pawlik, H. Pfeiffer, N. Lichtenstein, Oclaro, Inc. (Switzerland)

Seed sources with a broadband emission spectrum centered at around 1060 nm are highly desirable in high energy pulsed ytterbium doped fiber MOPA systems for mitigation of the nonlinear effects, such as the stimulated Brillouin scattering (SBS). Until now the most common approach is to use fiber coupled Fabry-Perot lasers. Here the emission spectrum broadening is limited to few nanometers, which can result in a relatively low SBS threshold in the fiber laser systems. We demonstrate here pulsed seed sources with full width at half maximum > 10 nm in 1060 nm wavelength region. The devices are based on well-known Bookham high-power single mode InGaAs/AlGaAs SQW laser diodes grown by molecular beam epitaxy. The active layer composition was adjusted to shift the gain maximum to ~1060 nm. The laser design is modified to significantly increase the threshold current so that the device works in sub-threshold (superluminescent) regime up to pump currents exceeding 2 A in CW and pulse operation. The emission from the diode is coupled into a single-mode fiber with mode field diameter of 6.6 µm using a fiber lens. A fiber coupling efficiency of ~80% is achieved. Our time resolved spectral studies show that the device is demonstrating fast modulation rate and very high peak optical power up to 1 W at 2 A current while maintaining the broad (>10 nm) emission spectrum. We will discuss various design aspects influencing spectral width and stability of the source.

7616-57, Session 13

High-power high-brightness semiconductor tapered diode lasers for the red and near-infrared spectral range

B. Sumpf, H. Wenzel, G. Erbert, Ferdinand-Braun-Institut für Höchstfrequenztechnik (Germany)

The most promising concept to achieve high-output power together with a good beam quality is the tapered laser consisting of a straight ridge waveguide (RW) section and a tapered gain-region. The RW section should support only the fundamental guided mode suppressing higher order modes and the taper angle had to be selected with respect to the lateral divergence expected from beam propagation from the RW section. The implementation of a separated excitation of RW and tapered section allows the independent control of the fundamental mode operation in the RW section and the output power in the tapered part.

In this work, high brightness tapered devices with separated contacts in the wavelength range between 645 nm and 1085 nm will be presented.

For red emitting tapered lasers around 650 nm, the output power is limited to about 1 W due to the properties of the laser material. At this output power a beam propagation ratio M2 of 1.3 and a brightness of 100 MW cm-2 sr-1 will be shown.

Devices made from laser structures with low vertical divergence down to 25° (95% power included) without a significant deterioration of device parameters will be presented for the longer wavelength range near 1 µm. For tapered lasers manufactured from these structures, nearly diffraction limited output powers larger than 10 W and a brightness of 1 GW cm-2 sr-1 were measured. Devices with monolithically integrated gratings had an emission width below 100 pm, which allows their direct use for non-linear frequency conversion.

7616-58, Session 14

Room-temperature continuous operation of long-wavelength IR distributed feedback quantum cascade lasers

M. Troccoli, X. Wang, J. Fan, AdTech Optics, Inc. (United States)

In this paper we present our most recent results on distributed feedback (DFB) quantum cascade (QC) lasers operation. The devices were grown by metalorganic vapor phase epitaxy and fabricated into buried heterostructure lasers with different waveguide dimensions in width (12um, 14um) and length (2mm, 3mm). The gratings were dry etched into a sacrificial layer in close proximity to the active region and successively buried by re-growth of the waveguide claddings. The devices have been mounted epi-side down on copper heat spreaders and have shown pulsed and continuous wave operation at room temperature on a single mode with a side mode suppression ratio (SMSR) of 30dB. The active region was designed for emission in the wavelength range between 7.5um and 8um. The wavelength emission and tuning with grating period is consistent with our modeling of the active region and the expected waveguide coupling. Devices emitting in the 7.5-8um range have shown peak powers of more than 150mW for pulsed operation and average powers of more than 5mW for continuous operation, with threshold current densities of 1.4 and 2kA/cm2 for pulsed and CW operation, respectively. The difference between pulsed and cw current densities suggests that there is large room for improvement of the continuous wave operation with better packaging solutions. Consistently, the wavelength sensitivity to temperature changes is slightly larger than the typical observed values, with a tuning coefficient of 0.5nm/K. The output powers recorded from these devices are in a useful range for most sensing applications.

7616-59, Session 14

High-performance long-wave infrared quantum cascade lasers at wavelength ~9 um

X. Wang, AdTech Optics, Inc. (United States)

A high performance Quantum Cascade Laser (QCL) at longer wavelength is reported. The active region used is a four quantum well double phonon design, with InAlAs-InGaAs lattice-matched to InP substrate. Waveguide structure was optimized for low optical loss, high modal gain, and better heat dissipation. All layers were grown by in-house MOCVD, and the grown wafer was processed into a standard BH laser. The finished devices were mounted epi-side down on copper for better heat extraction. For a laser lasing at ~8.9um with active region width about 10.5um and cavity length of 5mm, as cleaved facet, under Continuous Wave (CW) operation at 15C, the total optical output power of 1.1 Watt was obtained, with Jth of 1.25kA/cm2, maximum WPE of 4.76%. This high WPE value indicates the quantum efficiency is close to the good results reported for the shorter wavelength if considering the wavelength difference. A CW operation of this same laser was confirmed to operate CW up to 60C, still with total output power of 0.6 Watt, Jth of 1.71kA/cm2, WPE of 2.64%. The testing stopped at 60C only because the testing stage limitation. The internal loss was estimated to be around 6cm-1. This low internal loss value for this wavelength is partially attributed to the high performance of this QCL laser. Further possible improvements on the Long Wave QCL will also be discussed. Our other high power QCLs at wavelength ~ 7um, 8um, and even longer than 10um will also be presented.

7616-60, Session 14

Power-scaling of quantum cascade laser modules via multi-emitter beam combining

S. Hugger, R. Aidam, W. Bronner, F. Fuchs, Q. K. Yang, J. Wagner, Fraunhofer-Institut für Angewandte Festkörperphysik (Germany); E. Romasew, M. Raab, H. D. Tholl, Diehl BGT Defence GmbH & Co. KG (Germany); B. Höfer, A. Matthes, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany)

An increasing number of in particular security-related applications, such as directed infrared (IR) countermeasures, results in an increased interest in high-beam-quality mid-IR (2 µm - 5 µm) laser sources with output powers up to the multiple Watt level. Semiconductor lasers are well suited for these applications, as they constitute compact, robust, wavelength versatile laser sources and feature the required output modulation capability.

For the wavelength range above 3.5 µm, quantum cascade (QC) lasers constitute the most promising semiconductor laser technology at present, offering excellent beam quality and watt-level output power at room temperature. Besides optimization of laser design and packaging, a further increase in output power can be achieved by using multiple emitter chips and a suitable beam combining scheme. We present results on three different coupling schemes: (i) Spectral beam combining of multiple emitter QC laser array using an external cavity scheme, and (ii) polarization coupling of two QC lasers. Both approaches produce a single collimated output beam of excellent quality (M2 <= 2). The third approach (iii) is based on QC laser arrays with an adapted micro-lens array placed in front of the output facets. This technique produces a set of closely spaced parallel output beams. Advantages and relative figure of merits will be discussed for each approach. Furthermore, options for further optimization and improvement in output power and beam quality will be presented.

7616-61, Session 14

High to ~460 K of 13.5 µm quantum cascade lasers based on indirect pump scheme

K. Fujita, M. Yamanishi, T. Edamura, S. Furuta, A. Sugiyama, T. Ochiai, A. Ito, N. Akikusa, H. Kan, Hamamatsu Photonics K.K. (Japan)

The high performance of quantum cascade lasers (QCLs) has been achieved by the adoption of bound-to-continuum, double phonon resonance or single phonon resonance-continuum depopulation scheme, each which results in fast electron extraction from lower laser states. On the other hand, since the first demonstration of QCL, for pump process, only the direct pump scheme in which upper laser states are pumped directly by electron tunneling from ground states in injectors has continued to be utilized. In this work, we demonstrate high performance of long wavelength (lambda~13.5 µm) QCLs based on indirect pump (IDP) scheme.

In the IDP scheme, electrons are injected into the intermediate state, level 4 (not level 3) via electron tunneling from the ground state, level 1' in the previous injector and then, are relaxed very quickly down to the upper laser state, level 3 by LO-phonon emissions. In this circumstance, the electron population at level 4 is expected to be low, implying that the backward tunneling current is kept to be low even when the electron population at level 3 approaches a high value, N3~Ninj, in turn, the population N1 in the injector is completely depleted. The IDP-QCLs operating at 13.5 µm exhibit a low threshold current density of 6 kA/cm2 at room temperature and an extremely high T0-value of 460 K around room temperature, which is the highest record among semiconductor lasers. The high T0-value is induced by optical absorption quenching associated with the strong suppression of electron population in the injector, which is specifically visualized by the IDP scheme.

7616-62, Session 14

Ring resonator-based surface emitting quantum cascade lasers

E. Mujagic, M. Nobile, H. Detz, P. Klang, A. M. Andrews, W. Schrenk, Technische Univ. Wien (Austria); G. Strasser, Technische Univ. Wien (Austria) and Univ. at Buffalo (United States); C. Deutsch, K. Unterrainer, Technische Univ. Wien (Austria); J. Chen, C. F. Gmachl, Princeton Univ. (United States)

Quantum cascade lasers (QCLs) are well established as reliable laser sources from the midinfrared (MIR) to the terahertz (THz) spectral region. These coherent sources of light are attractive compact emitters for a broad range of applications, such as free space communications, military countermeasures, spectroscopy, imaging and heterodyne detection. For most of these applications, symmetric far fields and low beam divergence are of special interest. However, due to small dimensions and elongated shape of the resonator, the emitted light of standard Fabry-Pérot and surface emitting QCLs is typically broad and asymmetric. Especially for THz QCLs, the sub-wavelength dimensions of laser ridge facet lead to inhomogeneous diffractive-like patterns and limited output intensities.

We describe ring cavity surface emitting lasers (RCSELs) and demonstrate how MIR and THz emission can effectively be emitted using an advanced ring geometry. Beam narrowing is given by constructive interference of light waves passing through the slits of a radial, light out-coupling grating on top of the laser. This results in the realization of single-mode operating ring-cavity QCLs with strongly collimated symmetric surface emission, with a full width at half maximum of 3° and 15° for MIR and THz emitters, respectively. For the latter the reduced divergence gives a two-fold power enhancement compared to standard edge-emitters. We will present an extensive study in terms of output power, threshold behavior, beam shaping, dynamic beam steering and polarization characteristics. Furthermore we will talk about coherent coupling, two-dimensional integration of ring QCLs and their applicability in spectroscopy.

7616-63, Session 14

Near-infrared quenching effects on mid-infrared quantum cascade lasers

D. Guo, F. Choa, L. Cheng, X. Chen, Univ. of Maryland, Baltimore County (United States)

We report in this work near-IR optical quenching effects in Mid-IR quantum-cascade-lasers (QCLs). The quenching effect is both intensity and wavelength dependent. A group of strain-compensated InGaAs/InAlAs, 4.8µm mid-IR QCLs, were used in the experiment. The pump lasers are near-IR lasers. The first pump laser is a 1.2 µm wavelength Raman fiber laser. To optimize the power coupling into QCL waveguides, we minimize the series resistance of QCLs by adjusting coupling locations. After the pump laser is well coupled into the QCL waveguide, the combined near-IR and mid-IR beams are separated by a spectrometer. By varying the near-IR laser power from 0 mW to 20 mW, the corresponding mid-IR output quickly drops initially and then gradually reduces down to zero. The second pump source is a tunable 1550nm laser. The near-IR laser power was fixed and the wavelength was tuned from 1510nm to 1570nm. We found that the shorter the pump wavelength, the stronger the quenching effect. The 3rd , 4th, and 5th pump sources are a 790 nm GaAs/AlGaAs laser, a 656 nm AlInGaP/GaAs laser, and a green Argon laser. The quenching effects in the 790 and 656nm lasers are very weak. The green Ar laser can not affect the mid-IR QCL output at all. It seems to us that when the pump laser wavelength is shorter than 950 nm, the majority of the generated electrons may move above the conduction band edge of the InAlAs and be swept off as photoconductive current without affecting the QCL intersubband operations.

Conference 7617: Light-Emitting Diodes: Materials, Devices, and Applications for Solid State Lighting XIV

Tuesday-Thursday 26-28 January 2010 • Part of Proceedings of SPIE Vol. 7617

Light-Emitting Diodes: Materials, Devices, and Applications for Solid State Lighting XIV

7617-01, Session 1

En route to 100% external quantum efficiency nitride-based LEDs over the full visible and UV spectrum region

H. Amano, S. Kamiyama, M. Iwaya, I. Akasaki, Meijo Univ. (Japan)

In this presentation, we would like to discuss the issues which limit the external quantum efficiency of nitride-based LED for each wavelength by comparing the experimental results with simulation. We will also discuss light extraction efficiency issues both experimentally and theoretically. Advantage of the nano scale structure on the performance of the LEDs will be shown.

7617-02, Session 1

progress in nonpolar and semipolar GaN-based materials and devices

J. S. Speck,

In this talk, we review 2009 progress at UCSB in nonpolar and semipolar GaN-based materials and devices, including progress toward green lasers and high performance violet, blue, green and yellow LEDs.

7617-03, Session 1

Phosphorescent OLEDs: status and opportunities for solid state lighting

M. G. Hack, P. Levermore, C. Lin, S. Xia, M. S. Weaver, R. C. Kwong, J. J. Brown, Universal Display Corp. (United States)

Using our phosphorescent OLED (PHOLED) technology, we have demonstrated white OLEDs exceeding 100 lm/W, together with white PHOLEDs with 68 lm/W and LT70 = 17,000 hours at an initial luminance of 1,000 cd/m2. In this presentation we will review the current status of the technology, and introduce OLED lighting and compare to alternative technologies. We will discuss OLED device designs for lighting, and the opportunities for white PHOLEDs to become a new source of solid state lighting. Finally we will outline some of the manufacturing and cost issues associated with the launch of OLED lighting products.

7617-04, Session 2

Trend of LED backlight technologies for LCD

B. Yang, T. Jang, Samsung Electronics Co., Ltd. (Korea, Republic of)

LED backlight systems are attracting huge interest in LCD TV and notebook-PC applications with their capability of making LCD modules thinner and thinner as well as enhancing noteworthy power savings. Technologies for slimming down the module's form factor are discussed, comparing direct type and edge-lit type backlight structures. Backlight active driving technologies such as local dimming and the line scanning are also covered in this talk. These technologies are adopted to enhance the picture quality as well as the power saving. The advent of LED are evolving backlight systems to be smarter and opening a new market for LCD industry. The business trend and the strategy of the LED backlight are addressed as well.

7617-05, Session 2

LED wafer level integration for BLU and lighting applications

C. Han, T. Lee, H. Liu, S. M. Hong, M. Hsieh, M. Jou, Epistar Corp. (Taiwan)

LED is becoming a key component for backlight modules for laptop computers and LCD TV and also for lighting luminaires. To improve system functionalities, performances and packaging density, a wafer-level hybrid chip integration technology is developed. Several LED chips are placed precisely on a substrate with a pre-designed configuration (based on required power, lumens, or CRI target) and berried inside certain filling materials for passivation. Connection metal is then deposited via photolithography. This technology will be used as a platform on which various sub-systems can be developed. With combination of different phosphor coating and LED chips with pre-chosen wavelengths, we can optimize the CRI and efficacy.

Sub-systems developed for BLU application with high NTSC and for lighting application with high efficacy will be demonstrated.

7617-06, Session 2

Planar lighting by blue LEDs array with remote phosphor

C. Tien, C. Hung, B. Xiao, H. Huang, Y. Huang, C. Tsai, National Chiao Tung Univ. (Taiwan)

The blue light emitting diodes (LEDs) were widely used in the lighting system for the purpose of the white light illumination. The conventional direct-emitting sources for LCD back-lighting use white LED arrangement, where the YAG-phosphor is coated on the surface of blue LED chips and packaged inside the whole device. For high quality LCD displays, the spatial brightness uniformity of backlight should be over 80%. To decrease LED arrangement period or increase the light-mixing distance could get high planar uniformity, but a large amount of LED should be used and thickness of backlight module will be increased.

In this paper, we proposed the blue light excited planar lighting (BLPL) system, which is a novel LEDs-based direct-emitting planar source. BLPL system consists of the blue LED array and a remote YAG-phosphor film. The YAG-phosphor is coated on a PET substrate by roll-to-roll coating method. The first part of this paper is the introduction of the BLPL system. Then, the light emitting mechanism and the optical properties of the proposed module will be introduced. The third and forth parts are the structure optimization by simulation and the experimental results of a prototype, respectively. Finally, the conclusion will be given. For this optical set up, BLPL has high lighting efficiency and uniformity than the conventional direct-emitting planar light source with white LEDs.

7617-07, Session 2

An innovative technical design to decrease LED lamps fabrication cost considerably in compare with state-of-the-art common LED lamps

A. Rahmani Nejad, Independent Researcher (Iran, Islamic Republic of)

Energy efficiency is paramount combating global warming. Towards more efficient use of electricity, we present a novel indoor LED lamp

that provides uniform light distribution without using any optical devices like lenses, glasses, or diffusers. The invention achieves uniform light distribution by arranging hundreds of high brightness LEDs in a very small volume (Semi-Cylindrical volume). The result is 20%-40% more efficiency than the most efficient lamps (like compact fluorescent lamps, induction lamps, discharge lamps, common LED lamps, traditional fluorescent lamps.)

Technical Description: high brightness LEDs are arranged in a 2D pattern of linear rows and a semi-cylinder. Eliminating the epoxy lens of high brightness LEDs results in an expansive light output pattern by each LED; by setting the LEDs in a semi-cylindrical arrangement, each LED acts like a light pixel and because of the high density of LEDs in a small semi-cylindrical volume, the output pattern will be uniform thereby eliminating the need for a diffuser or diminishing glasses to enhance and smooth LED light output.

Benefits: 1. Indoor LED lamps have the highest efficiency compared with all other commercially available light sources. 2. Uniform light distribution without using any optical devices that makes the lamp bigger, more expensive. 3. Dense arrangement of hundreds of LEDs in a very small volume. 4. Standard cylindrical lamps waste significant energy due to the light thown into the back of the fixture, thus the semi-cylindrical lamps have higher efficiency. 5. Working life of ordinary LEDs. 6. Lower manufacturing costs than standard LED lamps. 7. Approximately twenty years working life.

Stage of Development: semi-industrial prototype

Ref:

http://otlportal.stanford.edu/techfinder/technology/ID=25772/A11119873754

7617-09, Session 2

Effect of metal-core LED substrate dimensions on heat-dissipation performance

C. Yang, C. Liu, National Central Univ. (Taiwan)

Thermal dissipation is the one of key issues for the application of high-power GaN LEDs. To achieve an excellent thermal system for high-power LED, an effective thermal substrate is required. Currently, metal-core LED substrate is widely used for high-power LED chips. However, there is no systematical study on investigating the effect of the dimensions on the thermal performance of metal-core substrates.

In this study, firstly, we developed a reliable junction-temperature measurement system for high-power LED on metal-core substrate. Then, the junction temperatures of LED chips on metal-core substrates with different thicknesses and surface area were measured. The thickness of the metal-core substrates varies from 0.6 mm to 1.5 mm and the substrate area varies from 80 mm2 to 490 mm2. Also, we changed the power of blue LED chips on metal-core substrates from 1 W to 5 W. Then, we can study the effect of LED chip power and metal-core substrate dimensions on the thermal dissipation of metal-core substrates. Beside the measurement of the diode junction temperature, thermal images on the LED chips will be collected on all different metal-core substrates. The detail comparison study on the thermal images will be present in this talk. At last, the ultimate light output power of high-power LED chips on various metal-core substrates would be correlated to the thermal dissipation effectiveness of the metal-core substrates.

7617-10, Session 3

Enhancement of angular flux utilization and light extraction efficiency based on micro array in GaN LEDs

C. Sun, S. Tsai, National Central Univ. (Taiwan); T. Lee, Epistar Corp. (Taiwan); W. Chien, National Central Univ. (Taiwan)

In this paper, based on Monte Carlo ray tracing we simulate the light extraction efficiency as well as the directionality of the light pattern of sapphire-based and Thin-GaN LEDs with or without lens encapsulation (LEC). We have shown that pyramid arrays with different slanted angles implanted in the LEDs are useful to increase effective flux utilization through enhancement of light extraction efficiency as well as high directionality. In the case of the sapphire-based GaN LEDs, the slanted angle in a range of 45o to 55o, with LEC, the enhancement ratio of AFU is as high as 390 %. In the case of Thin-GaN LEDs, both the slanted angle of 25o without LEC and 45o with LEC are effective ways to obtain high AFU. The enhancement ratio of AFU is as high as 500 % or more and the LEE in 30o light cone reaches more than 18%.

7617-11, Session 3

Ultra-high extraction efficiency of a semiconductor hemisphere for LED applications

S. Wu, Arizona State Univ. (United States); S. Yu, Univ. of Arkansas (United States); S. R. Johnson, D. Ding, Y. Zhang, Arizona State Univ. (United States)

The wall-plug efficiency of LEDs is determined by both internal quantum efficiency and light extraction. Various geometric structures have been used to increase extraction efficiency for conventional LEDs. In this work, high extraction efficiency is achieved by fabricating a hemisphere using the LED GaAs substrate. The hemisphere is coated with a ZnO anti-reflection layer to further increase the light extraction. Theoretical simulations show that this structure offers an extraction efficiency that can eventually approach 100% when the structure is properly designed. The hemisphere with optimal curvature is fabricated using the following steps: i) Photoresist AZ4620 is spun on to the substrate for three times followed by a standard photolithography process to form circular photoresist mesas; ii) The photoresist mesas are reflowed to create lens-like domes by slowly heating up the sample from 60 °C to 125 °C; iii) Inductive coupled plasma etching is used to etch through the lens-like photoresist domes to form the desired hemispheres in the GaAs substrate. The entire device fabrication process requires nine photolithography steps with eight different masks. The devices are characterized and the extraction and external-quantum efficiencies are carefully measured using a calibrated integration sphere. More detailed results will be presented.

7617-12, Session 3

Patterned-sapphire substrate fabricated by simple wet-etching processes

Y. Chen, C. Liu, National Central Univ. (Taiwan)

Patterned-sapphire substrate has attracted a serious attention, because it can improve the lighting performance based on the two major issues: (1) better quality of LED epi-structure on patterned-sapphire substrate (2) light extraction enhancement by scattering emitting light with the patterned structure on sapphire wafer. Currently, many processes have been used to fabricate the patterned sapphire substrate, such as, conventional dry-etching and wet-etching combined with lithography process, or un-conventional nano-impression.

In this work, without any lithography mask pattern on the sapphire, a simple wet-etching process was used to fabricate the patterned sapphire, which is named as i-PSS. MOCVD GaN-based LED epi-structure was grown on both i-PSS and c-plane flat sapphire wafers. After MOCVD process, 40-mil LED chip process was done on both LED wafers. Our preliminary results show that the performance (light out-put) of the LED chips on i-PSS is about 50 % higher than the LED chips on c-plane flat sapphire wafer. Other optical and electrical analysis will also be present in this talk.

7617-13, Session 3

Application of transverse junction structure in white-light generation devices: light-emitting diodes and superluminescent diodes

S. H. Guol, National Taiwan Univ. (Taiwan); M. Z. Zhou, H. W. Huang, J. Shi, National Central Univ. (Taiwan)

In this paper, we reported works on the white-light generation devices based on transverse p-n junction structure combined with chirped multiple quantum wells (MQWs) in different semiconductor materials, including InP, GaAs, and GaN. These devices are characterized as the concentrated transverse carrier flow spread in each quantum well horizontally instead of vertical well-by-well injection. Therefore, nonuniform carrier distribution can be minimized among different MQWs, which is a problem in vertical-junction light-emitting diodes (LEDs) and superluminescent diodes (SLDs) whose electroluminescent spectrum (EL) is governed by the center wavelength of QWs near the p side. By use of this technique, in InP-based system, we can demonstrate ultra-broadband (3dB bandwidth: 580nm) LED with less sensitivity of applied bias current. In InGaAs/GaAs material system, we can realize superluminescent phenomenon by employing a bent ridge waveguide structure to suppress lasing. In InGaN/GaN-based materials, we can achieve phosphor-free white-light or blue LEDs with simultaneous advantages of improved differential quantum efficiency (DQE), minimizing current crowding effect, and less bias-dependent shape of EL spectra when increasing forward bias currents. All of these works promote a promising prospect for white-light generation in semiconductor materials.

7617-14, Session 3

Enhanced thermal stability of Ag-based ohmic contacts to p-type GaN using Ni/Ag multilayer structure

J. H. Son, Y. H. Song, B. J. Kim, J. Lee, Pohang Univ. of Science and Technology (Korea, Republic of)

Vertical-structure by laser lift-off (LLO) have been exploited for high-power and high-efficiency GaN-based light emitting diodes (LEDs). In V-LEDs, Ag-based reflective ohmic contacts with high reflectance and low resistance are widely used due to its high reflectance (>95%) and surface plasmon coupling to visible light emissions. Preventing Ag from oxidation and/or agglomeration is a key aspect in obtaining high quality Ag-based ohmic contacts suitable for high-performance V-LEDs. In this work, new metallization scheme with high reflectance and excellent thermal stabiltiy has been developed for obtaining low resistance ohmic contacts on p-type GaN. Ni/Ag multi-layer contact showed lower contact resistivity as low as 8.2×10-6 Ωcm2, higher reflectance of 84.3% at 460 nm than Ni/Ag single-layer contact after annealing at 450oC in air ambient. To evaluate the thermal stability of the contacts, the changes of contact resistivity and light reflectance as a function of annealing time at 500 °C were measured. The contact resistivity increased from 4.6×10-5 to 6.1×10-3 Ωcm2 for the Ni/Ag single-layer contact after annealing for 24 hrs, but it only increased from 2.1×10-5 to 8.5×10-4 Ωcm2 for the Ni/Ag multi-layer contact. Furthermore, light reflectance of the Ni/Ag single-layer contact decreased to 72% after annealing for 24 hrs, but the Ni/Ag multi-layer contact showed higher reflectance of 81%. High-resolution x-ray diffraction were carried out to evaluate the microstructural changes of the contacts. In this presentation, we propose the origin on the enhanced thermal stability of Ni/Ag multi-layer ohmic contact on p-type GaN.

7617-15, Session 3

Nanostructure Pt alloy contact to p-type GaN

C. Chang, C. Liu, National Central Univ. (Taiwan)

In this study, we will present a low-resistance and high-reflectance nano-meshed Pt-based electrode on p-type GaN LED. According to our preliminary results, Pt and Pt(Ag, Au, Al) alloy can form excellent ohmic contact to P-GaN layer. While annealing the Pt alloy thin films on the P-GaN layer, a particular nano-structure self-formed on the Pt alloy thin films. In this talk, we will discuss the formation of sefl-formed structure of the annealed Pt alloy thin films on the P-GaN layer with different temperatures and different annealing ambients. Beside the good contact resistance performance, the annealed Pt alloy thin films on the P-GaN layer also showed good transmittance in the visible light region.

7617-16, Session 3

Abbreviated GaN metalorganic vapor phase epitaxy growth mode on nano-patterned sapphire for enhanced efficiency of InGaN-based light-emitting diodes

Y. Ee, X. Li, Lehigh Univ. (United States); J. Biser, Lehigh Univ. (United States) and Lehigh Univ. (United States); W. Cao, H. M. Chan, R. P. Vinci, N. Tansu, Lehigh Univ. (United States)

Reduction of dislocation density in GaN template grown on sapphire substrate is important for enhancing the internal quantum efficiency (IQE) and device reliability of III-Nitride light-emitting diodes (LEDs) for solid state lighting. Here, we demonstrated a novel approach to enhance the radiative efficiency of InGaN quantum wells (QWs) LEDs grown on nano-patterned sapphire substrate, by employing abbreviated GaN growth mode (AGGM) using metalorganic vapor phase epitaxy (MOVPE). The sapphire substrates were patterned with a novel AGOG technique of converting metallic aluminum into single crystal sapphire through oxidation and annealing processes. The nano-patterns comprised of 100nm thick aluminum arranged in hexagonal arrays of 200nm width, with center-to-center spacing of 400nm. The MOVPE of the GaN template was done using abbreviated growth mode, which utilized a thin 15-nm low-temperature GaN buffer, followed by high-temperature GaN growth without the conventional etch-back and recovery processes. The IQE of InGaN QWs LEDs (peak=445nm) grown on nano-patterned sapphire with AGGM (LED-1) was improved by 24% in comparison to conventional LEDs (LED-2). The LED grown using AGGM on planar sapphire (LED-3) exhibited 28% reduction in output power than that of the LED grown using the conventional method on planar sapphire. High-resolution TEM reveals the threading dislocation densities of LED-1, LED-2 and LED-3 as 2x10^7cm^-2, 4x10^8cm^-2 and 1x10^9cm^-2, respectively. The MOVPE growth of GaN by employing abbreviated growth mode on nano-patterned sapphire leads to a 20-times reduction in threading dislocation density in the epitaxial layer, which in turns leads to improved radiative efficiency of the InGaN QW LEDs.

7617-17, Session 4

Understanding efficiency limitations of InGaN quantum wells

M. H. Crawford, D. D. Koleske, S. R. Lee, A. M. Armstrong, K. R. Westlake, N. A. Missert, M. A. Miller, K. C. Cross, Sandia National Labs. (United States)

A continuing challenge for solid-state lighting is the realization of highly efficient InGaN LEDs at green and longer wavelengths. Understanding the reduced radiative efficiency at these wavelengths requires deconvolving the impact of higher-indium-composition InGaN quantum well (QW) growth conditions and materials properties (e.g., increased strain, polarization, compositional inhomogeneities). As one example, achieving higher-indium-composition InGaN QWs requires a lower growth temperature that, in itself, may lead to reduced optical efficiency through structural degradation and increased incorporation of impurities and defects. One goal of this work is to more clearly isolate the impact of quantum well (QW) growth temperature (TQW) on the efficiency of InGaN QWs and LEDs. As green InGaN QWs have a more limited TQW range, our approach targets blue InGaN QWs of fairly high indium concentration (In~0.17) and employs a wide range of trimethylindium flows to reproduce the same QW structure over an 80°C TQW span (680-760°C). Through the application of a range of techniques, including temperature-dependent photoluminescence, cathodoluminescence, x-ray diffraction with dynamical diffraction modeling, and a novel deep-level optical spectroscopy technique, we reveal the mechanisms by which TQW may limit InGaN QW radiative efficiency. Additional studies of the effect of extended defects on InGaN QW efficiency will be presented along with implications for the growth of high-efficiency LEDs. Sandia is a multi-program laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under Contract No. DE-AC04-94AL85000.

7617-18, Session 4

Auger recombination in nitride light emitters: a theoretical perspective

K. T. Delaney, Univ. of California, Santa Barbara (United States)

Abstract not yet in.

7617-19, Session 4

Explanation of the efficiency droop in InGaN multiple quantum well light-emitting diodes by the reduced radiative recombination probability

J. Shim, H. Kim, Hanyang Univ. (Korea, Republic of); H. Ryu, Inha Univ. (Korea, Republic of)

Blue or green nitride-based light-emitting diodes (LEDs) suffer from the reduction of efficiency at high injection current which has been called the "efficiency droop". Various models for the efficiency droop have been proposed such as electron overflow assisted by the piezo-electric field, Auger recombination, and carrier delocalization. However, each model is not sufficient to explain observed experimental results all together.

In this study, we propose a model which can explain experimental results comprehensively. All of previous models have focused on the increased nonradiative recombination rates as optical or electrical pumping increases. The essence of our model is that the radiative recombination probability reduces as carrier density increases in InGaN QWs, which mainly results from the momentum mismatch between electrons and holes. In addition to this, the carrier redistribution is partly in charge of the efficiency droop.

We observed experimentally in the time-resolved photoluminescence (TRPL) at room temperature that carrier lifetime in InGaN QWs increases with increasing optical pumping intensity. This cannot be explained with increasing nonradiative recombination rates in constant ABC carrier rate equation model. Our detailed study showed that the carrier lifetime is determined by saturation characteristics of both the radiative recombination coefficient B and the optical absorption coefficient. In electroluminescence experiments, we also found that the efficiency droop and the carrier lifetime are also influenced by the carrier redistribution at high injection level in addition to the B(N) characteristics.

Based on the proposed model, we can successfully explain ever reported experimental results on the efficiency droop all together.

7617-20, Session 4

Effect of piezo-electric polarization on quantum efficiency of thin-GaN LED

C. Chang, C. Liu, National Central Univ. (Taiwan)

Piezoelectric polarization is known to cause an out-of-plane electrical field in the GaN LED epitaxial layer. The resultant electrical field would distort the energy band structure of the MQWs (multi-quantum wells) in GaN LED epi-structure, which further affects the electrical and optical properties of MQWs. In this research, the MOCVD-grown GaN LED epitaxial layer was transferred onto a metal substrate and processed into Thin-GaN LED chip. Then, a mechanical force was applied on the metal substrate to create different strains on the Thin-GaN LED chips on the metal substrate. EL (Electroluminescence) and PL (Photoluminescence) measurements were performed on Thin-GaN LED chips with different strain conditions. Our preliminary results show that the wavelength of strained Thin-GaN LED chips blue-shifted and, remarkably, the intensity of Thin-GaN LED chip increased with the degree of strain. We believe that the light output enhancement of the strained Thin-GaN LED is due to the relief of the residual compressive stress in the GaN LED epi-layer after MOCVD process. The compressive stress relief reduces the the piezoelectric field, therefore, the internal quantum efficiency (IQE) improved. The detail relationship between IQE and the piezoelectric polarization will be discussed and proposed in this talk.

7617-21, Session 4

Carrier lifetime of GaInN LEDs: streak camera measurements

U. T. Schwarz, Fraunhofer-Institut für Angewandte Festkörperphysik (Germany) and Univ. Regensburg (Germany); M. Maier, M. Kunzer, T. Passow, K. Köhler, J. Wagner, Fraunhofer-Institut für Angewandte Festkörperphysik (Germany)

The internal efficiency of UV, blue and in particular green light emitting LEDs with InGaN quantum wells has to be improved for more power efficient displays and solid state lighting (SLL) applications. Efficiency droop in the high carrier density regime has been discussed in terms of Auger losses and carrier overflow. In the microscopic picture, quantum confined Stark effect (QCSE), alloy fluctuations and carrier localization modify carrier lifetime. An accurate measurement of carrier lifetime as a function of a well defined current density is a key experiment towards a correct interpretation of the different radiative and nonradiative processes in a GaInN LED.

We use time-resolved electroluminescence (TR-EL) to measure the carrier decay time as a function of current density. The LED is driven by a fast pulse generator with a fall time of less than 1 ns at the trailing edge of the pulse. The pulse is long enough (e.g. 400 ns) for the system to reach a stationary state, allowing a precise measurement of current density. The decay of the EL signal and its spectral variation is captured by a streak camera with sub-nanosecond time resolution. The shift of the EL peak wavelength with time provides additional information on a change in the internal field.

Short pulses are combined with a cw bias to study the interplay of the piezoelectric field with the field due to the built-in potential of the p-n junction. This method has the advantage that current density and carrier life time can be measured simultaneously. Therefore, carrier density can be calculated, and carrier life time can be plotted as function of carrier density and fitted by Shockley-Read-Hall, radiative and Auger recombination.

7617-23, Session 4

A study on the reverse-bias and ESD instabilities of InGaN-based green LEDs

M. Meneghini, N. Trivellin, E. Ranzato, M. Dal Lago, Univ. degli Studi di Padova (Italy); B. Hahn, U. Zehnder, OSRAM Opto Semiconductors GmbH (Germany); G. Meneghesso, E. Zanoni, Univ. degli Studi di Padova (Italy)

Over the last years, important efforts have been done in order to understand the degradation mechanisms of GaN-based LEDs submitted to forward-bias stress tests. On the other hand, only little work has been done to understand the degradation of LEDs submitted to reverse-bias stress. However, this topic is of high interest, since (i) the reverse-bias robustness of the LEDs is strongly correlated to their stability under Electrostatic Discharge (ESD) events and (ii) the analysis of the reverse-bias degradation can provide important information on the role of high electric fields and reverse current in limiting the reliability of the LEDs.

Therefore the aim of this paper is to describe a detailed investigation on the reverse-bias degradation of GaN-based LEDs. The results described in this paper indicate that: (i) under reverse bias, current conduction occurs by tunnelling through localized structural defects; (ii) reverse-bias tunnelling determines radiative recombination, due to the injection of carriers in the quantum-wells; (iii) reverse-bias stress can induce the degradation of the electrical characteristics of the LEDs (increase in reverse-current, decrease in breakdown voltage), due to the generation of point defects in proximity of pre-existing defective regions; (iv) reverse-bias degradation is induced by hot carriers, and the degradation rate is proportional to the stress current level.

Furthermore, the analysis indicate that the defective regions responsible for reverse-current conduction can constitute weak points with respect to ESD events: ESD failures are determined by the shortening of the junction in proximity of the defective sites responsible for reverse-current conduction.

7617-24, Session 5

Growth of opto-electronic devices on 6-inch sapphire substrates in a mass production MOCVD Planetary Reactor®

M. Heuken, A. Alam, AIXTRON AG (Germany); C. Sommerhalter, B. Dlugosch, AIXTRON Inc. (United States); B. Schineller, AIXTRON AG (Germany)

We addressed the need for larger wafer sizes to facilitate a further reduction of the cost of ownership with the introduction of the 6x6 inch Planetary Reactor. The introduction of a triple inlet for the reactant gases featuring a metal-organics (MO) inlet sandwiched between two hydride inlets allows for unprecedented uniformity control by introducing an additional degree of freedom for tuning. InGaN multi-quantum-well structures were grown on 6 inch wafers of 1mm to 1.3mm thickness in an AIX 2800G3 HT reactor. The curvatures of the wafers measured with an in-situ deflectormeter vary with growing GaN buffer layer thickness and go up to 85/km and 170/km for the 1.3mm and 1mm thick substrates, respectively, before they drop to values between 8/km and 45/km during the MQW growth step. The PL-wavelengths are comparable with 452.9nm (sigma=2.8nm) and 449.5nm (sigma=2.45 nm) for substrate thicknesses of 1 mm and 1.3 mm, respectively. A 20-fold increase in PL-intensity was measured for the 1mm thick substrate, although process optimization was done for 1.3mm-thick wafers. The thicknesses measured by white-light interference of the said GaN layers were 5.27 µm (sigma=1.9%) and 5.33 µm (sigma=2.44%) for the 1.3 mm and 1 mm thick substrates, respectively. XRD measurements yielded full-width at half maximums (FWHM) of 245.2 arcsec (1 mm substrate) and 264.6 arcsec (1.3 mm substrate) for the (002) reflex, and 302.3 arcsec and 291.3 arcsec for the (102) reflex, respectively. We will report additional data detailing the influence of strain on bow for substrates of different thicknesses.

7617-25, Session 5

Etching mechanism on n-GaN epitaxial layer by KOH solution

Y. H. Chang, C. Liu, National Central Univ. (Taiwan)

In this study, thin-film flip-chip GaN LED was fabricated to study the mechanism of wet etching on n-GaN epitaxial layer by KOH solution. Surface morphology evolution and dislocation distribution of n-GaN epilayers were investigated by scanning electron microscopy (SEM) and transmission electron microscopy (TEM). The preliminary results showed that the density of hexagonal pyramids created on the etched n-GaN surface decreased with etching time, but, the size of the pyramids increased with time. Also, from TEM images on the n-GaN epi-layer, we realized that the maximum dislocation density occurred at the very-top n-Gan surface and decreased toward inside n-GaN epi-layer. So, we believed that the morphology evolution of pyramids on the etched n-GaN surface morphology had a strong relationship with the threading dislocation distribution in the epitaxial n-GaN epi-layer. The detail mechanism will be discussed and present in this talk.

7617-26, Session 5

Surface roughness of gallium nitride with volcano-like protrusions formed by KrF excimer laser etching

S. Wang, W. Lee, National Cheng Kung Univ. (Taiwan); K. Uang, T. Chen, WuFeng Institute of Technology (Taiwan); D. Kuo, P. Wang, P. Wang, National Cheng Kung Univ. (Taiwan)

Gallium nitride (GaN) has been regarded as the most promising material for the fabrication of devices in applications for light-emitting diodes (LEDs), detectors, and laser diodes (LDs). Vertical-structure GaN-based LEDs (abbreviated as V-LEDs) based on the transfer of sapphire substrate to a metal or semiconductor substrate have recently shown being very favorable to enhance the light output, efficiency, thermal conductivity and power capability of the GaN-based LEDs. It has been reported that the internal quantum efficiency of GaN-based LEDs has reached over 85% due to the development of growth techniques. However, the external quantum efficiency is still low. One major reason is related to the high refractive index (n~2.5) of GaN material, resulting in the critical angle for a light escape cone of about 23 degrees to air and thus causing a light extraction ratio from the surface as low as 4%. In this work, to enhance the light extraction efficiency, use of deep ultraviolet KrF laser irradiation to roughen the V-LED surface with volcano-like protrusions was proposed and investigated. After pulse irradiations of KrF laser (750-850 mJ/cm2), the rate of electron-hole (e-h) pair recombination at sites with dislocation defects is greater than for crystalline GaN, favoring for the formation of Ga2O3, and in turn, resulting in a relatively lower etching rate therein and leading to a roughened surface with volcano-like protrusions. The protrusions formation is believed to be a good indication of dislocation distributions in GaN. Typical diameter/height and density of protrusions are of around 2~4 um/2 um and 10E+6/cm2. Through the use of KrF laser and KOH etching, an enhancement in the root-mean-square (RMS) surface roughness by 250 times and an improvement in Lop by 25% at 750 mA as compared to regular V-LEDs samples.

7617-27, Session 5

Enhanced performance of vertical GaN-based LEDs with highly reflective ohmic contact and nano-roughened indium-zinc oxide surface using a nanospheres process

D. Kuo, S. Wang, National Cheng Kung Univ. (Taiwan); K. Uang, T. Chen, WuFeng Institute of Technology (Taiwan); W. Lee, P. Wang, National Cheng Kung Univ. (Taiwan)

The use of Polystyrene Spheres (PSs) to produce nano-roughened Indium-Zinc Oxide (IZO) surface and a high reflective ohmic p-contact to improve the optoelectronic properties of larger-area (1x1 mm2) Vertical Metallic-substrate GaN-based light-emitting diodes (VM-LEDs) were proposed and investigated. A metal system consisting of (annealed-Pt)/Al/Pt was employed to serve as a reflector and ohmic contact to p-GaN, which exhibits a good ohmic contact (1.95×10E-3 Ωcm2) and high reflectivity (87% at 465 nm). After the removal of sapphire using laser lift-off process (LLO) and etching of u-GaN by inductive coupled plasma (ICP), Ti/IZO film was then deposited to serve as a transparent conduction layer (TCL). After that, the PSs (400 nm) were dispersed on the IZO surface, followed by second sputtering-deposition of IZO film to fill the space between neighboring PSs. The PSs were then removed to form a nano-roughened IZO top-layer. Compared to regular VM-LEDs with Ni/Au ohmic contact and Ti/Al/Ti/Au as reflector layer but without TCL, the fabricated VM-LED shows a typical increase in light output power (i.e., Lop/Lop) by 72.2% at 350 mA and a decrease in forward voltage (Vf) from 3.42 V down to 3.32 V. Even compared to the VM-LEDs with broad-area IZO non-roughened top-layer, a 20.2% enhancement in Lop with the same Vf (3.32 V) has been achieved at 350 mA from the samples prepared by the PSs nano-roughening technique.

7617-28, Session 6

High-efficiency III-nitride photonic crystal LEDs

A. David, Philips Lumileds Lighting US LLC (United States)

Despite the high efficiency of existing InGaN/GaN LEDs, improvement of their light extraction is still an area of active research. Surface roughening is currently the most effective and widespread scheme, and relies on the randomization of light trajectories inside the LED. However, the use of photonic crystals enables a deterministic engineering of the light extraction process, and may improve extraction efficiency towards its ultimate limit.

This contribution will focus on the use of a photonic crystal as a diffraction grating. We will discuss the basic design rules for an efficient photonic-crystal light extractor, presenting the mechanisms which limit light extraction efficiency and how to address them. We will then review recent progresses reported in academic research. Finally, we will discuss results recently obtained at Philips Lumileds. [1]

[1] J. Wierer et al., “III-nitride photonic-crystal light-emitting diodes with high extraction efficiency” Nature Photonics 3, 163 (2009)

7617-29, Session 6

Plasmonic crystal applications in light-emitting diodes

A. V. Zayats, Queen’s Univ. Belfast (United Kingdom)

Plasmonic crystals are formed when a metal surface or a film is nanostructured in a periodic manner on the length scale comparable to a wavelength of surface plasmon polaritons (SPPs) supported by its interface. The periodic structure leads to formation of SPP Bloch modes and allowed and forbidden bands in the SPP dispersion. Therefore, SPP crystals provide a great deal of flexibility in engineering of photonic density of states and thus light transmission, reflection in absorption in metallic structures. By changing periodicity, size and shapes of features forming the crystal, the spectrum of enhanced transmission, polarization properties and efficiency can be controlled.

In this talk we will discuss the opportunities provided by plasmonic crystals to engineer radiation properties of light emitting diodes (LEDs). These applications require consideration of plasmonic crystal properties on high-refractive-index substrates that may considerably different from conventionally used crystals. Plasmonic crystal formed in a Au thin film deposited on active surface of LED or indeed formed in the Ohmic contact layer allows to control LED’s polarization properties and/or directionality, achieve efficient light extraction through Ohmic contacts, and, most importantly, the extraction of light that is otherwise is totally internally reflected within the active layer due to its high refractive index.

This work was supported by the EC FP6 project PLEAS: Plasmon Enhanced Photonics. The authors are grateful to R. Windisch and J. Moosburger of OSRAM Opto Semiconductors for fruitful discussions and LED structures used in the experimens.

7617-30, Session 6

Light-emitting diode with surface plasmon coupling

K. Shen, Y. Lu, C. Chen, C. Lu, C. Lin, C. Liao, T. Tang, C. Yang, National Taiwan Univ. (Taiwan)

The enhanced and partially polarized output of a green light-emitting diode (LED), in which its InGaN/GaN quantum well (QW) couples with surface plasmons (SPs) on a surface Ag grating structure is demonstrated. Compared with an LED sample of no (flat) Ag coating, the total output intensity of an LED of SP-QW coupling can be enhanced by ~59 (~200) % when the grating period and groove depth are 500 nm and 30 nm, respectively. Also, a bottom-emission polarization ratio of 1.7 can be obtained under the condition of 15 nm in groove depth. Based on the comparison with a sample of larger spacing between the metal and QW and numerical simulation, it is concluded that the output enhancement and polarization behaviors are mainly attributed to the QW coupling with localized surface plasmons generated on the grating grooves. We also demonstrate the further enhancement of the emission efficiency of an InGaN/GaN single QW LED, in which the QW is coupled with SPs generated on an Ag nano-grating structure on the top of the LED, by inserting a SiO2 layer between the p-type GaN layer and the Ag nano-grating. This SiO2 layer can change the SP behaviors, including the reduction of metal dissipation rate and the elongation of SP evanescent field. With such changes, the SPs generated on the Ag nano-grating can couple with a QW of longer distance and the effective emission efficiency of the SP-QW coupling system can be increased.

7617-31, Session 6

Determination of light extraction parameters in photonic crystals LEDs

C. Weisbuch, E. Matioli, E. L. Rangel, B. Fleury, E. L. Hu, J. S. Speck, Univ. of California, Santa Barbara (United States)

Photonic crystal (PhC) LED have produced high efficiency LEDs. Their study has allowed in-depth understanding of properties of PhCs such as the determination of their key parameters (band structures, diffraction patterns for instance).

Still, one needs to assess quantitatively the parameters that lead to high efficiency of the PhC as photon extractors: pattern, periodicity, etch depth, ... These translate into dynamical diffraction properties such as the extraction lengths of the various photon modes in the LED structure. The comparison of the extraction lengths to the characteristic lengths of dissipative mechanisms in LED structures, mainly metal contact absorption and quantum well reabsorption, yields the light extraction efficiency of the PhCs.

We have developed a method to extract the various parameters from the detailed analysis of PhC emission in PhC LEDs. We find that for most of the modes, in well-designed structures, the PhC extraction length is of the order of 100 µm, while the QW absorption length is at least 300µm. The metal absorption length needs special designs, in particular for p side-metal bonded structures, to be also kept longer than 100 µm.

All the results are in good agreement with detailed 3D electromagnetic simulations which allow to explore the design parameter space to determine optimal structures for efficient light extraction.

These results, both experimental and theoretical, point to the fact that PhCs can indeed act as quasi-perfect structures for light extraction in LEDs.

7617-32, Session 6

Nanophotonic emission rate control in LEDs: role of dipole orientation

A. F. Koenderink, W. Vos, I. Nikolaev, FOM Institute for Atomic and Molecular Physics (Netherlands)

Nanophotonic texturing or patterning is a widely pursued route to improve the directive properties, brightness, internal and external quantum efficiency of emissive devices. Plasmonic approaches, grating texturing and photonic crystal strategies alike target both the directionality of emission, and the rate of spontaneous emission decay. Enhancing spontaneous emission rates can improve the internal quantum efficiency and maximum output power of emissive devices. It is well known that spontaneous emission rate enhancements depend on the spatial alignment of the nanophotonic mode structure relative to the layer in which emission dipoles are located. However, the role of the orientation of the emission dipole moment on emission is hitherto unexplored.

In this presentation, we derive a general representation of the spontaneous emission rate on the orientation of the transition dipole relative to the nanophotonic structure. This representation only invokes a general symmetry of the Green function, and therefore holds for any nanophotonic texturing. We find that the rate depends quadratically on dipole orientation and is always determined by rates along three principal axes. Visualizing the orientation dependence of emission rates provides great insight on how preferred orientations for enhancement depend on emission frequency and location for a given structure. Our analysis provides insight into the degree to which orientation of the emission dipoles can be used to control or even switch emission rates, as we show for examples such as mirrors, plasmonic spheres, and photonic crystals. Finally, we show how emission rates can be efficiently calculated for any orientation within any simulation method.

7617-33, Session 6

Surface plasmon dispersion engineering utilizing double-metallic Ag/Au layers for InGaN quantum wells light-emitting diodes

H. Zhao, G. Liu, N. Tansu, Lehigh Univ. (United States)

InGaN quantum wells (QWs) LEDs play important role for solid state lighting. As the InGaN QWs are coupled to surface plasmon (SP) mode of metallic film, the radiative recombination rate can be enhanced due to the increased photon density of states (DOS) near the SP frequency. Recent approach based on metallo-dielectric stacked structures had been proposed to tune the SP frequency, however the enhancement is significantly reduced for frequency regime away from SP frequency of metal / GaN.

Here, we propose a new method to achieve wide-spectrum tuning of the Purcell peak enhancement of the spontaneous recombination rate for InGaN QWs by utilizing double-metallic layers on GaN. The dispersion analysis is based on transfer matrix method taking into account both damping and interband transition metallic losses. The use of double-metallic layers (Ag/Au) with optimized thicknesses allows the tuning of the Purcell enhancement factor between the SP frequencies of Ag/GaN and Au/GaN. By varying the thickness combination of Ag and Au layers, the double-metallic layers can be used to achieve large Purcell enhancement for SP-based InGaN QW LEDs emitting in spectral regime between the SP frequencies of Ag/GaN and Au/GaN. Experiments by employing Ag/Au double-metallic layers on InGaN QWs will be presented and compared with theory. For green spectral regime, the Purcell enhancement predicted by the double-metallic layer approach is 4-times larger than that of metallo-dielectric stacked structures. The double-metallic layers concept can be extended with other metals on GaN to tune SP frequency from UV up to red spectral regime.

7617-34, Session 7

Retrofit and modules

H. Nikol, Philips Lighting B.V. (Netherlands)

Abstract not yet in.

7617-35, Session 7

Influence of the injection current on the degradation of white high-brightness light-emitting diodes

S. Bouchard, H. Lemieux, M. Côté, S. Thibault, Univ. Laval (Canada)

Since high-power LEDs show great potential in reducing energy consumption worldwide, a great deal of research has been performed to understand their degradation rate. As reported in many publications, temperature is of critical importance so lifetests are mainly based on the internal temperature of the junction (Tj). A common testing method is to overdrive the LED with high current in order to cause self-heating. However, by doing so, it is assumed that current does not produce self-degradation. This topic is of great importance nowadays because of the recent development of LEDs used to increase operating current. We have conducted a lifetest on LEDs to isolate the influence of current by using a thermally controlled heatsink to keep the same Tj for different driving currents. For each LED, Tj was evaluated using a new DC method proposed by NIST in 2008 that consists in cooling the LED to increase the forward voltage to V(Tset). This paper presents the experimental setup with the associated protocol used in the experiment. We will also present preliminary results from the tests. We used high-power white LEDs from two manufacturers. These were stressed at currents ranging from 0,350A to 1A and at temperatures ranging from 75°C to 150°C. To our knowledge, this type of measurement has not been report in the litterature. In the future, we would like to use a Weibull statistical model to study the combined effects of temperature and current on the degradation of LEDs

7617-36, Session 7

‘No blue’ LED solution for photolithography room illumination

H. Ou, Technical Univ. of Denmark (Denmark)

A photolilthography room is part of a cleanroom, where the key pattern transfer process takes place. The room dedicated for photolithography could be easily distinguished from the others because it is yellow. A big problem for the yellow room is the bad color rendering. People working in a photolithography room for a couple of hours suffer a difficult adjustment to normal light. In addition, people may meet problems when they need to make judgement according to colors. White light emitting diodes (LED) are emerging as a promising general illumination light source because they are energy-efficient, environment friendly, and have a long lifetime. Inspired by this and aiming to improve the color rendering of conventional yellow fluorescent tube (YFT), this paper

explored the feasibility of using a LED-based bulb as the illumination light source for photolithography room. A no-blue LED was designed, and the prototype was fabricated. The spectral power distribution of both the LED bulb and the YFT was measured. Based on that, colorimetric values were calculated and compared on terms of chromatic coordinates, correlated color temperature, color rendering index, and chromatic deviation. Gretagmacbeth color charts were used as a more visional way to compare the two light sources, which shows that our no-blue LED bulb has much better color rendering ability than the YFT. Furthermore, LED solution has design flexibility to improve it further. The prototype has been tested with photoresist SU8-2005. Even after 15 days of illumination, no effect was observed. So this LED-based solution was demonstrated to be a very promising light source for photolithography room illumination due to its better color rendering in addition to energy efficiency, long life time and design flexibility.

7617-37, Session 7

Thermal management for solid state lamp for recessed-light applications

J. Vetrovec, Aqwest (United States)

High-brightness light emitting diodes (LEDs) are being developed for solid-state lighting for general illumination in commercial and household applications while offering up to 75% savings in electric power consumption over conventional lighting systems. Realizing the full potential of this new and highly efficient light source requires major improvements in cooling of the LED chip and the LED package to prevent early degradation in light output and catastrophic failures.

We report on testing of a novel heat sink for solid-state lamp intended as a screw-in replacement for a reflector-type incandescent lamp (e.g., R30) in recessed light applications.. The heat sink, which couples directly to standard high-brightness LED packages such as Luxeon K-2 efficiently removes high-flux waste heat from LED slug, spreads it, and transfers it to ambient air. Unlike previous solid-state lamp concepts employing large and heavy metal components, the innovative heat sink is lightweight and uses very small amount of metal in its construction.

This paper presents the heat sink physics, engineering design, and data from initial testing. Concepts for integrated LED-heat sink assemblies aimed for specific product types (especially recessed light applications) are discussed. This work was in-part funded by a grant from the U.S. Department of Energy.

7617-38, Session 7

Novel sensor for color control in solid state lighting applications

A. Gourevitch, T. Thurston, R. Singh, B. Banachowicz, V. Korobov, C. Drowley, Cypress Semiconductor Corp. (United States)

LED wavelength and luminosity shifts due to temperature, dimming, aging, and binning uncertainty can cause large color errors in open-loop light-mixing illuminators. Multispectral color light sensors combined with feedback circuits can compensate for these LED shifts. Typical color light sensor design variables include the choice of light-sensing material, filter configuration, and read-out circuitry. Cypress Semiconductor has designed and prototyped a color sensor chip that consists of photodiode arrays connected to an I/F (Current to Frequency) converter. This architecture has been chosen to achieve high dynamic range (~100dB) with excellent linearity and to provide flexibility for tailoring sensor response. Several different optical filter configurations were evaluated in this prototype. The color-sensor chip was incorporated into an RGB light color mixing system with closed-loop optical feedback. Color mixing accuracy was determined by calculating the difference between (u`,v`) set point values and CIE coordinates measured with a reference colorimeter. Color precision Δu`v` <0.004 has been demonstrated over a wide range of colors, a temperature range of 50C, and light dimming up to 80%.

7617-22, Poster Session

Effect of current crowding on the ideality factor in MQW InGaN/GaN LEDs grown on isolated substrates

V. K. Malyutenko, S. S. Bolgov, A. V. Zinovchuk, V. Lashkaryov Institute of Semiconductor Physics (Ukraine)

To date, the reason of high ideality factor (n >2) in GaN-based LEDs grown on sapphire substrate is not fully understood and explained. It is believed that n-factor exceeding 2.0 originates from the trap-assisted tunneling and carrier leakage inside the active MQW LED region or is due to additional junctions available in the LED circuit. In this research, we demonstrate that higher values than those predicted by the carrier diffusion (n=1) and generation recombination process (n=2) may be connected to current crowding (CC) effect that is difficult to avoid in LEDs grown on isolated substrates. By analyzing theoretical model and testing commercially available p-side up lateral blue LEDs with two different p-electrode pattern we show that n-factor could increase from 2.0 (current spreading geometry) up to 3.5 (current crowding geometry). This CC affected modification of n-factor occurs mostly in the intermediate range of current (10 mkA - 10 mA, the space charge region dominates in LED performance) and therefore could be erroneously treated as the change of carrier transport mechanism and carrier recombination nature. At higher current (series resistance dominates) even insignificant increase of n-factor makes the current value of the efficiency rollover to decrease (from 35 mA to 15 mA) and the efficiency droop to increase by 10%.

7617-56, Poster Session

White-light-emitting (Ba, Ca)2SiO4:Ce3+, Eu2+, Mn2+ phosphors for white-light-emitting diode

K. W. Park, J. B. Lee, Pukyong National Univ. (Korea, Republic of); T. H. Kim, Kyungpook National Univ. (Korea, Republic of); J. S. Kim, Pukyong National Univ. (Korea, Republic of); P. Kung, S. M. Kim, The Univ. of Alabama (United States)

White-light generation is achieved through Ba1.2± Ca0.8±- SiO4:Ce3+, Eu2+, Mn2+ phosphors. They exhibit three emission colors: deep blue emission from Ce3+, green emission from Eu2+, and red emission from Mn2+. The strong energy transfers among three emission centers are observed: Ce3+ Eu2+, Ce3+ Mn2+, and Eu2+ Mn2+. They show a high quenching temperature of about 175 with same decay rates of them, resulting in no temperature or/and power-dependent variation in white-color quality. The white-light-emitting diode using this phosphor and a 405 nm chip demonstrated a warm-white light with a deluxe color rendering index of more than 90.

7617-57, Poster Session

Novel blue-emissive Sr3Ga2O5Cl2:Eu2+ phosphor for blue-light-emitting diode pumped by ultraviolet light

J. B. Lee, Pukyong National Univ. (Korea, Republic of); J. J. Lee, Yonsei Univ. (Korea, Republic of); K. W. Park, P. K. Shon, S. N. Lee, Pukyong National Univ. (Korea, Republic of); J. C. Choi, Yonsei Univ. (Korea, Republic of); J. S. Kim, Pukyong National Univ. (Korea, Republic of)

The novel blue-emissive Sr3Ga2O5Cl2:Eu2+ phosphors were synthesized by a conventional high-temperature solid-state reaction technique for the first time. The excitation spectrum ranges from ultraviolet to blue region. The emission spectrum shows the pure-blue emission peaking at 450 nm of Eu2+ ion. The pure-blue-light-emitting diode is fabricated

by integrating 405-emitted chip with the phosphor. This blue-emissive Sr3Ga2O5Cl2:Eu2+ phosphor can be a promising phosphor of blue-light-emitting diode pumped by ultraviolet light.

7617-58, Poster Session

On the mechanisms of electroluminescence efficiency droop in (In,Ga)N quantum well diodes

K. Kaneda, H. Jimi, K. Fujiwara, Kyushu Institute of Technology (Japan)

Electroluminescence (EL) external quantum efficiency of (In,Ga)N quantum well diodes degrades with increasing injection current, and the origins of EL droop has been attracted a great deal of recent attention. To realize the high power light emitting diodes (LED's) it is very important to elucidate the mechanisms behind the EL droop in these highly strained (In,Ga)N/(Al,Ga)N heterostructure material systems. Previously, the phonon-assisted Auger nonradiative recombination is considered to be the main reason causing the EL droop. Electron escape under the influences of piezo-polarization field is also claimed as the origin recently, being consistent with the necessary inclusion of the p-type (Al,Ga) N electron blocking layer in the usual nitride LEDs to reduce electron overflow. Thus, the origin of EL efficiency droop is still controversial. In this paper, EL and photoluminescence (PL) properties of (In,Ga) N quantum well diodes have been investigated, with an emphasis on the forward bias (external field) effects. One striking experimental fact observed by several workers is that, when the temperature is slightly decreased to only 260 K, for example, from 300 K where the phonon-assisted carrier relaxation is still expected, the EL droop starts at a lower current level than at 300 K within the same diode, thus, enhancing the EL droop. This fact obviously conflicts with the phonon-assisted Auger nonradiative mechanism. When carriers are generated by ac optical pumping by direct photoexcitation where the input photons are only absorbed in the wells, the ac PL efficiency is significantly reduced, as the forward bias voltage is increased to the value used for current injection. This means that the radiative recombination efficiency in the wells is in fact greatly influenced by the external bias field and leads to a reduction by exceeding the forward bias, thus suggesting the carrier escape.

7617-59, Poster Session

Photoluminescence and electroluminescence properties of CdS nanoparticles synthesized with macrowave irradiation

M. Molaei, Tarbiat Modares Univ. (Iran, Islamic Republic of); N. Taghavinia, Sharif Univ. of Technology (Iran, Islamic Republic of); E. Saievar Iranizad, Tarbiat Modares Univ. (Iran, Islamic Republic of); M. Marandi, Sharif Univ. of Technology (Iran, Islamic Republic of)

Nanocrystals or quantum dots are nanometer-scale particles that are neither small molecules nor bulk solids. Semiconductor nanocrystals, which exhibit properties different from bulk materials, are a new class of material that hold considerable promise for numerous application in the fields of electronics and photonics. As the diameter of semiconductor crystal approaches its exiton Bohr diameter, the optical properties begain to change and quantum confinement effects become important. As a consequence of quantum confinement, the optical absorption onset of small semiconductor crystals occurs at higher energies versus absorption of bulk materials.

Due to the fascinating color tenability as function of the size of semiconductor nanocrystals such as CdSe, CdTe and CdS, most studies have been on undoped rather than doped semiconductor nanocrystals.

In this article we synthesized CdS nanoparticles in aqueos solution with CdSO4 and Na2S2O3 as initial materials and thiyogelicerol as capping agent with macrowave irradiation, particles size were between 2.8-3nm and they were superhydrophilic and high luminescence with a 580 nm emissive wavelenght.

We used these particles as emissive layer in ITO/Pani(polyaniline)/CdS/Al organic/inorganic multilayer structure.

Pani deposited with electrochemical deposition method, CdS were deposited with spin coating method. our device turn on voltage was 12v and I-V digram and our device emissive picture were as follow.

7617-60, Poster Session

Polarization-dependent GaN grating reflector for short wavelength

J. Lee, S. Ahn, H. Chang, Seoul National Univ. (Korea, Republic of); J. Kim, Advanced Institutes of Convergence Technology (Korea, Republic of); H. Jeon, Seoul National Univ. (Korea, Republic of) and Advanced Institutes of Convergence Technology (Korea, Republic of)

In this study, we have found that, despite the low refractive index contrast in between GaN and the air, a simple surface grating (not a sophisticated membrane-type grating) shows enough reflectance/transmittance characteristics. This surface grating structure has enormous possibility for various applications due to its relatively much simpler fabrication process.

The rigorous coupled-wave analysis method was used to find the optimal design at 450 nm: period of 419 nm, filling factor of 0.4, and grating height of 114 nm. The grating reflector exhibits high reflectance over a broad spectral range for the TE-polarization direction while its reflectance for the TM-polarization direction is suppressed down to near zero. The TE-polarization represents the light whose electric field parallel to the grating lines.

For the actual fabrication, after depositing SiO2 and Cr layers on a thick GaN epilayer in sequence, a grating pattern was generated by utilizing holographic lithography. The pattern was transferred to the hard mask layers and to the GaN epilayer, using reactive-ion-etch (RIE) and inductively-coupled-plasma RIE processes, respectively.

Reflectance spectra of the fabricated grating reflector were measured. Using a pinhole and a Xe lamp, white light was incident on the grating reflector through the polished sapphire substrate. The TE-polarized light shows high reflectance over 90 % for broad spectral bandwidth near 450 nm. In addition, the measurements results were in good agreement with simulation results. These results suggest that the proposed surface grating reflectors could replace the conventional reflectors, which suffer from either absorption or non-conducting nature.

7617-61, Poster Session

Syntonized white up-converted emission by Tm3+-Yb3+-Er3+-Ho3+ doped ZrO2 nanocrystals

D. Sólis, T. López Luke, O. Meza, S. Anderson, E. De La Rosa, Ctr. de Investigaciones en Óptica, A.C. (Mexico)

Although the general properties of the rare earths' electronic states and transitions are well understood, much less is known regarding the relationships between them and the electronic band states of a crystal lattice. These interactions can enhance or inhibit performance and provide mechanisms for manipulating the material's optical properties. Up-conversion emission properties of ZrO2:Tm3+, Yb3+, Er3+, Ho3+ nano-crystalline samples were synthesized by sol-gel method and analyzed as function of different concentrations of rare earth ions. The samples were pumped at 970 nm with a semiconductor laser source. The introduction of different ion concentrations affects the shape and peak intensities of the measured blue, green and red bands. Results showed in this work tend to demonstrate a feasible control of the

chromaticity coordinates of emission and present an approximation to the equipotential white chromaticity coordinates. Color coordinate dependence with pump power was also analyzed.

Acknowledgment. We acknowledge the cooperation of Roman de la Vara, Andres Christen and Victor Aguirre for their contribution on factorial analysis.

7617-62, Poster Session

Efficiency enhancement in white phosphor-on-cup light-emitting diodes using short wave-pass filters

S. Cho, Korea Advanced Institute of Science and Technology (Korea, Republic of); J. R. Oh, Kookmin Univ. (Korea, Republic of); Y. Lee, Korea Advanced Institute of Science and Technology (Korea, Republic of); Y. R. Do, Kookmin Univ. (Korea, Republic of)

Technologies for achieving high-efficiency white light-emitting diodes (LEDs) have been studied actively in recent years for applications to solid-state lighting. Major developments in wide-band-gap III-V nitride compound semiconductors and color converted phosphors have led to the commercial production of white phosphor-converted light-emitting diodes (pcLEDs)

The development of phosphors for white phosphor-converted LEDs has expanded LED applications to light bulbs or lamps with high durability and low energy consumption. For the conventional case of a InGaN/YAG:Ce white LED, half of the phosphor-converted yellow light is emitted directly back into the InGaN chip or submount. This results in considerable loss of the yellow emitted light because the powder phosphor is emitted omni-directionally into space. Therefore, it is important to reduce this phosphor conversion loss.

This paper reports a simple approach for the design of blue-excitation-light passing and phosphor-yellow-emission-light reflecting dielectric multilayers to recycle the backward emission of Y3Al5O12:Ce3+ (YAG:Ce) yellow phosphors on top of a blue InGaN light-emitting diode (LED) cup.

The insertion of modified quarter-wave films of alternate high- and low-refractive index dielectric films (TiO2/SiO2) into the interface between a YAG:Ce phosphor layer and glass substrate resulted in 1.64 and 1.95 fold increase in efficiency and luminous efficacy of the forward white emission compared with that of a conventional phosphor on top of a blue LED cup with a lower correlated color temperature (< 4000K, warm white).

7617-63, Poster Session

Dirty LED: effect of dirt on light output

I. Moreno, D. Esparza, Univ. Autónoma de Zacatecas (Mexico)

Although a light-emitting diode (LED) has a very long life, its output power is affected on two ways: aging and dirt buildup. Environment and surroundings are typically characterized by the presence of substances, dust, liquids or vapors that may stick to the LED, reducing its light output. Knowing the relationship between dirt and LED output power, manufacturers and users can efficiently design a cleaning or maintenance program. In this work, several LEDs were subjected to output power tests for different degrees and types of dirt. For example, light flux reduction due to various dust deposition densities of several clay types is measured. In summary, extensive measurements indicate how high can be the efficiency drop when the LED is not clean.

7617-64, Poster Session

Sensitivity and fabrication issues for LED secondary optics

C. Ou, Hsiuping Institute of Technology (Taiwan)

Recently, the luminous efficiency of a light emitting diode (LED) is increasing rapidly, which resulting in a new ways for the designing of the secondary optics. Requirements on the sensitivities analysis are also become important since the quantum efficacy of an LED chip is much better than the outer extraction efficiency. Several researchers already discuss the differences between the aspheric surface design and the aspheric surface union approximate R design. We proposed a methodology to design the optical performance of the LED illumination system through the construction of the appropriate potential function on the detector plane. In a backlight unit, the requirement for optical characteristics of a LED is quite different for highly directional conventional ones, and a novel type LED secondary optics is required to fulfill the BLU application. A non-spherical lens is demonstrated for the uniformity optimization and the sensitivities analysis, and a great improvement in uniformity through a novel Hamiltonian based function is proposed. The Hamiltonian metric on the detector plane is proposed to increase both the extraction energy and the spatial uniformity on the illuminated plane. We are focusing on constructing the potential function of the lens's shape, such that the uniformity can be written in a more general form. Based on this general form, the sensitivity of the LED secondary optics design now much easier for the fabrication control.

7617-65, Poster Session

LED beam shaping with use of diffuser with micro-lens array

X. Lee, W. Chien, Y. Lo, C. Sun, National Central Univ. (Taiwan)

In this paper, we will present the study of beam shaping to LED lighting with use of a specific diffuser of micro lens array. The diffuser consists of micro lens array to perform a lighting pattern as desired. In order to perform a specific light pattern of LED lighting with the developed technology, a design of street light is chosen as the example, where we started from precise optical modeling of the light source, and then the design of the micro lens array will be presented. The optimization of the design in regarding to the LED, the diffuser and the light pattern will be discussed.

7617-66, Poster Session

Mechanism for Al Ohmic contact formation of laser-irradiated N-face n-GaN

Y. Song, H. W. Jang, J. H. Son, J. Lee, Pohang Univ. of Science and Technology (Korea, Republic of)

Recently, Vertical-structure designs were exploited in GaN-based LEDs to improve the light extraction efficiency. In these configurations, the laser lift-off (LLO) process has been demonstrated to be very effective for vertical LEDs which is removed sapphire substrate. In the Vertical LEDs, low electrical resistivity N-face n-GaN ohmic contact must be essential for increasing light efficiency. However, thermal degradation at the wide range of temperatures temperatures (200-700°C) has been observed as a weak point of the laser-irradiated N-face n-GaN, whereas ohmic contacts to Ga-face GaN can be easily formed using conventional Al-based metallization after annealing. Therefore, preventing thermal degradation is a key aspect in obtaiing high quality Al-based N-face n-GaN ohmic contacts. Until now, surface states, point defects, and interfacial compounds have been reported to cause the annealing-induced degradation of ohmic contacts to the N-face GaN, the exact origin is still unclear. And no work has been reported yet about the change of the interfacial band bending with annealing in metal contacts to N-face GaN.

In this presentation, we investigated Al ohmic contacts to laser irradiated Ga-face and N-facce n-GaN as a method to prevent thermal degradation at elevated temperatures. Using synchrotron photoemission spectroscopy (SRPES), we will discuss the origin of the different behavior in band bendings and electrical properties in terms of ohmic defects and polarity dependent polarization charges at the interfacial regions.

7617-67, Poster Session

Grating coupled enhancement of light emission from IR light-emitting diode devices

N. C. Das, W. Change, Army Research Lab. (United States)

Recently, there has been a great interest in using infrared light emitting diode (LEDs) devices as light sources in IR scene projection experiments. Type II Interband cascade electroluminescence in the 5-8- m spectral region from an LED structure was first reported by Yang et al [1]. Using a type II broken gap InAs/GaInSb quantum well (QW), Lin et al [2] have demonstrated experimentally the interband cascade laser. Recently, we have reported construction and operation of an LED array in the 3 to 4-μm wavelength region [3]. The LED emission characteristics depend on many factors such as quantum well design and growth parameters, processing techniques, mesa sizes, device temperature, and physical processes such as carrier relaxation and radiative recombination phenomena. Windisch et al 4] reported increase in light out put by using surface texturing etc from LEDs emitting in visible spectral regions. In this paper, we report the effect of different grating geometries and etch depth on both MWIR and LWIR LED device performance.

The interband cascade (IC) LED structure was grown by molecular-beam epitaxy on an n-type GaSb substrate. The active region, sandwiched between a 1.4-μm-thick top p-type contact layer and a 0.4-μm bottom contact layer. For MWIR structure we have used 18 periods with 769 angstrom thickness of active/injection layer and for LWIR structure we used 30 periods with 478 angstrom thickness of active/injection layer. Each period includes an asymmetric InAs/Ga1-xInxSb/InAs “W” quantum well preceded by an n-type digitally graded InAs/Al(In)Sb injector.

The LED fabrication process starts with reactive ion etching down to the bottom contact layer to define the mesas. Silicon nitride is deposited by a PECVD technique, following which contact windows are opened and Ti/Au metal layers were deposited. The current-voltage (IV) curves of the devices with and without grating are shown in Figure 1. The device with grating has higher voltage drop than the device without grating. From the current-light (IL) curves in figure 2, is seen that 45 degree grating device has the highest light put power among all the devices.

References:

[1]. Yang RQ, Lin C-H, Chang PC, Murry SJ, Zhang D, Pei SS, Kurtz SR, Chu A-N, and Ren F. Electron. Lett. 32, (1996), p.1621.

[2]. Lin C.H., Yang R.Q., Zhang D., Murry S. and Pei S.S., Applied Physics Letters, 72, (1998), p. 2220.

[3]. Das NC, Olver K, Towner F, Simonis G, Shen H. Applied Physics Letters, 87, (2005), p.041105.

[4]. Windisch R., Heremans P., Knobloch A., Kiesel P., Dohler G.H., Dutta B. and Borghs G., Applied Physics letters, 74, (1999), p.2256.

7617-68, Poster Session

Improving the performance of white LED by using dielectric film technique

L. Wang, P. Gu, Zhejiang Univ. (China); S. Jin, China Jiliang Univ. (China)

High efficiency white light emitting diodes based on ultraviolet (UV) LED with blue and yellow phosphor are proposed by using dielectric film. The dielectric film consisting of alternating layers of HfO_2 and SiO_2 is added between phosphor layer and sapphire substrate of the LEDs. Monte Carlo simulations model and theoretical analysis for this design show that the light efficiency is enhanced by 9% and the correlated color temperature is also improved from 7458 K to 6924 K. These are attributed to reflecting upward the back-scattered blue and yellow light from the phosphor layer.

The structure of dielectric film can be viewed as Sub1/(HL)^nH/Sub2, where Sub1 is Sapphire with reflective index of 1.72, Sub2 is encapsulation material with reflective index of 1.5, H is HfO_2 with refractive index of 2.06, L is SiO_2 with refractive index of 1.45, and (2n+1) =29 is layer number; d=(∑Li+∑Hi), which is 2463.23 nm in the simulation model, denotes the total thickness of the film. The reflectance of the thin film is a function of refractive indices, layer thickness of the two different materials, and it also depends on the number of periods and the incident angles. The reflectance curves shows rather high transmittance can be achieved in the ultraviolet spectrum peaked at 375 nm. Likewise, high reflectance occurred at a center wavelength of 470 nm and 570 nm which are the two peak emission wavelengths of phosphor respectively. Optical powers of blue and yellow light from the LED are presented in Monte Carlo simulations. Then we analyze the luminous efficiency of white LED with and without the dielectric film .In the theoretical analysis, a Gaussian line shape is assumed for the two emission bands. Based on photometric and colorimetric theories, the correlated color temperature (CCT), the chromaticity coordinates and the Luminous Flux are all calculated.

7617-69, Poster Session

Phosphor concentration and geometry for high-power white-light-emitting diode

K. Moon, S. An, J. Chae, H. Kim, Y. Park, Samsung LED (Korea, Republic of)

The most common method of making white light emitting diode(LED) is to mix the blue light from the LED die and the wavelength converted yellow light from the phosphor layer. The color conversion efficiency depends on the geometry and concentration of the phosphor layer including phosphor material. Thus the optimization of the phosphor geometry and concentration make increase the luminous efficiency of the white LED. In this paper, the remote phosphor scheme is optimized focusing on increasing the luminous efficiency in high power. The phosphor layer is separated by the silicone resin from the LED die. The silicone resin covers the LED die with dome shape to increase the extraction efficiency. The phosphor layer has very large volume with dilute concentration. The separation of phosphor layer from LED die and very large volumetric dilute phosphor layer were great important role in increasing the luminous flux. The improved luminous flux was 15% for 1mm2 LED die at 750mA .

7617-71, Poster Session

High-power 2.2mm light-emitting diode from strained quaternary GaInAsSb multiple-quantum well active region

J. Tan, J. T. Olesberg, L. Murray, J. P. Prineas, The Univ. of Iowa (United States)

A strained GaInAsSb/AlGaAsSb multiple-quantum well (MQW) light emitting diode (LED) emitting at 2.2mm infrared region is investigated. The heterostructure was grown by molecular beam epitaxy and consists of an active region which contains three compressively strained 12nm thick $Ga_{0.64} In_{0.36} As_{0.06} Sb_{0.94}$ QWs separated by 20nm thick $Al_{0.28} Ga_{0.72} As_{0.02} Sb_{0.98}$ barrier in a separate confined heterostructure.

X-ray diffraction measurement was used to verify the MQW alloy composition. The sample was processed into variable sized surface emitting LEDs. The emission wavelength was measure with spectrograph and the electroluminescent power (L) was characterized versus current (I) and voltage (V). A peak emission power of 13mW/mm^2 /sr from the 200x200mm^2 LED was observed at room temperature with 3000A/cm^2 peak drive current density at 1% duty cycle. Compared to the single junction bulk LED, the MQW LED exhibited an increase in the output power from 4.5 to 13mW/mm^2 /sr. We will also present the analysis of series resistance and the radiative efficiency of these devices.

7617-39, Session 8

Novel concepts for OLED lighting

B. Lüssem, T. Rosenow, S. Reineke, K. Leo, Technische Univ. Dresden (Germany)

Starting from a lab-curiosity, organic light emitting diodes have matured into a promising technology that has entered commercial markets. In particular for lighting applications, OLEDs can take advantage of their outstanding properties such as a high power efficiency, good color quality and new design possibilities such as illumination by flat light sources. In this contribution, new results on two approaches for highly efficient white OLEDs are presented: the all-phosphorescent concept and the triplet-harvesting approach.

In the all-phosphorescent concept, white light is generated by stacking phosphorescent red, blue, and green layers in a single OLED. By a sophisticated choice of materials and stack design, we have recently reached power efficiencies of 90lm/W [1], demonstrating the potential of this approach. However, the drawback of the all-phosphorescent approach is the instability of the blue phosphorescent emitter. These concerns can be avoided by the triplet-harvesting approach: It allows to replace the phosphorescent blue emitter with a fluorescent one [2,3]. When the triplet energy of the blue emitter is located above the triplet level of the red emitter, triplets formed on the fluorescent blue layer can diffuse to the red emitter and can be harvested there. Thus, in principle all excitons can be utilized and an internal quantum efficiency of 100% is possible.

[1] S. Reineke, F. Lindner, G. Schwartz, N. Seidler, K. Walzer, B. Lüssem, and K. Leo, Nature 459, 234 (2009)..

[3] G. Schwartz, M. Pfeiffer, S. Reineke, K. Walzer, and K. Leo, Adv. Mater. 19, p. 3672, 2007.

[3] G. Schwartz, S. Reineke, T.C. Rosenow, K. Walzer, K. Leo, Adv. Funct. Mat. 19, p.1319, 2009.

7617-40, Session 8

Light-outcoupling enhancement strategies in organic light-emitting diodes

W. Bruetting, J. Frischeisen, S. Nowy, Univ. Augsburg (Germany)

In recent years, great efforts have been devoted to the improvement of the luminous efficiency of organic light emitting diodes (OLEDs). In particular, the low light extraction efficiency due to the coupling to waveguide (WG) modes and surface plasmon polaritons (SPP) remains a challenge. In the first part of this talk we will present a simulation based approach to quantify different optical loss mechanisms in multi-layer OLEDs. Treating the emitting molecules as radiating dipoles, we are able to investigate the influence of various parameters, such as the position of the emitting dipoles within the OLED stack, their orientation and their radiative quantum efficiency together with the feedback of the OLED cavity on the latter quantity. Using different OLED designs, including bottom-emitting OLEDs, microcavity OLEDs and transparent metal-free OLEDs, we will demonstrate how the energy is distributed between different optical channels. In the second part we will discuss strategies to either reduce coupling to nonradiative modes (waveguided modes or plasmons) or to recover energy lost to these modes in order to increase the efficiency of OLEDs. The different approaches are validated by simulation and experimental studies on simple model devices.

7617-41, Session 8

On the lighting design aspect of OLED lighting

P. Ngai, Acuity Brands Lighting (United States)

OLED holds the promise of being the next generation Solid State Lighting. Due to the characters of its light emission, it is considered more than just a new light source such as LED. It offers new lighting design opportunities that are not possible currently. It has the potential of transforming the lighting industry.

The developmental directions on OLED performance will determine the degrees in which OLED will be adapted in lighting designs. Some of the important performance attributes include Efficacy (for energy efficiency), Brightness, Lumen depreciation, Life, Color, Physical Ruggedness, cost, among other.

This presentation will focus on three of these - Brightness, Efficacy and Lumen Depreciation. It will show, with realistic Lighting design models, the interdependence of these three attributes. It will demonstrate how lighting design applications will be affected by them.

The presentation will consider the followings factors:

- Sizes of the spaces to be lit

- Reflectance of the space - ceiling, wall and floor

- Efficiency of the OLED Luminaire (separate from the OLED panel efficiency)

- Coefficient of light utilization

- Light Loss factors -

a. Room Surface Dirt Depreciation

b. Luminaire Dirty Depreciation

c. Lamp Lumen Depreciation

d. Light Burnout factor

e. Driver Efficiency

- Illumination requirement of the space at three levels: 50FC (500 lux), 30FC (300 lux), and 15FC (150 lux).

- Density of OLED luminous area as a percentage of the ceiling - 100%, 20%, 10%, and 5%.

- Energy density requirements -

a. Currently in effect at about 1.0 watt/sq ft (10 watts/sq. meter)

b. Future direction .75 -.65/watts per square foot (7.5 to 6.5 per sq. m)

- Appropriate Life Time of OLEDs for Lighting Applications

7617-42, Session 8

Measuring the internal electroluminescence quantum efficiency of OLED emitter materials

M. Flämmich, N. Danz, D. Michaelis, C. A. Wächter, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany); M. C. Gather, K. Meerholz, Univ. zu Köln (Germany)

One major performance parameter for OLEDs in display and illumination applications is the overall efficiency of the device. This external quantum efficiency (EQE) is directly affect by the emitters internal electroluminescence quantum efficiency q, which is defined by the ratio of the radiative decay rate and the sum of all (radiative and competing non-radiative) decay rates in an unbound medium of the emitter material. Measurements of the photoluminescence quantum efficiency provide a rather rough (over-)estimation of the emitters q as the non-radiative decay processes severely depend on e.g. temperature and current density in the emissive layer as well as on its local environment. Thus it is very desirable to measure q of the emitter in-situ during electrical operation.

The internal electroluminescence quantum efficiency q is not only a multiplicative factor to the EQE but is also associated to the coupling probability to the different modes (air, substrate, guided, surface plasmon) which varies with the position of the emitter in the OLED cavity. We will show how q can be determined from a relative comparison of current efficiencies of a series of OLEDs with varying emitter cathode distance. This avoids the difficult and sometimes imprecise absolute measurements of the EQE and lowers the number of assumptions involved. For reliable determination of q a complete optical characterization of the devices is performed, including the measurement of all materials optical properties and layer thicknesses as well as the analysis of the emitters internal electroluminescence spectrum, the profile of the emission zone in the emissive layer and the orientation-distribution of the emissive dipoles.

7617-43, Session 8

Outcoupling efficiency in small-molecule OLEDs: from theory to experiment

M. Furno, R. Meerheim, M. Thomschke, S. Hofmann, B. Lüssem, K. Leo, Technische Univ. Dresden (Germany)

The extraction of the luminous power internally generated by organic light emitting diodes (OLEDs) is still the most severe limitation in the overall efficiency of these devices.

We present a joint theoretical and experimental study aimed to quantitatively evaluate the light outcoupling limitations of planar p-i-n type small-molecule OLEDs, both in bottom and top emission configurations. The total power radiated within the OLED active layer is calculated by means of a classical electromagnetic model, which i) exploits the equivalence between emitting molecules and a driven, damped harmonic dipole oscillator and ii) includes the effect of the OLED stack by a generalized transfer matrix approach.

The calculated power spectra are convoluted with the photoluminescence spectra of the emitting molecules in the OLEDs and are converted to wavelength and angle resolved spectra. The latter are validated against the measured electroluminescence spectra of different device configurations such as conventional and enhanced cavity bottom emitting OLEDs and top emitting OLEDs. The commonly quoted OLED figures-of-merits (FOMs), namely current, power, and external quantum efficiencies are finally derived from both calculated and measured data, to provide a quantitative evaluation of the performances of the different OLED architectures which we consider as case-studies. The simulations show that a trade-off exists between maximal light outcoupling on the one hand and maximal OLED FOMs on the other hand. We discuss the physical origin of this trade-off by analyzing internal optical losses and overall light conversion efficiency in OLEDs.

7617-44, Session 9

Nonpolar and semipolar GaN LEDs on sapphire substrates

J. Han, Yale Univ. (United States); Q. Sun, Yale University (United States)

No abstract available.

7617-45, Session 9

Anisotropic properties of nonpolar M-plane GaN

S. Feng, C. Yang, National Univ. of Kaohsiung (Taiwan); L. Tu, National Sun Yat-Sen Univ. (Taiwan); Q. Sun, J. Han, Yale Univ. (United States)

The spontaneous and piezoelectric polarizations of c-plane III-nitride result in a large internal electric field and a lower recombination efficiency. To overcome these obstacles and improve device efficiency, epilayers and devices fabricated along the nonpolar and axes have been demonstrated [1-3]. Due to the anisotropic structure, nonpolar III-nitride has shown many unique characteristics [1-3]. Although the unique characteristics of nonpolar III-nitride have been reported, the effects of anisotropic strain on the striation feature and anisotropic properties were not well discussed.

In this study, the overall issue of the relationship among striation surface morphology, in-plane strain distribution, and polarization anisotropy was studied. Four nonpolar m-GaN samples on SiC substrates with different NH3 flow rates were prepared. It was observed that the degree of the surface striation was highly correlated with the NH3 flow rate. In the high NH3 flow rate sample, a larger tensile strain along the a-axis and a compressive strain along the c-axis lead to a more apparent striation pattern. Furthermore, it was found that the higher NH3 flow rate, the lower the degree of polarization. By using k. p perturbation approach, our simulation results show that as the anisotropic in-plane strains increase for and , the degree of polarization for E1, E3, and all transitions decreases. Simulation results agree with our experimental results. By controlling the NH3 flow rate, one can modify the striation pattern, in-plane strain distribution, and anisotropic properties in the nonpolar GaN.

7617-46, Session 9

M-plane InGaN light-emitting diodes grown by PAMBE

S. Chou, T. Liang, S. Y. Chiang, M. Hsieh, Y. Q. Chen, P. V. Wadekar, P. V. Chinta, L. Tu, National Sun Yat-Sen Univ. (Taiwan)

Group III-nitride-based semiconductors are one group of materials useful for photonic devices. However the spontaneous and piezoelectric polarization effects in c-plane GaN templates degrade the radiative efficiency. One way to overcome this issue, is to grow heterostructures on non-polar (a-plane and m-planes) substrates [1], thereby reducing the polarization effects and improving the efficiency [1-2] and functionality [3]. Typical substrates used for m-plane growth are LiAlO2, ZnO, SiC, Al2O3. Among these, m-plane Al2O3 is more suitable for large scale manufacturing because of low cost and high availability. In addition, the thermal stability Al2O3 is better than that of LiAlO2 or ZnO, since the latter tend to decompose at high-temperature necessary for GaN growth.

In this study, we report the structural and optical properties of m-plane GaN epilayers grown directly on m-plane sapphire substrate by plasma-assisted molecular beam epitaxy. The m-plane GaN surface is optically smooth and mirror-like. X-ray diffraction /2 profile for (1-100) diffraction of GaN with the x-rays parallel to the c axis of the substrate shows sharp peaks for GaN (1-100) and sapphire (1-100), indicating the growth of m-plane GaN on the m-plane sapphire. We have found that, ex-situ thermal annealing can improve the surface morphology of the substrate. The reflection high energy electron diffraction (RHEED) streaks with clear Kikuchi patterns of sapphire substrates are obtained by annealing in air at temperatures 1400 °C for 3 hours. In comparison, the m-sapphire surface without such treatment exhibits rough surface morphology and a spotty RHEED pattern. This surface treatment leads to a high quality m-plane GaN growth and InGaN light-emitting diode.

REFERENCES:

[1] P. Waltereit, O. Brandt, A. Trampert, H. T. Grahn, J. Menniger, M. Ramsteiner, M. Reichem, and K. H. Ploog, Nature 406, 865 (2000).

[2] K. Okamoto, H. Ohta, S. F. Chichibu, J. Ichihara, and H. Takasu, Jpn. J. Appl. Phys., Part 2, 46, L187 (2007).

[3] N. F. Gardner, J. C. Kim, J. J. Wierer, Y. C. Shen, and M. R. Krames, Appl. Phys. Lett. 86, 111101 (2005).

7617-47, Session 10

LEDs on Si Substrates

K. M. Lau, Hong Kong Univ. of Science and Technology (Hong Kong, China)

No abstract available.

7617-48, Session 10

High-power GaN-based blue LEDs grown on Si substrate by MOCVD

L. Wang, F. Jiang, X. Wang, C. Mo, X. You, C. Zheng, W. Liu, Y. Zhou, C. Xiong, Lattice Power (Jiangxi) Corp. (China)

We report results on vertical injection thin film blue and white InGaN/GaN LEDs grown on (111) Si substrate by MOCVD. Wafers were grown in a MOCVD reactor on silicon substrate using a patented growth technique to control cracking. After growth, a reflecting P-contact was deposited and wafer bonded to a carrier substrate. The original silicon substrate was removed by wet etch followed by roughening and patterned N-contact.

At 350mA drive current, a 1x1mm LED has achieved greater than 480mW output power at 450nm wavelength. White LEDs made from these chips have achieved greater than 100lm cool white at 350mA with color temperature of 5200K and CRI of 70. Accelerated life-tests have shown these devices grown on Si substrate are as reliable as high power LEDs grown on sapphire substrates.

7617-49, Session 10

Nanoarchitecture light emitting diode microarrays

G. Yi, Seoul National Univ. (Korea, Republic of)

Nanoarchitecture light emitting device (LED) microarrays were fabricated using vertically aligned coaxial nanorod/nanotube heterostructures that have GaN/InGaN multi-quantum well structures grown on ZnO nanotube arrays. These nanoarchitecture arrays enable us to take advantage of accurately controlling positions, thicknesses, and compositions of quantum structures embedded in the nanoarchitectures, all of which may be useful for fabricating integrated optoelectronic devices and high-brightness LEDs. The nanoarchitecture LED microarrays consist of GaN-based p-n homojunction heterostructures with GaN/InGaN multi-quantum well structures (MQWs), which are coaxially coated on the entire surface of ZnO nanotube arrays. To fabricate nanoarchitecture LED microarrays, position-controlled ZnO nanotube arrays with a good vertical alignment were first prepared by the catalyst-free metal-organic vapor phase epitaxy. The diameters of the nanotubes, the interdistances between nanotubes, and the area density of arrays can be easily controlled by changing geometric parameters in the hole-patterned mask layer. Using ZnO nanotube arrays as a template, GaN-based p-n homojunction heterostructures with GaN/InGaN MQWs were fabricated. I will also discuss the electrical and optical characteristics of the nanoarchitecture LED microarrays.

7617-50, Session 10

Silicon nanocrystals-based light-emitting diodes integrated utilizing all inorganic metal oxide as the charge transport layers

A. Cheng, R. W. Liptak, U. R. Kortshagen, S. A. Campbell, Univ. of Minnesota (United States)

Air-stable luminescence silicon nanocrystals (Si-NCs) were synthesized using a novel in-flight system composed of a Si-NC synthesis SiH_4/Ar plasma and an SF_6 plasma which etches and passivates the NCs. The etch plasma can efficiently tailor the Si-NC size and the surface functionalities by tuning the gas flow rate, applied power, and pressure of the plasma.

Si-NCs based light emitting diodes (LEDs) were fabricated by using the Si-NCs as the recombination center for injected electron-hole pairs. Si-NCs were deposited in between two inorganic metal oxide layers, nickel oxide (NiO) and zinc oxide (ZnO), which served as the hole transport layer (HTL) and electron transport layer (ETL), respectively. NiO and ZnO have been chosen by considering their energy band offsets with respect to Si-NCs, and their band offsets to the electrodes which should produce roughly comparable carrier concentrations once the contacts are forward biased to get charge balance at the Si-NCs. The as-prepared metal oxides were confirmed to be stoichiometric using XPS. Four-point probes measurements show the oxide resistivity in the range of 2-5×106 Ω/ .

The as-prepared etched Si-NCs generated orange photoluminescence at a peak intensity of 632nm and the quantum efficiency is 23%. I-V characteristics and light intensities of the Si-NCs LED without depositing the top ZnO ETL have been studied with respected to the Si-NCs thickness. LEDs made using a two minute Si-NCs (approximately 250nm) deposition showed an easily visible air-stable light emission; however, the light intensity decreased by 60% for a thicker (1.5 m) Si-NC films. The current of the thin Si-NC layer LED with the top ZnO ETL turned on as low as 2V and reached 0.1A at of 5.2V. At the highest current densities some degradation of the device was observed, otherwise device operation was consistent and yield was good. The I-V characteristics of the Si-NC LED made using all inorganic metal oxides showed Schottky behavior as well as good light intensity.

7617-51, Session 10

Stability of binary-doped ZnO thin film in high-humidity environment

H. Hsieh, C. Liu, National Central Univ. (Taiwan)

Aluminum-Zinc-Oxide (AZO) thin film is known as potential candidate for replacing the current widely-used Indium-Tin-Oxide (ITO). But, there are several considerable problems about AZO. For examples, its relative lower electrical conductivity and poor humidity-resistance are the two major concerns.

In this study, the Gd: AZO and Ti: AZO thin films were prepared on quartz substrates by magnetron co-sputtering system. Then, both Gd: AZO and Ti: AZO thin-film samples were annealed at elevated temperatures ranging from 200 oC to 500 oC in vacuum to activate the functions of the doping elements. Then, put them into chambers with high humidity (90±5 RH%). Hall measurement and four-point probe were used to monitor the electrical resistivity, carrier concentration and mobility with exposure times. Our preliminary results reveal that the dopants in AZO thin-films could stabilize the resistivity for a longer period of time, compared to the pure AZO thin-film. Also, we found that the higher AZO deposition and annealing temperature help resisting the resistivity decay against the exposure time in high humid ambient. The detail mechanism of the doping effect will be discussed in this talk.

7617-72, Session 10

High efficiency green LEDs using II-VI color converters

T. J. Miller, M. A. Haase, X. Sun, B. Hao, J. Zhang, T. L. Smith, T. Ballen, J. Xie, A. S. Barnes, F. Kecman, J. Yang, J. Thielen, C. A. Leatherdale, 3M Co. (United States); R. Wirth, A. Biebersdorf, K. Engl, S. Groetsch, OSRAM Opto Semiconductors GmbH (Germany)

II-VI semiconductors can exhibit strong photoluminescence throughout the visible spectrum and are excellent candidates for filling the so-called “green gap”. We report on the performance of green color-converted LEDs fabricated by bonding CdMgZnSe multiple quantum well structures to high-efficiency blue-emitting InGaN LEDs. A device efficacy of 181 lm/W at 537 nm (dominant) is measured under room temperature, 350 mA/mm2 quasi-cw conditions, more than twice as efficient as typical commercial green LEDs today. The thermal roll-off is shown to be less than that of typical green InGaN LEDs. Finally, the implications of the availability of high-efficiency, narrow-band, green and yellow emitters in display applications will be discussed.

7617-52, Session 11

Recent progress of 220-280nm-band AlGaN based deep-UV LEDs

H. Hirayama, RIKEN (Japan)

We demonstrated 222-282 nm AlGaN-based efficient deep-ultraviolet (DUV) light-emitting diodes (LEDs) fabricated on low threading dislocation density (TDD) AlN template. Low TDD AlN on sapphire were realized by using ammonia (NH3) pulse-flow multilayer (ML) growth technique. We observed marked increase of internal quantum efficiency (IQE) from around 1% to 30 % by reducing the edge-type TDD from 1×1010 to 7×108 cm-2. We also obtained quite high IQE (~80%) from slightly-In-incorporated (0.3%) InAlGaN QWs and obtained over 10 mW CW output power for 280 nm-band InAlGaN based LED. The maximum output power obtained were over 10 mW for 264-282 nm LEDs, 1.2-5mW for 240-256 nm LEDs and sub-milliwatt for 222-237 nm LEDs. The maximum external quantum efficiency (EQE) of 280 nm-band LED was 1.2%.

7617-53, Session 11

Improved performance of near-ultraviolet InGaN/AlGaN LEDs with various insertion structures

D. Wuu, W. Lin, Y. Tsai, S. Huang, R. Horng, National Chung Hsing Univ. (Taiwan); C. Liu, National Chiao Tung Univ. (Taiwan)

The near-UV LEDs have a great potential as the pumping source for high color-rendering-index and highly stable white-light emission. However, one problem associated with UV LEDs is their high sensitivity to threading dislocation (TD) density. It is well known that TDs which directly penetrate multiple quantum wells can work as non-radiative recombination centers, further degrading light emission efficiency as well as output power. Furthermore, these degradations in the UV LED samples are more pronounced than those in the blue LED ones. Therefore, several previous researches were proposed to reduce TD effects in UV LEDs. In particular, the epitaxial lateral overgrowth which uses the SiO2 mask to block TDs was found to be efficient in reducing the TD density in the GaN eplayers. In this study, two approaches using various insertion structures are proposed. One is through a single MOCVD process where a heavily Mg-doped GaN insertion layer (HD-IL) technique is employed to improve crystalline quality of the GaN layer and followed by rest of required GaN-based LED structure. The TD reduction by HD-IL is confirmed by the cross-sectional TEM examination where an overgrowth of GaN and blocking mechanism for TDs is observed. Another approach was demonstrated by the near-UV LEDs with an embedded distributed SiO2-disk structure. The periodically spaced hexagonal disk-shaped SiO2 mask array (one micron thick) was deposited on the GaN/sapphire template using electron-beam evaporation and followed by the MOCVD re-growth process. These improvements contribute the high-performance 380-nm LEDs with enhanced output powers by 20-40% in magnitude.

7617-54, Session 11

Low-resistive Ni/Ag ohmic contacts to p-AlGaN for UV LEDs

T. Passow, R. Gutt, M. Kunzer, W. Pletschen, R. Schmidt, J. Wiegert, S. Liu, K. Köhler, J. Wagner, Fraunhofer-Institut für Angewandte Festkörperphysik (Germany)

Low resistive ohmic contacts to p-type AlGaN are difficult to obtain due to the low hole concentration in p-AlGaN and the lack of a contact metal with a sufficiently large work function. However, low resistive ohmic contacts are instrumental for LEDs to achieve an efficient hole injection, low forward voltage, and thus low heat generation. Hence, a relatively thick (>=20 nm) p-type GaN cap layer is usually introduced between p-AlGaN and the metal layers in AlGaN-based UV-LEDs resulting in a strong light absorption within the p-type contact.

Contacts based on Ag are well known to have a low contact resistance and high reflectivity for GaInN-based LEDs. As an example, for near-UV LEDs (lambda=400 nm) with Ag-based contacts, we achieve a by 0.5 V lower forward voltage at 20 mA and a 50% higher output power compared to a Ni/Au contact. Here, we report on the development of a reflective Ag-based contact for AlGaN-based LEDs emitting at 350 nm. The thickness of the intermediate p-GaN layer could be reduced to 7 nm due to the low contact resistivity of 3.5×10^-3 ohm cm^2, which is a factor of 20 lower compared to a Ni/Au contact. We further present improvement of the forward voltage and output power for our UV-LEDs.

In addition, we even observed ohmic I-V characteristics for Ag-based contacts directly on p-AlGaN (x_Al<15%). Properties of a semi-transparent Ag-based contact combined with an Al reflector to extend the reflectivity of the contact layer to wavelengths below 350 nm are finally discussed.

7617-55, Session 11

Development of high-power nitride LEDs and its application

C. Sone, Samsung Electro-Mechanics (Korea, Republic of)

No abstract available.

Conference 7618: Emerging Liquid Crystal Technologies V

Monday-Wednesday 25-27 January 2010 • Part of Proceedings of SPIE Vol. 7618

Emerging Liquid Crystal Technologies V

7618-01, Session 1

Quantum dot light emitting devices with heavy metal-free materials

S. A. Coe-Sullivan, P. T. Kazlas, J. S. Steckel, J. E. Ritter, QD Vision Inc. (United States)

Quantum dot light emitting diodes (QD-LEDs) are an emerging electroluminescent device technology that is desirable for both information displays and solid-state lighting applications owing to its excellent color, material stability and high efficiency at a low cost of manufacture. Quantum dot semiconductor nanocrystals (QDs) permit the combination of the soluble nature and processability of organic dyes with the high efficiency and stability of inorganic semiconductors. QDs are more stable in the presence of water vapor and oxygen than their organic semiconductor counterparts. Because of their quantum-confined emissive properties, their luminescence is extremely narrow-band and yields highly saturated color emission, characterized by a single Gaussian spectrum. Finally, because the nanocrystal diameter controls the QD optical band gap, fine tuning of absorption and emission wavelength can be achieved through synthesis and structural changes, facilitating the process for identifying and optimizing luminescent properties.

Thus, Quantum dot (QD) light emitting diodes (QD-LEDs) are a printable thin film electroluminescent technology that delivers exceptional color and efficiency at low cost of manufacture for display and solid-state lighting applications. In this paper we report on QD-LEDs with peak external quantum efficiency exceeding the critical 5% mark for the first time. Specifically, we report to the best of our knowledge the highest achieved peak external quantum efficiency (>7% EQE) and the highest achieved brightness (>13,000 nits) for a QD-LED as well as the highest achieved efficiency for a QD-LED without Cadmium-based QDs (>3% EQE). We also discuss the performance potential of QD-LEDs.

7618-02, Session 1

Design of a free-form single-element see-through head-worn display

O. Cakmakci, K. Thompson, Optical Research Associates (United States); J. Rolland, Univ. of Rochester (United States)

This paper presents the impact of a change of basis from polynomials to radial basis functions for describing free-form optical surfaces. A design example of a single freeform element see-through head-worn display is presented. The single element see-through head-worn display is designed to have a 3 mm eyebox diameter, 15 mm eye clearance, 24 degrees diagonal full field of view, 320x240 (qvga) panel resolution, and to operate in the visible wavelength range (465-642 nm).

7618-03, Session 1

Next-generation head-mounted display

J. P. McGuire, Jr., Optical Research Associates (United States)

Optical head mounted display systems (HMDs) have been utilized by the military for various applications since the 1980's. In the 1990's, this technology migrated to the consumer market. Most of these early system suffered the major drawback that they were "look-at" system, that prevented the user from seeing their environment. This reduced the utility of the devices and could potentially lead to safety issues.

This presentation discusses the optical design of a novel "see-through" High Definition display device with a 40 degree field of view.

7618-04, Session 1

High-power high-bandwidth laser diode driver for next-generation laser projectors

A. Streck, W. Stork, Univ. Karlsruhe (Germany); A. Wagner, ELOVIS GmbH (Germany)

Employed in projection domes or in general, applications involving spherical surfaces, like professional flight simulators or automobile head-up displays, laser projectors offer great benefits over techniques involving liquid crystals or digital mirror devices. With the development of red and especially blue laser diodes with output powers in the range of several Watts, new prospects have been opened for compact and cheap laser projectors by direct modulation of the lasers with the pixel rate in scanning systems.

In this paper, the requirements and challenges for the laser driver circuits are highlighted. For displaying high definition graphics and video resolutions with pixel rates above 100 MHz, the drivers need to provide very high bandwidth broadband modulation capability. Additionally high output currents in the Ampere region are required when driving high power laser diodes. Focusing on the parasitic effects of the laser diodes packages and the interconnection between drivers and lasers, restrictions and solutions for achieving the combination of these two requirements are shown. A 1.5 A, 100 MHz driver module which was developed under derived design rules is presented and test results are given for high power diodes in TO-Can and C-Mount packages.

7618-05, Session 2

Overview of 3D/2D switchable liquid crystal display technologies

B. Lee, Seoul National Univ. (Korea, Republic of); J. Park, Chungbuk National Univ. (Korea, Republic of)

[This is an invited paper.]

Three-dimensional (3D) displays attract great attention recently. Rapidly developing flat-panel two-dimensional (2D) display technology increases the system bandwidth, making 3D displays more and more feasible. One of the most important factors for the successful penetration of the 3D displays into display market is considered as 3D/2D switching capability. Although 3D displays provide unique values by presenting additional dimension, it is only accomplished at the expense of image resolution. For the viewers who are already accustomed to high resolution of current 2D displays, 3D experience with reduced resolution is pleasing only for short period of time. Insufficient 3D content is another limiting factor for 3D-only displays. Therefore, 3D/2D switching capability is indispensible for commercial success of 3D displays.

3D/2D switching is accomplished by using active optical devices. Liquid crystal has electrically controllable optical properties, making it highly versatile for 3D/2D switching. Nowadays liquid crystal is being used to give 3D/2D switching capability to wide variety of 3D display techniques. Two-view or multi-view autostereoscopic displays, which are the most prominent solution for near-term commercialization, use active parallax barrier or lenticular lens made of liquid crystal. By controlling electric field applied to liquid crystal, the optical function of parallax barrier or lenticular lens can be turned on and off, switching the display mode between 3D and 2D. Integral imaging which provides more natural 3D images can also have 3D/2D switching feature by using liquid crystal to make active diffuser. 3D/2D switchable stereoscopic (glasses type) display is another example of usage of liquid crystal as switching means.

In this report, we review various techniques for 3D/2D switchable displays using liquid crystal and discuss the critical issues. Image processing techniques for 3D/2D contents conversion, which is another key technology for the success of 3D displays, will also be discussed briefly.

7618-06, Session 2

Static 3D image space

B. Koudsi, J. J. Sluss, Jr., Univ. of Oklahoma (United States)

Recent 3D developments, such as volumetric display, generate 3D images within actual 3D space. More specifically, the CSpace® volumetric display generates a truly natural 3D image comprised of perceived width, height, and depth within the confines of physical space. Wireframe graphics allow viewers a true 360-degree display without additional visual aid. The research presented in this paper focuses on the selection and testing of several rare earth, single-doped, fluoride crystals, namely 1%Er: NYF4, 2%Er: NYF4, 3%Er: NYF4 , 2%Er:KY3F10, and 2%Er:YLF, to be used as a material for the CSpace® display in a Two-Step-Two Frequency Up-Conversion process.

A number of significant determinants were explored and identified to aid in the selection of a suitable medium. Wavelengths of two infrared lasers were considered with respect to the highest absorption cross-section, demonstrating the extent to which the infrared laser will be efficiently absorbed by the materials at any given specific wavelength. The characterization of the highest emission was addressed by comparing the optical emitted power results for all crystals examined. By comparing fluorescence and optical emitted power measurements for the same crystal at different doping concentrations, the effect of doping concentration on the fluorescence was demonstrated. Finally, the effect of the material response time on image brightness was expressed by measuring the optical emitted power in relation to the changing speed of the projected slice.

The results show that 2%Er: NYF4 has good optical emitted power and an acceptable response-time. In addition, a superior level of brightness makes it the most suitable candidate for the CSpace® display. Testing also proved 2%Er: KY3F10 crystal to be a promising medium.

7618-08, Session 2

Super multiview display and electronic holography as future 3D display

Y. Takaki, Tokyo Univ. of Agriculture and Technology (Japan)

Conventional 3D displays have two problems with respect to human 3D perception. One is the accommodation-vergence conflict that causes visual fatigue, and the other is the absence or imperfection of motion parallax that reduces the presence of 3D images. A natural 3D display, which is free from these two problems, needs to be developed as a future 3D display.

The super multi-view (SMV) display has been proposed as a natural 3D display. The SMV display technique makes an interval of viewpoints smaller than the pupil diameter, so that two or more rays passing through the same point in space pass through the pupil simultaneously. Therefore, the eyes can focus on that point so that the accommodation-vergence conflict does not occur. Smooth motion parallax is also obtained. The high-density directional (HDD) display has also been proposed, which samples the ray proceeding direction with a small angle pitch. SMV and HDD displays have to display a large number of images. HDD display that generates 64, 128, and 256 images are reviewed.

Holography is an ideal 3D display technique because the wavefront of light is reconstructed. Although ultra high resolution is required for a spatial light modulator (SLM), the accommodation-vergence conflict does not occur and smooth motion parallax is obtained. Horizontal-parallax-only (HPO) holography can dramatically reduce the number of pixels requied for the SLM, because a high resolution is required only in the horizontal direction. The use of resolution redistribution optical system and the use of horizontal scanning for HPO holography are reviewed.

7618-09, Session 2

Resolution analysis of Fourier-hologram generated by integral imaging and its enhancement

C. Ni, J. Park, K. Nam, B. Yoon, Chungbuk National Univ. (Korea, Republic of)

Holography has been considered as a perfect technique for three-dimensional display, since it can provide flawless three-dimensional images with complete human depth cues. The complicated capture process of hologram, however, has been problematic. Recently, hologram synthesis method using integral imaging which generates a hologram from multiple orthographic view images of three-dimensional objects has been reported. In this method, coherent optical system is not required. It is also possible to obtain the multiple orthographic projection images from a single capture process. Therefore hologram capture process is much simplified by this method. Moreover, the manipulation of the three-dimensional information of the objects is easily achieved. In addition, the exact Fourier hologram can be generated in a straightforward way without any approximations. However, the resolution of the hologram generated by this method is limited. Experimental verification has been performed only for simple objects of low details. The exact theoretical analysis on the resolution of the hologram generated by this method has not been conducted yet.

In this paper, we present an analysis on the reconstruction resolution of the Fourier hologram generated from multiple orthographic view images of three-dimensional object. Based on this analysis we also propose a method to enhance the resolution of the reconstruction by using lens array shift method.

In the analysis, we analyze both the maximum size and the spatial resolution of the reconstruction. For the maximum size of the reconstruction, we found that the main factor is the orthographic projection angle interval. Too large projection angle interval causes overlapping in the reconstruction space domain. For the spatial resolution, there are three factors, i.e. the capturing lens array pitch which determines the sampling rate of the original three-dimensional objects, the maximum orthographic projection angle, and the spatial frequency bandwidth of the object. Which one is the main factor depends on the relationship among these three factors. Based on this analysis, we will prove that the lens array shift method can enhance the resolution of the reconstruction. The principles will be verified both computationally and experimentally.

7618-10, Session 2

A new method for laser speckle suppression

M. M. Tilleman, Elbit Systems of America (United States)

A new method for speckle suppression is presented in which the illuminating laser source is remote from the image projector. Its beam is conveyed to the projector by a multimode fiber, a section of which is dithered. This section may be located adjacent to the laser and distant from the projector. Thus, neither geometrical hindrance is presented nor motion is transferred to the projector. Further, the outcoupled beam from the fiber is propagated through a microlens beam-homogenizer onto a spatial modulator residing in the projector. This results in image formation in which the speckle contrast is reduced to less than 12% for dithering frequencies of at least 25 Hz, and the attainment of an illumination field with homogeneity of less than 20%.

The new method is compared with several state-of-the-art techniques such as source diversity and diffuser rotation showing similar performance. Here speckle suppression by decoherence has been demonstrated by combining a multitude of uncorrelated lasers, constituting a combination of angle and wavelength diversity. Also, we attained laser decoherence by mode coupling over a long multimode conduit. Speckle averaging was used by rotating the screen on which the image was projected.

Despite their proven ability to suppress speckles, their main disadvantage of the existing methods is their employment of many lasers or the use of a very long, often lossy, conduit, or for averaging methods in cases where a large screen is used or where the available space for the imaging system is limited the introduction of motion elements may be prohibitive.

7618-11, Session 2

An artifact metrics which utilizes laser speckle patterns for plastic ID card surface

M. Yamakoshi, National Printing Bureau of Japan (Japan); X. Rong, California Polytechnic State Univ., San Luis Obispo (United States); T. Matsumoto, Yokohama National Univ. (Japan)

Artifact-metrics is an automated method of authenticating artifacts based on their measurable intrinsic characteristics such as microscopic random-patterns and the like which are emerging in their manufacturing process. They are very difficult to copy and control even for legal manufacturers. Taking such an advantage, artifact-metrics can be used as a new type of anti-counterfeiting techniques for security documents such as banknotes, ePassport, etc. This paper describes the feasibility of an artifact-metric system using laser speckle patterns of the surface of target objects such as plastic cards and papers. Speckle patterns of the surface differ from each other depending on their microscopic geometry; they can be authenticated automatically by some matching algorithm that compares the input with the previously enrolled data. Our system consists of a laser diode and a CCD camera which are attached firmly to a rigid metal frame and a matching algorithm by phase-only correlation method. One of the most important requirements for artifact-metrics is the stability, which means the ability for reliable reading the data from the object at the verification phase. To obtain good stability and find a superior setting for optical paths, we investigate the influence of a minute change of angle and width of laser emission, and resolution of the camera in a matching experiment for 300 of ID 1 sized cards. The experiment shows the FMR/FNMR curves obtained by calculating similarity scores, which imply that about 1 % EER can be achieved by using matching area of 1 x 3 (mm) on the card surface.

7618-12, Session 3

Resonantly-pumped optical Kerr nonlinearity in liquid crystalline materials (Keynote Presentation)

Y. Shen, Univ. of California, Berkeley (United States)

Optical-field-induced molecular reorientation can be resonantly enhanced through enhanced molecular polarizability when the pump light approaches an electronic resonance. However, much more significant resonant enhancement can be expected if orientational interactions between excited-state and ground-state molecules are stronger than those between ground-state molecules. This latter effect can be understood as a consequence of photo-induced guest-host interactions with the excited molecules treated as guests and ground-state molecules as hosts. It should be readily observable in rod-like liquid crystalline materials. We describe an experiment that demonstrates such an effect in 5CB in both isotropic and nematic phases.

Liquid crystal as a dielectric medium incorporated in a metamaterial could be used to electrically or optically tune the plasmon resonances of the metamaterial. We describe briefly a case how optical pumping modulates the optical properties of a fishnet metamaterial structure.

7618-13, Session 3

Photoreactive third-harmonic generation in liquid crystalline azopolymer thin films

C. C. Hsu, J. H. Lin, H. C. Kan, National Chung Cheng Univ. (Taiwan); L. Chien, Kent State Univ. (United States)

Photoreactive third-harmonic (TH) generation in liquid crystalline (LC) azopolymer thin films is investigted. TH generation can be controlled by a nanosecond laser with two different wavelengths excitation. When the 365 nm pump beam is turned on, TH signal possesses large anisotropic distribution. In particular, after turning off the pump beam, the TH saturation signal is three times larger than its original TH level and forms isotropic distribution. After that providing the 460 nm excitation, TH signal presents anisotropic distribution. The TH orientatonal distribution (isotropic or anisotropic) can be controlled by either using 365 nm or 460 nm pumping. This particular property of the LC azopolymer thin films could be useful for optoelectronics applications such as rewritable optical data storage.

7618-47, Session 3

Liquid crystal waveguides: new devices enabled by >1000 waves of optical phase control

S. R. Davis, S. D. Rommel, G. Farca, A. W. Martin, B. Luey, S. Johnson, M. H. Anderson, Vescent Photonics Inc. (United States)

A new electro-optic waveguide platform, which provides unprecedented voltage control over optical phase delays (> 2mm), with very low loss (< 0.5 dB/cm) and rapid response time (sub millisecond), will be presented. This technology, developed by Vescent Photonics, is based upon a unique liquid-crystal waveguide geometry, which exploits the tremendous electro-optic response of liquid crystals while circumventing their historic limitations. The waveguide geometry provides nematic relaxation speeds in the 10's of microseconds and LC scattering losses that are reduced by orders of magnitude from bulk transmissive LC optics. The exceedingly large optical phase delays accessible with this technology enable the design and construction of a new class of previously unrealizable photonic devices. Examples include: 2-D analog non-mechanical beamsteerers, chip-scale widely tunable lasers, chip-scale Fourier transform spectrometer (< 5 nm resolution demonstrated), widely tunable micro-ring resonators, tunable lenses, ultra-low power (< 5 microWatts) optical switches, true optical time delay devices for phased array antennas, and many more. All of these devices may benefit from established manufacturing technologies and ultimately may be as inexpensive as a calculator display. Furthermore, this new integrated photonic architecture has applications in a wide array of commercial and defense markets including: remote sensing, micro-LADAR, OCT, FSO, laser illumination, phased array radar, optical communications, etc. Performance attributes of several example devices and application data will be presented.

7618-15, Session 4

Quantum dot self assembly in liquid crystal media

L. S. Hirst, University of California, Merced (United States)

In recent years the dispersion and directed assembly of nano-particles in liquid crystal media has proved an interesting field for investigation and one that may yield new hybrid materials for optical applications and fundamental research. We have investigated the dispersion of quantum dots in the nematic and smectic A liquid crystal phases, looking at aggregation, pattern formation and coupling effects between the dots. Quantum dot self-assembly in liquid crystals is dependent on the particle surface properties and also on particle size. By varying these parameters

we observe some fascinating structures and electro-optical behavior using microscopy and photoluminescence measurements.

7618-16, Session 4

Nanoparticle-dispersed liquid crystal prepared by a simple sputter deposition

M. Ozaki, H. Yoshida, K. Kawamoto, A. Fujii, T. Tsuda, S. Kuwabata, Osaka Univ. (Japan)

Nanoparticle (NP) dispersion in liquid crystals (LCs) has attracted considerable attention from both scientific and industrial points of view because of the expectation of improved response speed and lowering of the Frederiks transition threshold.

We demonstrated a single-step method to prepare metal-NP-dispersed LC without having to chemically modify NPs' surfaces. Highly dispersed gold NP-LC suspensions are prepared simply by sputter-depositing the target material on the host LC. The existence of the NP is supported by optical extinction measurements, polarization optical microscopy and transmission electron microscopy. An improved electrooptic response, namely, a decrease in the threshold voltage is also demonstrated in TN devices using the resultant NP-dispersed LC. Besides these electrooptic characteristic, many interesting effects of NP-dispersion are observed in material characteristics such as phase transition behaviors.

This technique is in principle applicable to any kind of material and LC phases, and thus provides a versatile route to prepare stable NP dispersed LCs.

7618-17, Session 4

Control of colloidal interactions in liquid crystals by tailoring their shapes and using light-sensitive molecular monolayers

I. I. Smalyukh, Univ. of Colorado at Boulder (United States); C. P. Lapointe, T. G. Mason, R. Trivedi, A. Martinez, J. S. Evans, P. ACKERMAN, University of Colorado at Boulder (United States)

Discovery of novel colloidal interactions in nematic liquid crystals has stimulated a rich theme of interdisciplinary research at the interface of colloid and liquid crystal sciences. We demonstrate the profound effects of colloidal shape on the symmetry of ensuing interactions in nematic fluids and have found that they can switch from dipolar to quadrupolar through changing the number of sides of model polygonal platelet inclusions from odd to even. Remarkably, the particles induce elastic distortions with no bulk topological defects, suggesting that the symmetry of interactions and assembled structures can be preserved down to nanometer size scales. The discovery of this shape parity effect provides fundamental insights into the scope of utilizing anisotropic elastic interactions to self-assemble new types of tunable electro-optic materials with controlled structures and compositions. Furthermore, utilizing both polymer and metal particles of different shapes and with sizes ranging from 50nm to 10 microns, we show that the alignment and interaction between the colloidal particles can be controlled using light-sensitive monolayers.

7618-18, Session 5

High performance spectroscopic ellipsometer using linearized liquid crystal phase modulators

H. Yokoyama, Liquid Crystal Institute, Kent State University (United States); Y. Tabe, Waseda University (Japan)

Liquid crystal optical phase modulators are known for many years, but their phase-voltage characteristics are highly nonlinear, thereby making their applications and performance rather limited. Based on the scaling property of the liquid crystal elasticity at high applied voltages, we devised a new driving shceme for phase modulator that allows a sufficiently wide range of linearized phase-voltage relation. Using a pair of linearized liquid-crystal phase modulators with their respective optic axes set at 45 degrees, a fast and high precision spectroscopic ellipsometer, working in the null ellipsometry, has been developed. For monochromatic light, the ellipsometric parameters of the sample, i.e. the phase difference and the amplitude ratio, can be independently and directly obtained from the optical phase values set on the liquid crystal phase moleculators. Exploiting the linearized phase-voltage behavior in conjunction with multi-variate analysis, the ellipsometer allows simultaneous polychromatic measurement without scanning the wavelength, which opens up an application for quasi-realtime polarized image analysis.

7618-19, Session 5

30-ns liquid-crystal optical shutters

M. G. Geis, R. J. Molnar, G. W. Turner, T. M. Lyszczarz, MIT Lincoln Lab. (United States); R. M. Osgood, U.S. Army Soldier Systems Ctr. (United States) and Natick Lab. Army Research, Development, and Engineering Ctr. (United States); B. R. Kimball, U.S. Army Soldier Systems Ctr. (United States)

Liquid crystal (LC) applications have been limited to the millisecond range because of their relatively slow response. However, by using low molecular weight LC, and optimizing the driving voltage and temperature, <100 ns response time can be obtained.

The switching time of liquid-crystal cells using the liquid crystal, 5CB, has been characterized as a function of applied voltage, V, and temperature, T. The switching time from 90 to 10% transmission scales as V-2 and is limited to 30 ns by the breakdown electric field, ~106 V cm-1. The time from the initial voltage step to 90% transmission, delay time, also scales as V-2, but plateaus to ~40 ns at electric fields >105 V cm-1. The plateau time is related to the dielectric response of the liquid crystal.

The switching and delay times both decrease linearly with increasing temperature. Above 10°C the switching can be characterized with a single time constant, but below 10°C and down to the super cooled temperature of 5°C the switching time is characterized with two time constants. One is a continuation of the switching time from higher temperatures and the second time constant is ~5 times longer than the first. Decreasing the switching and delay times with other liquid crystals and polymer additives will be discussed.

7618-23, Session 5

Electroactive super-elongation of carbon nanotube aggregates in liquid crystal medium and its application for displays

S. H. Lee, Chonbuk National Univ. (Korea, Republic of)

No abstract available.

7618-20, Session 6

Cell biology and active liquid crystals

D. J. Needleman, J. Brugues, Harvard University (United States)

A wide variety of subcellular structures exist in a non-equilibrium steady-state with a constant flux of matter and energy continuously maintaining their architecture. A prime example of this is the spindle: a self-organizing ensemble of proteins that segregates chromosomes during cell division. The spindle is a dynamic steady-state structure composed rigid polymers, called microtubules, and a plethora of molecules which control microtubule nucleation, growth, and motion. While many of the individual

components of the spindle have been studied in detail, it is still unclear how these molecular constituents self-organize into this structure and how this leads to the internal balance of forces that are harnessed to divide the chromosomes. More generally, there is no accepted framework for understanding the organization of ensembles of active, biological molecules, such as the spindle.

A number of groups have suggested that certain cellular structures can be understood using modified forms of continuum models from liquid crystal physics, but it is still unclear how profitable this approach is. We are testing if such active liquid crystal models are valid for describing the spindle by measuring the spindle's internal fluctuations, structure, and response to perturbations. This work uses a combination of single molecule tracking, spinning disk confocal microscopy, quantitative polarized light microscopy, and magnetic tweezers. The results from these quantitative experiments are being compared with predictions from various coarse-grained models to determine if spindles really are active liquid crystal.

7618-21, Session 6

Spatio-temporal growth of membrane patterns and lipid raft domains on a nanotopographic solid support

S. Lee, S. Lee, Seoul National Univ. (Korea, Republic of); T. Yoon, Korea Advanced Institute of Science and Technology (Korea, Republic of)

Cell membranes consist of lipid bilayers that play a critical role for the transport of biological components including ions and molecules. Phase separated domains in cell membranes, known as liquid-ordered (Lo) domains (or lipid rafts), serve as an essential ingredient for regulating important biological events such as receptor-mediated signaling. Liquid-ordered (Lo) domains reconstituted in model membranes have provided a viable platform for in vitro studies of the lipid-raft model where signaling membrane molecules are thought to be compartmentalized in sphingolipid- and cholesterol-rich domains. As one of model membranes, a variety of supported membranes have been widely used for studying the phase-separation phenomena. In this work, for the purpose of prescribing the size and spatial distribution of the Lo domains, we first describe the dynamic formation of supported lipid membranes from small unilamellar vesicles on solid substrates with binary, nano-corrugated and nano-smooth topographies. We then show that the site-selective reconstitution of nanoscale Lo domains by predefining a landscape of energy barriers using topographic surface modifications. Our approach will open a new paradigm of tuning the kinetics of the lipid rafts to manipulate such biochemical processes that are mediated by them. In addition, the concept of cell patterning based on the membrane elasticity will be demonstrated to construct a machinary for studying a variety of cellular activities in bioarrays.

7618-22, Session 6

Printable sensor based on cholesteric liquid crystal for temperature and amine detection.

K. B. Pacheco, Technische Univ. Eindhoven (Netherlands); D. J. Broer, Philips Research Nederland B.V. (Netherlands); C. W. M. Bastiaansen, Technische Univ. Eindhoven (Netherlands)

Food freshness is an important area for consumers and always must be guaranteed. Here we describe a fast, inexpensive and printable material based on cholesteric liquid crystal with irreversible response to moderate temperatures and amine vapors that can be used as a strip to detect food freshness. The material is based on liquid crystal monomers and a chiral dopant molecule dissolved in a solvent. Exposition to these two external stimuli creates expansion and shortening of the helix as responses. We explored the effect of time at different temperature and amine vapors exposition at different concentration on the sample.

7618-24, Session 7

Novel cinnamic-acid-derived hydrogen-bonded mesogens with relatively wide blue phases

W. He, H. Yang, Univ. of Science and Technology Beijing (China)

Novel chiral hydrogen-bonded liquid crystal (H-bonded LC) complexes had been built from hydrogen bond self-assembly of an achiral nonmesogenic proton acceptor, 4-(4-propylcyclohexyl) phenyl isonicotinate (PPI), and a chiral nonmesogenic proton donor, (S)-4-(2-octanyloxy) cinnamic acid (SOCA). The induced blue phases (BP*s) was found in relatively wide temperature range and broad concentration region, the widest range of which is about 10.5 , which demonstrate that wide BP* range could be facilely obtained in the different H-bond self-assembly systems.

7618-25, Session 7

Liquid crystal and photoluminescent properties of gold(I)-alkanethiolates complexes and their transformation into gold nanomaterials

J. Lee, Seoul National Univ. (Korea, Republic of)

The gold(I)-alkanethiolates containing one type of alkyl group, Au(I)-SRs, and two types of alkyl groups, Au(I)-(SR)x(SR')ys, were synthesized by mixing HAuCl4 with the desired n-alkanethiols in tetrahydrofuran, respectively. From X-ray diffraction, FT-IR spectroscopy, and polarized optical microscopy studies, both of the Au(I)-SRs and Au(I)-(SR)x(SR')ys were found to be mesomorphic and have a highly ordered layer structure. Also, Au(I)-SRs and Au(I)-(SR)x(SR')ys emit a bright orange-red light visible to the naked eye upon irradiation with UV light, and the emission intensity increases with increasing length of the alkyl chain. We found that these gold(I)-alkanthiolates can be used as precursors for the gold nanoparticles. Upon heating the gold(I)-alkanethiolates, the conformation of the alkyl groups changed from the initial all-trans state at room temperature to the gauche containing disorder state along with the decrease of emission intensity, and then Au(I)-SRs changed to a mixture of di-n-alkyl disulfide, di-n-alkyl sulfide, and gold nanoparticles stabilized by the n-alkanethiolates. The gold nanoparticles stabilized by two types of alkanethiolates could be prepared by reducing the Au(I)-(SR)x(SR')ys using tetrabutylammonium borohydride (TBABH) as a reducing agent. Elemental analysis results of Au(I)-(SR)x(SR')ys and gold nanoparticles prepared from Au(I)-(SR)x(SR')ys indicated that that the longer alkanethiols are more reactive for the formation of Au(I)-(SR)x(SR')ys and also the longer alkylthiolate are preferentially absorbed on the gold particles compared with the shorter ones. The details of the liquid crystal and luminescent properties of gold(I)-alkanethiolates will be given in the meeting.

7618-26, Session 7

Plastic substrate technologies for flexible displays

T. Hanada, Teijin Ltd. (Japan)

The interests for future electronics devices have been significantly increased to create flexible displays, photovoltaics, batteries, and sensors by using plastic substrates. Such flexible electronics devices have a potential for realizing thin, lightweight, robust and rollable electronic products. The objective of this work is to improve properties of gas barrier and transparent conductivity that is especially important for the plastic substrate of flexible displays. A heat-resistant polycarbonate (PC) film for a base of the substrate was studied to reduce birefringence and thermal shrinkage. The retardation value is less than 1 nm at a wavelength of 550 nm (film thickness is 120 μm). Even at 180 , the

elastic modulus is 2 GPa and thermal shrinkage is less than 0.01%. The surface roughness of the PC film is less than 0.5 nm (measured by AFM). As a gas-barrier layer, silicon oxide (SiOx) was deposited by pulsed DC magnetron reactive sputtering method on the extra smooth surface of the PC film. In addition, a unique organic-inorganic hybrid material is coated on the SiOx to upgrade gas-barrier performance. Furthermore, Indium Zinc Oxide optimized for the plastic substrate was deposited on the other side of the SiOx film by the roll-to-roll pulsed DC magnetron sputtering method, and high total transmittance and the low resistivity had been achieved. These excellent properties are preserved even after the accelerated aging test (160 for 4 hrs, and 60 degree C and 90% R.H. for 1000 hrs.).

7618-27, Session 7

Regular undulation morphology observed in fracture and film surfaces of chiral Sc* polymer

J. Watanabe, C. Zhang, S. Edo, R. Ishige, M. Tokita, Tokyo Institute of Technology (Japan)

Chiral smectic C (SC*) liquid crystal (LC) is one of the most fantastic LC phases since it exhibits the ferroelectric response and forms the helical structure. Especially, the helical structure has been attracted from its characteristic optical properties, huge optical rotation and selective reflection of the circularly polarized light, which can be applied to optical materials. By these reasons, the chiral SC* phase has been extensively studied in the low-molecular-weight molecular system. The chiral SC* LC is also formed from the main-chain type of polymers with the mesogenic groups linked by the aliphatic spacer.In this polymer system, the mesogenic groups participate to form the smectic layer so that the polymers themselves form the helical conformation to conform to the helical LC field. This situation is completely different from that in the low-molecular-weight system where each molecule forms each layer. In this lecture, we report that the characteristic undulation morphology is observed on the fracture surface of the glassy SC* LC because of the helical association of polymer molecules. The peak to peak distance of undulation corresponds to the helical pitch of chiral SC* phase (150 ~ 600 nm depending on the chiral content in polymers) and the depth of the undulation is around 20-80 nm. A preferential cleavage along the helical polymer chain is considered to create such an undulation surface. Together with the easy preparation of wide-area monodomain, polymeric SC* phase provides the powerful way to fabricate the surface undulation which can be applied to the diffraction grating.

7618-28, Session 7

A continous flow synthesis of micrometer sized actuators from liquid crystalline elastomers

C. Ohm, Johannes Gutenberg Univ. Mainz (Germany); C. Serra, Lab. d'Ingénierie des Polymères pour les Hautes Technologies, CNRS (France); R. Zentel, Johannes Gutenberg Univ. Mainz (Germany)

The use of liquid crystalline elastomers for actuator applications has been reported for several years. When the mesogens in a crosslinked liquid crystalline polymer change their orientation during a phase transition from the LC phase into the isotropic phase, the polymer backbone has to follow this motion, which results in a deformation of the material. This makes these compounds interesting canditates for the production of actuators.

To realize strong shape changes, it is necesary to orient the mesogens into a liquid crystalline monodomain before the polymer is crosslinked. This orientation step is very crucial in the preparation of good LC based actuators. Until now, methods like the drawing of fibers or the streching of pre-crosslinked films have been used mainly, yielding macroscopically structured actuators.

Using microfluidics, we realized a continous flow synthesis of spherically shaped particles from a crosslinked liquid crystalline polymer. In this approach, a mixture of a liquid crystalline monomer [1] with crosslinker and UV-initiator are melted and injected through a very thin needle into a co-flowing stream of silicon oil. For this we used a very simple setup, self-build from needles and PTFE tubing [2]. The resulting droplets are then cooled into the liquid crystalline phase and exposed to UV light while still flowing. This initiates polymerization as well as crosslinking, producing solid particles which leave the reactor dispersed in oil.

The size of the particles can be controlled by several parameters, mainly the viscosity of the silicon oil and the flow rate ratio between oil and monomer. Thus we obtained particles with a diameter between 200 and 500 micrometers with a size variation coefficient as low as 1%.

Due to the parabolical flow velocity profile in the tubing, the mesogens in the monomer dropletts are preferentially oriented parallel to the flow direction when the polymerization takes place. This gives the particles characteristics of a liquid crystalline monodomain.

Upon heating them into the isotropic phase under a microscope the particles change their shape from a spherical to a rod like conformation. Thereby length changes of more then 70% can be observed. The actuation is completely reversible and very fast, which was shown by rapidly cooling particles in the streched conformation by a flow of cold air. We also show that the intensity of the shape change strongly depends on the flow rate at which the particles were polymerized. The same conformational change can be achieved by swelling the particles with a suitable solvent, which also induces a phase transition.

REFERENCES

(1) Donald L. Thomsen III, Patrick Keller, Jawad Naciri, Roger Pink, Hong Jeon, Devanand Shenoy, Banahalli R. Ratna, Macromolecules 2001, 34, 5868-5875.

(2) Michel Bouquey, Christophe Serra, Nicolas Berton, Laurent Prat, Georges Hadziioannou, Chemical Engineering Journal 2008, 135S, S93-S98.

7618-29, Session 8

Fast electro-optical Kerr effect of nano-structured liquid crystals

H. Kikuchi, Kyushu Univ. (Japan); Y. Haseba, Chisso Petrochemical Co. Ltd. (Japan); S. Choi, Kyung Hee University (Korea, Republic of); S. Yamamoto, Chisso Petrochemical Co. Ltd. (Japan); T. Iwata, NOF Corporations (Japan); H. Higuchi, Kyushu Univ. (Japan)

The Kerr effect is the phenomenon that the birefringence is induced in an optically isotropic substance in proportion to the square of the electric field. We prepared optically isotropic liquid crystals composed of chiral liquid crystals and nanostructured polymer networks, including the polymer-stabilized blue phases, and investigated the structural and physical parameters affecting the optical properties and the electro-optic response. We found that the cooperation effect of chirality of liquid crystal and polymer networks was possibly responsible for inducing an optically isotropic state in liquid crystalline composites in which nano-sized liquid crystal domains were uniformly embedded. It is also reveled that the elastic constant of the host liquid crystal and polymer structure are a dominant factor of the magnitude of Kerr constant in addition to the birefringence and dielectric anisotropy of the host liquid crystal. We successfully prepared the optically isotropic liquid crystalline material with extremely large Kerr constant and fast electro-optical response. We developed a novel strategy to control the polymer aggregation structure in the polymer-stabilized blue phase based on polymerization kinetics. The reactivity ratios of the monomers in the precursors clearly affected on the kinetics of cross-linking copolymerization and on the resulting polymer aggregation structures within the polymer-stabilized blue phase. A possible process of the construction of highly ordered nanostructured polymer networks in the polymer-stabilized blue phases is proposed. We present a new LCD mode by using optically isotropic liquid crystal composites, the polymer-stabilized blue phases and the polymer-induced isotropic phases, which show response time less than 1 ms and require no surface alignment.

7618-30, Session 8

Polymer-networked liquid crystal cell for omni-directional viewing angle switching

T. Yoon, J. Baek, K. Kim, J. Kim, Pusan National Univ. (Korea, Republic of)

We propose a viewing-angle switching method based on the control of the luminance at the off-axes. In the previously proposed methods, an additional panel or an additional backlight system is required to control the beam diverging angle (BDA), because the main liquid crystal (LC) panel plays the role as a polarization modulator for displaying images. On the other hand, we use the LC panel for not only displaying images but also controlling the BDA. By employing the scattering mode of the LC in addition to the retardation mode, we can realize a VAS mode through controlling the luminance at the off-axes without an additional panel or an additional backlight system.

In the proposed method, a collimated backlighting unit (BLU) with a small BDA is employed. Then, the wide viewing-angle (WVA) mode can be obtained by diffusing the backlight, for which randomly aligned LC cell is employed. On the other hand, the homogeneous-aligned LC modulates the polarization state of the backlight. Since a small BDA is maintained in passing through the LC layer, this can be used as a bright state for the narrow viewing-angle (NVA) mode. In both operating modes, the dark state can be obtained by aligning the LC vertically. To realize a device, a three-electrode structure is employed for both in-plane and vertical switching. For the initial bright state of the WVA mode, polymer networks are formed in the LC cell to scatter the light illuminated by the BLU. Detailed research results will be demonstrated.

7618-31, Session 8

Liquid crystal directed-polymer nanostructure for vertically aligned nematic devices

V. Borshch, L. Chien, Kent State Univ. (United States)

Dispersions containing polymers and liquid crystals have been recently studied intensively and have a broad range of applications. The dispersion systems containing 2-3% of the polymer are called polymer stabilized liquid crystals (PSLC). Such polymer networks in liquid crystals are normally used for display and many other applications.

The monomer gains the orientation of the host liquid crystal and polymerizes while the solution is kept in preferred alignment between two plates. The morphology of the polymer network defines the electrooptical performance of a cell. Here, the effect of various photopolymerization conditions on the morphology of liquid crystal/polymer composite systems has been studied. Composites were prepared by free-radical polymerization of a dilute solution of a monomer (2.99 wt % RM257) and a small amount (0.08 wt %) of photoinitiator Irgacure 651 in a liquid crystal solvent (ZLI-4788-000 from Merck) .

Polymer networks with different morphologies and different electrooptic properties were obtained by varying the irradiance of the UV light. The final morphology, ranging from a collection of neat spikes to random fibrillar network, was studied using scanning electron microscope (SEM). The network, primarily localized in the vicinity of only one of the cell surfaces, was created using 320 nm filter. Electrooptic studies were performed on all the morphologies obtained. Threshold voltage, response time, and scattering of composite sample cells are directly dependant on the polymerization conditions. The experimental investigation presented here demonstrates the feasibility of controlling polymer morphology and electrooptical properties of a liquid crystal cell.

7618-14, Session 9

Band-tunable color cone lasing emission based on a dye-doped cholesteric liquid crystal film

C. Lee, S. Lin, National Cheng Kung Univ. (Taiwan); H. Yeh, National Kaohsiung First Univ. of Science and Technology (Taiwan); T. Ji, J. Liu, P. Yang, National Cheng Kung Univ. (Taiwan); T. Mo, Kun Shan Univ. of Technology (Taiwan); S. Huang, Chung Shan Medical Univ. (Taiwan); C. Kuo, National Sun Yat-Sen Univ. (Taiwan); K. Y. Lo, National Chiayi Univ. (Taiwan); A. Y. Fuh, National Cheng Kung Univ. (Taiwan)

This study reports for the first time a novel phenomenon, called band-tunable color cone lasing emission (CCLE), based on a single-pitched one-dimensional photonic crystal-like dye-doped cholesteric liquid crystal (DDCLC) cell. The lasing wavelength in the CCLE pattern is distributed continuously at 676.7-595.6 nm as the oblique angle increases continuously from 0° to 50° relative to the helical axis. The variation of the lasing wavelength in the CCLE with the oblique angle is consistent with that of the wavelength at the long-wavelength edge (LWE) of the CLC reflection band (CLCRB) with the oblique angle. Simulation results obtained utilizing Berreman's 4 by 4 matrix method show that, at each oblique angle, the associated group velocity and DOS are near zero and large at the short-wavelength edge (SWE) and LWE of the CLCRB, respectively, and are in good agreement with experimental results. The inhomogeneous angular distributions of the relative intensity and, thus, the energy threshold of the CCLE can be attributed to the angular dependences of the loss of fluorescence from the multi-reflection process and fluorescence spectrum of the spontaneous emission of laser dyes at the LWE. The particularly strong lasing ring emission at a cone angle of ~35° can be explained to be likely due to a special effect that, under the condition of overlap between the LWE of the CLCRB measured at 35° and the SWE of the CLCRB measured at 0°, the LWE and SWE fluorescence propagating along 35° and 0°, respectively, may indirectly enhance each other due to individual enhanced rate of spontaneous emission. Furthermore, the lasing band of the CCLE can be tuned from long-wavelength (deep red~orange) to short-wavelength (orange~green) regions by changing the concentration of the chiral or by photo-irradiation. Therefore, this color cone laser has advantages of the output of the lasing band and its multi-tunability.

7618-32, Session 9

Guest-host liquid crystal devices

B. Taheri, AlphaMicron, Inc. (United States)

Guest-host liquid crystals are a broad class of materials wherein an optically active guest dopant is introduced in the liquid crystal host. The guest can be range from dichroic dyes, photoactive chromophores, fluorescent dopants and nano-sized materials. A new class of devices is now emerging based on various guest-host liquid crystal systems. In these devices, an optical characteristic of a guest is coupled with responsive nature of the oriented host to obtain a unique optical property. These new systems present an opportunity in applications where conventional polarizer based liquid crystal systems do not have the required performance. In this paper, we explore a few of these applications with focus on some of the work performed by AlphaMicron in the areas of guest host systems on plastic substrate films. We have recently discovered a class of materials that have a response opposite to that of azo-dye doped liquid crystal system. In particular, contrary to conventional azo doped liquid crystals, in these system, the chromophore enhances the orientation order of the host upon light excitation resulting in increased Tni and related properties. This system offers the potential for new science and application. We will present our findings and explore their use for polarized photochromic devices.

7618-33, Session 9

Bistable device using anchoring transition of nematic liquid crystals on perfluoropolymer surface

S. Dhara, Univ. of Hyderabad (India); J. K. Kim, F. Araoka, S. M. Jeong, R. Kogo, K. Ishikawa, H. Takezoe, Tokyo Institute of Technology (Japan)

We report a strong discontinuous orientational transition (anchoring transition) of liquid-crystal molecules with a large transverse dipole moment on perfluoropolymer surface. Using discontinuous anchoring transition in the sample, we demonstrate a novel bistable memory device writable by a laser beam. The device utilizes the hysteresis of a temperature-driven discontinuous anchoring transition orientation change in a dye-doped nematic liquid crystal. The laser light irradiation switches the stable orientation from homeotropic to planar in a liquid crystal on perfluoropolymer surface. The recorded images were kept at least for a day, i.e., memory effect. We also showed that the temperature range of the hysteresis can be brought down to room temperature using a binary mixture system.

7618-34, Session 9

Reflective display based on biphotonic effect-induced phase transition in dye-doped cholesteric liquid crystals

A. Y. Fuh, S. Huang, Y. Chen, H. Jau, M. Li, J. Liu, National Cheng Kung Univ. (Taiwan)

This work studies the biphotonic effect in samples that are cholesteric liquid crystals (CLCs) doped with azo-C5. The experimental results show that the photo-isomerization of azo-C5 not only changes the clearing point of the sample, but also shifts the reflection band that is associated with the planar texture. Additionally, azo dye-doped CLCs (DDCLCs) have bi-stable or tri-stable states, as determined by the ambient temperature. Photo-switching between these bi-stable/tri-stable states is systematically studied. The result indicates that photo-addressing one of these states (planar, focal conic, and isotropic states) using a low- or high-intensity Ar+ laser beam is feasible. The results thus obtained are used to fabricate a photo-rewritable DDCLC display.

7618-35, Session 10

Electrically switchable diffractive devices based on LC and polymer composites

J. Stumpe, O. V. Sakhno, Fraunhofer-Institut für Angewandte Polymerforschung (Germany)

A new type of electrically switchable diffractive devices was developed based on mixtures of liquid crystals and photo-curable monomers. The new composite material in combination with holographic patterning method results in volume phase gratings with high diffraction efficiency (up 99%) and excellent electro-optical parameters. The non-droplets grating morphology consisting of alternating almost pure polymeric- and aligned LC-areas are created due to photopolymerization and phase separation during the holographic exposure. Negligible light-scattering, strong anisotropy of the diffraction efficiency, low driving voltages (ca. 2-5 V/um), fast time-response (ca. 30-100 usec) and high switching contrast are achieved.

7618-36, Session 10

The dynamics of human sperm droplets on a liquid crystal and polymer composite film

F. Lu, Ton Yen General Hospital (Taiwan); Y. Lin, National Chiao Tung Univ. (Taiwan); W. Tsai, Ton Yen General Hospital (Taiwan); J. Li, T. Chu, National Chiao Tung Univ. (Taiwan); H. Hsu, W. Li, Chi-Mei Optoelectronics Corp. (Taiwan)

A switchable surface using a liquid crystal and polymer composite film (LCPCF) based on phase separation between liquid crystals (LC) and polymers after photopolymerization is developed recently. The wettability of LCPCF is electrically tunable because of the orientation of liquid crystal directors anchored among the polymer grains under an in-planed electric field. A water droplet on the top of LCPCF can be manipulated under an inhomogeneous electric field on the LCPCF owning to the wettability gradient. The dynamics of a droplet of human sperms on the LCPCF is demonstrated as well. Three motions of sperm droplets are observed: the droplet collapse, the droplet stretching, and the droplet movement. We found that the dynamics, concentrations, and activities of spermatozoa affect the motions of a sperm droplet. The potential applications of LCPCF are polarizer-free displays, liquid lenses, and the microfluidic device in assisted reproductive technology (ART).

7618-37, Session 10

Evaluations of liquid crystal panel as a random phase modulator for optical encryption systems based on the double random phase encoding

Y. Harada, S. Fukuyama, Kitami Institute of Technology (Japan)

Liquid crystal panels (LCPs) are widely used as a simple data projector, new media for displaying computer-generated hologram in real time, and amplitude- and phase-modulation device to realize optical tweezers. In these applications, the LCPs are used as a device to form desired- characterized-amplitude and phase distributions of laser light for each purpose. In the present paper, we consider a use of LCPs as a random phase modulator in the optical encryption system based on the double random phase coding [Optics Letters, Vol.20, 767(1995)] and evaluated its phase modulation property by computer simulations and experiments. It is found from simulation results that the required number of independent patches for phase modulations is greater than 128 x 128 pixels for LCPs with maximum phase modulation of 1.25¥pi. It is also found that the required maximum phase modulation can be reduced by increasing the number of independent patches. Experimental study using a commercially available LCP (EPSON, HTPS LCP, L3P14Y-55G00) verified these simulation results.

7618-38, Session 10

Electrical tuning of two-dimensional honeycomb photonic lattices using holographic polymer dispersed liquid crystalsuid crystals

R. Ohira, M. Miki, Y. Tomita, The Univ. of Electro-Communications (Japan)

We theoretically and experimentally investigate the spectral transmittance and wavelength dispersion properties of two-dimensional honeycomb photonic lattices using holographic polymer dispersed liquid crystals (HPDLCs) and demonstrate their electrical tuning. In our sample preparation monomers (Ebecryl 8301 and NOA65) and liquid crystals (TL203) were used, together with Rose Bengal, NVP and NPG, for obtaining the mixture in the single phase. The mixture was put into

an ITO-loaded glass cell of 10-micron spacing by capillary action. An optical setup for holographic three-beam interference was used to create honeycomb photonic lattices in an HPDLC film. We measured transmittance spectra and wavelength dispersion angles of transmitted beams without and with an applied electric field. It was found that the transmittance spectra had a strong dependence on the polarization state of an incident beam. In addition, a strong wavelength dispersion and peculiar (negative) refraction were observed. These non-0th order transmitted beams could be completely turned off by an application of an electric field. In our theoretical investigation we employed a statistical thermodynamic model to calculate the two-dimensional photo-polymerization dynamics of the single-phase mixture consisting of monomer and liquid crystal molecules under three-beam holographic exposure. By taking the effect of multiple reflections in the HPDLC film on the multi-beam interference into account, we could calculate spatial distributions of the formed polymer and liquid crystal molecules and the resultant anisotropic refractive index distribution having the honeycomb crystal structure. Using the calculated refractive index distribution, we performed photonic band calculations. It was found that measured transmittance spectra and wavelength dispersion angles were qualitatively in good agreement with the calculated results.

7618-39, Session 10

Ultrafast switching liquid crystals for next-generation transmissive and reflective displays

H. J. Coles, Univ. of Cambridge (United Kingdom)

We have recently synthesized and studied novel bimesogenic liquid crystals that have extremely large flexoelectric coefficients. Using these materials we have produced a variety of mixtures suitable for new photonic devices. In this paper we will discuss these materials and describe four main types of devices. Firstly we will describe devices using the so called uniform lying helix mode, that lead to in-plain switching, birefringence (or indeed guest-host) based displays with 100 microsecond switching times at low fields, i.e.2-5 V/micron, wide viewing angle and analogue or grey scale capability. Secondly we will describe devices using planar alignment and in-plane fields that have 20 microsecond switching times at similar field strengths, with optical contrasts in excess of 5000:1. The “off state” appears as perfect black irrespective of the alignment quality. This switchable phase device may be used both for telecommunications applications as well as birefringence based displays. Thirdly we will describe wide temperature range blue phase materials and their stabilization that lead to polarizer and color filter free fast switching “Bragg” diffractive devices and displays. The reflected color is varied as a function of the applied external electric field and wavelength range by the choice of materials. Switching times of a few milliseconds at fields of 10 volts / micron are readily achieved and in the reflective display (or indeed transmission display using polarisers) the colour gamut far exceeds that of current commercial displays. Finally we will show how these materials have been used to produce high efficiency, wide wavelength range tunable narrow linewidth liquid crystal laser reflectors with high reflection efficiencies suitable for use in hand-held displays. We will then compare and contrast the use of these four devices for next-generation displays both as hand-held devices and large area flat panel with a particular emphasis on next generation ie post 240 Hz frame rates displays.

7618-46, Session 10

High quality assembly of liquid crystal on silicon (LCoS) devices for phase only holography

Z. Zhang, A. M. Jeziorska-Chapman, N. Collings, M. Pivnenko, J. Moore, B. A. Crossland, D. P. Chu, Univ. of Cambridge (United Kingdom)

LCoS[1-4] for phase-only holography is ideally made to better optical tolerance than that for conventional amplitude modulating applications. This requirement translates largely to a tight tolerance of the uniformity of the thickness of the liquid crystal layer and therefore the uniformity of the cell gap.

Die-level assembly is suited to custom devices and pre-production prototypes because of its flexibility and efficiency in conserving the silicon backplane. The process flow is a composite, complicated multi-step procedure including glass and silicon substrate preparation, thin film deposition, mechanical and thermal treatments [5-6], and in particular optical inspection of the individual substrates before the assembly. This is because silicon and glass substrates often have quite different flatness profiles with deformation comparable with the optical wavelength in use, as illustrated in figure 1.

We select the best matching pairs of glass and silicon backplanes for optimized gap uniformity between these two surfaces. Finally, the cell is checked to ascertain the interferometric quality of the assembled device.

Combining die-level fabrication with automated assembly techniques allows high reproducibility and fast turnaround time, making a way for pre-production testing and customer sampling before mass production. Structures in figures 2 and 3 were two example devices which were assembled using a semi-automatic device bonder from SET as shown in figure 4.

The methodical approach developed for optimizing the overall LCoS cell construction process for phase related applications is next applied and further refined for larger, more complex LCoS devices.

Acknowledgement

We wish to acknowledge the Cambridge Integrated Knowledge Centre funded by EPSRC, ALPS Electric (UK) and Smart Equipment Technology for their support.

References

1. Neil Collings, W.A.Crossland, al. Evolutionary development of advanced liquid crystal spatial light modulators. Appl. Opt. Vol.28, No.22, (Nov 15th, 1989).

2. A. Georgiou, J. Christmas, J. Moore, A. Jeziorska-Chapman, A. Davey, N. Collings, and W.A. Crossland, “Liquid crystal over silicon device characteristics for holographic projection of high-definition television images”, Appl. Opt. Vol. 47, No.26 (Sep 10th, 2008).

3. William J Hossack, Eirini Theofanidou and Jason Crain, Kevin Heggarty and Martin Birch, “High-speed holographic optical tweezers using a ferroelectric liquid crystal microdisplay”, Optics Express, Vol.11, No.17 (Aug 25th, 2003).

4. WA Crossland, IG Manolis, MM Redmond, KL Tan, TD Wilkinson, MJ Holmes, “Holographic optical switching: the “Roses” demonstrator”, J. Lightwave Technol., 18,(12), pp.1845-1854.

5. Anupam Choubey, Frank Andros, Bahgat Sammakia, “Study of assembly processes for Liquid Crystal on Silicon (LCoS) microdisplays”, IEEE Transaction on Components and Packaging Technologies, Vol. 28, No.2, June 2005.

6. Peter T. Kazlas, Kristina M. Johnson, and Douglas J. McKnight, “Miniature liquid-crystal-on-silicon display assembly”, Optics Letter, Vol. 23, No.12 (June 15th, 1998).

7618-40, Poster Session

Smart windows with functions of reflective display and indoor temperature control

I. Lee, Y. Chao, C. Hsu, L. Chang, Taipei Municipal Lishan High School (Taiwan); T. Chiu, Yuan Ze University (Taiwan); J. Lee, National Taiwan Univ. of Science and Technology (Taiwan); F. Kao, National Yang-Ming Univ. (Taiwan); C. Lee, J. Lee, National Taiwan Univ. (Taiwan)

In this paper, a switchable window based on cholestreric liquid crystal (CLC) was demonstrated. Under different applied voltages, incoming light at visible and infrared wavelengths was modulated, respectively. A mixture of CLC with a nematic liquid crystal and a chiral dopant selectively reflected infrared light under zero bias, which effectively reduced the indoor temperature under sunlight illumination. At this time, transmission at visible range was kept at high and the windows looked transparent. With increasing the voltage to 15V, CLC changed to focal conic state and can be used as a reflective display, a privacy window, or a screen for projector. Under a high voltage (30V), homeotropic state was achieved. At this time, both infrared and visible light can transmit which acted as a normal window, which permitted infrared spectrum of winter sunlight to enter the room so as to reduce the heating requirement. Such a device can be used as a switchable window in smart buildings, green houses and windshields.

7618-41, Poster Session

Novel type of tunable infrared liquid crystalline filters

T. D. Ibragimov, Institute of Physics (Azerbaijan); G. M. Bayramov, Baku State Univ. (Azerbaijan)

In the present work the possibility using small particles-liquid crystal systems for operation of a position of transmission band maximum for infra-red radiation has been investigated.

Extinction spectra of the small aluminum oxide particles-MBBA system reveal the transmission band with a maximum of 1896 cm-1 at room temperature, which starts to shift to short-wave part of spectra at application of direct electric field more than 4 V to the system. Extinction spectra of the small aluminum oxide particles-the mixture 5CB-C2-H22 also show the transmission band with a maximum at one wavelength at application of alternative electric field of 1 kHz and another one at alternative electric field of 1000 kHz. The temperature dependences of transmission band position were studied in both systems.

The experimental results are explained by reorientation of LC molecules at application of electric field and passing of light through the system only at equality of effective refractive indices of particle and LC substances. Observed effects can be the base for creation of tunable infrared filters.

The work has been supported by Scientific and Technology Center in Ukraine (grant No 4172)

7618-43, Poster Session

Textured Zn2SiO4:Mn2+ phosphor film on quartz glass

J. B. Lee, J. H. Park, K. W. Park, Pukyong National Univ. (Korea, Republic of); K. I. Seo, Y. K. K. Kwon, MUJIN (Korea, Republic of); J. S. Kim, P. K. Shon, S. N. Lee, Pukyong National Univ. (Korea, Republic of)

Green-emissive textured Zn2SiO4:Mn2+ phosphor film was fabricated by a thermal diffusion of ZnO:Mn on quartz glass. The Zn2SiO4:Mn2+ phosphor films became transparent and textured along some hexagonal directions on the amorphous quartz glass. The inverse of decay time from Mn2+ showed the strong correlation with the degree of texture. The brightest Zn2SiO4:Mn2+ film showed the photoluminescence brightness of 65 % and the shortened decay time of 4.4 ms in comparison with a commercially Zn2SiO4: Mn2+ powder phosphor screen. Excellencies can be attributed to a unique textured structure and a continuous gradient of chemical composition at the interface.

7618-44, Poster Session

A metal-dielectric thin film with broadband absorption

S. Cho, J. Kang, M. Seo, J. Yang, S. Kang, Y. Lee, Korea Advanced Institute of Science and Technology (Korea, Republic of)

We propose and demonstrate a metal-dielectric thin film that delivers low reflection and high absorption over the entire visible spectrum. This thin black film consists of SiO2/Cr/SiO2/Al layers deposited on glass substrate. Measured reflectance and absorptance of the black film are 0.7% and 99.3%, respectively, when averaged over the range 380-780 nm. The total thickness of the black film is only about 220 nm.

This thin black film can be used as a thin absorbing layer for displays that require both broadband anti-reflection and high contrast characteristics.

7618-45, Poster Session

Multi-domain liquid crystal alignment based on periodical polyimide micro-bars fabricated by inkjet printing

J. Hwang, L. Chien, Kent State Univ. (United States)

We report a method for the preparation of multi-domain liquid crystal (LC) alignment layers on polyimide (PI) surfaces using inkjet printed micro-bars. The substrates of PI alignment films with micro-bars are assembled in crossed fashion to form a two-dimensional lattice to enable a fringe-field-like structure and thus, the multi-domain LC alignment. A LC cell with twisted nematic (TN) and electrically-controlled birefringence (ECB) domains can be obtained when the cells are assembled according to the printing directions of the printed PI layers. Electro-optical properties of such cells are studied. The obtained multi-domain structures can be used to improve the viewing angle of TN displays.

OPTO SPIE Photonics West

Conference 7619: Practical Holography XXIV: Materials and Applications

Sunday-Wednesday 24-27 January 2010 • Part of Proceedings of SPIE Vol. 7619

Practical Holography XXIV: Materials and Applications

7619-01, Session 1

Frameless hologram display module employing resolution redistribution optical system

Y. Takaki, Y. Tanemoto, Tokyo Univ. of Agriculture and Technology (Japan)

The resolution redistribution optical system that we proposed can increase the horizontal resolution and reduce the vertical resolution of a spatial light modulator (SLM). This system was applied for horizontal parallax only holography to increase the horizontal viewing zone angle.

In this study, a frameless hologram display module employing a modified resolution redistribution system is proposed. The frameless display modules can be aligned seamlessly so as to realize a large screen size. Because the previous resolution redistribution system uses a two-lens imaging system, i.e. a 4f imaging system, the screen size cannot be made larger than lenses. The frameless display module cannot be constructed using the previous optical system. In this study, the resolution redistribution system is constructed by the combination of a one-lens imaging system and a lens placed on the image plane. By making the magnification of the imaging system larger than unity, the screen size can be made larger than the imaging lens. A frameless hologram display module can be achieved using the new optical system.

The prototype module was constructed. A liquid-crystal SLM with a resolution of 1,980×1,080 and with a pixel pitch of 8.0 μm was used. Four optical fibers were used as point light sources which illuminate the SLM. The magnification of the imaging system was 2.88. The horizontal resolution was increased to 7,920 and the horizontal pixel pitch was reduced to 5.8 μm. The screen size of the module was 2.0 inches and the horizontal viewing zone angle was 6.3°.

7619-02, Session 1

Interactive holographic stereograms with accommodation cues

Q. Smithwick, J. Barabas, D. Smalley, V. M. Bove, Jr., MIT Media Lab. (United States)

Image-based holographic stereogram rendering methods for holographic video have the attractive properties of moderate computational cost and correct handling of occlusions and transparent objects. These methods are also subject to the criticism that (like other stereograms) they do not present accommodation cues consistent with vergence cues and thus do not make use of one of the significant potential advantages of holographic displays. We present an algorithm for horizontal-parallax-only (HPO) holographic stereograms with correct accommodation cues, allowing the viewer to focus at various depths. This creates correct vergence/accommodation linkage, visually controlled focal planes, and visually controlled centers of parallax. The algorithm is designed to take advantage of parallel and vector processing in off-the-shelf graphics processor chips using OpenGL with Cg vertex and fragment shaders. We introduce wavefront elements -- "wafels" -- as a progression of picture element "pixels," and directional element "direls." Wafel apertures produce variable wavefront curvatures in a variety of directions, providing accommodation cues in addition to disparity and parallax cues. We derive a virtual camera with an astigmatic frustum, allowing horizontal orthographic angular sampling of scene intensity, and correct vertical perspective from an array of wafel viewpoints. Based on simultaneously captured scene depth information, sets of directed variable wavefronts are created using nonlinear tangent chirps, which allow diffraction of the beam across multiple wafels for continuous angular sampling. We describe implementations of this algorithm on a single commodity graphics card (QuadroFX 5400) for interactive display on our Mark II and Mark III holographic video displays.

7619-03, Session 1

Holographic single-image velocimetry

L. Dixon, D. G. Grier, New York Univ. (United States)

We present a novel method for single-image velocimetry of micron scale spheres using holographic video microscopy. The hologram of a rapidly flowing particle exhibits characteristic blurring along the direction of motion. By measuring the variance in intensity of such a hologram as a function of angle, we find that its form is that of an ellipse whose eccentricity increases with velocity. Functionally, the velocity is proportional to the logarithm of 1-e. This was first measured in simulation, and confirmed in an experimental setting: quickly flowing 1 micron silica spheres across a microscopic objective. We show our method to be accurate for speeds which permit characterization of other properties of the sphere, such as radius and refractive index, and position in three dimensions. The result is that we gain a piece of information about the dynamics of a particle, without sacrificing any other measurements, from a single deinterlaced frame. We anticipate that this will significantly increase the rate at which we may gather statistics of particle motion in future experimental analyses.

7619-04, Session 1

Flow visualization and flow cytometry with holographic video microscopy

F. Cheong, D. G. Grier, New York Univ. (United States)

The video stream captured by an in-line holographic microscope can be analyzed on a frame-by-frame basis to track individual colloidal particles' three-dimensional motions with nanometer resolution, and simultaneously to measure their sizes and refractive indexes. Through a combination of hardware acceleration and software optimization, this analysis can be carried out in near real time with off-the-shelf instrumentation. An efficient particle identification algorithm automates initial position estimation with sufficient accuracy to enable unattended holographic tracking and characterization. This technique's resolution for particle size is fine enough to detect molecular-scale coatings on the surfaces of colloidal spheres, without requiring staining or fluorescent labeling. We demonstrate this approach to label-free holographic flow cytometry by detecting the binding of avidin to biotinylated polystyrene spheres.

7619-05, Session 1

Real-time color holography system for live scene using 4K2K video system

K. Yamamoto, T. Mishina, R. Oi, T. Senoh, T. Kurita, National Institute of Information and Communications Technology (Japan)

Holography is the technology to reconstruct 3-D objects perfectly. To realize ultra-realistic communications, we aim at creating a real-time color holography system that captures 3-D objects such as human beings under natural light and displays their reconstructed objects by electronic holography. We have already developed a system that uses 2K video system and presented it at SPIE Photonics West 2009. We will present the improved system in this talk.

Actually, the improved system consists of three blocks. The first block

is capture block that uses IP (Integral Photography) to capture colorful 3-D objects under natural light. It consists of a lens array with 236x132 lenses and a camera with 3840x2160 pixels. The second block is processing block that generates holograms rapidly by FFT (Fast Fourier Transform) with random phase adding in RGB planes. It consists of four high performance PCs (Personal Computers) to calculate holograms and one general PC to manage the four PCs. The final block is display block that displays holograms to reconstruct 3-D images. It consists of three LCDs (Liquid Crystal Display) that also have 3840x2160 pixels and lasers with some optical systems. We used half-zone-plate processing in the processing block and the single-sideband holography in the display block to show an observer object images without unnecessary images.

7619-06, Session 2

Single-shot digital holography applying spatial heterodyne method

Y. Iwayama, K. Maejima, K. Sato, Univ. of Hyogo (Japan)

The phase-shifting digital holography is widely used for recording objective wave front. However, it is difficult to apply this technology for recording a moving 3-D image. We need to develop single-shot digital holography for simultaneous recording of the complex-amplitude hologram. Recently, a method has been developed for extracting the approximated complex-amplitude hologram from an off-axis hologram by spatially sampling and interpolating the hologram.

In the present paper, a new technology of single-shot digital holography is developed for instantaneous recording of the complex-amplitude hologram applying the spatial heterodyne method. The correct complex-amplitude hologram can be directly extracted from the off-axis hologram for the reference light beam having general phase distribution. Numerical simulation and optical experiment are carried out to demonstrate single-shot recording of the complex-amplitude hologram using a reference light beam with usual phase distribution. Results show that fine images are reconstructed from the complex-amplitude hologram as a result of perfect elimination of the direct beam, the zero-order noise and the conjugate beam. The limitation of bandwidth in the single-shot digital holography is also discussed. The complex-amplitude hologram is correctly recorded when the bandwidth of object beam is smaller than a fourth of the Nyquist frequency. The bandwidth can be enlarged up to a half of the Nyquist frequency if the direct light beam is suppressed to a small value. The single-shot digital holography is applicable to the real-time recording of a 3-D image of moving objects or changeable phenomena.

7619-07, Session 2

Tolerance analysis in single-shot phase-shifting digital holography based on the spatial carrier interferometry

Y. Harada, A. Wan, Y. Sasaki, Kitami Institute of Technology (Japan)

Phase-shifting digital holography based on the spatial carrier interferometry makes available for snap-shot recording and reconstruction of three-dimensional objects in dynamic motion. Key point of the method is an introduction of tilt in the reference wave in recording a hologram so that relative phase difference of adjacent pixel of image sensors becomes 2¥pi/3 or ¥pi/2 for using well-know phase-shifting algorithm. This requires, however, rigorous alignment of incident angle of the reference wave in principle, and therefore, makes the method impractical. In the present paper tolerance range of the incident angle in the method is analyzed theoretically with regard to spectral bandwidth and variations of object waves. Preliminary experiments are also performed and its experimental results support the theoretical estimations in the range of tolerance incident angles of the reference wave in which the phase-shifting algorithms are available for calculating complex amplitude of the object wave.

7619-08, Session 2

Computer-generated holograms considering background reflection on various object shapes with reflectance distributions

K. Yamaguchi, Y. Sakamoto, Hokkaido Univ. (Japan)

Computer generated hologram (CGH) is a 3-D display technology that reconstructs natural 3-D objects. CGH generates hologram data by using computer simulations of optical diffraction, reflection, propagation, and interference. It satisfies the principle of holography, and it can produce 3-D reconstructed images as in optical holography and, reconstructs virtual objects generated by a computer.

However, a lot of problems have to be overcome in order to create 3-D displays based on CGH. In particular, the appearance of the reconstructed images poorer than that of holography is serious issue. Only a few studies have attempted to improve the appearance of the reconstructed images, and there has not been much research about an object's material affects its appearance. Thus, it has been difficult for CGH to reconstruct clear objects such as computer graphics.

In this paper, we propose a calculation method that takes into consideration the background reflection for CGH in order to improve the reality of reconstructed images. The background reflection is a characteristic of reflection on the metallic or mirror surface. Observers can see the environmental scene reflected off an object surface.
The proposed method calculates hologram data by considering the background reflection with various shapes and reflectance distributions on the object surface. Therefore, reflected images mapped on to it can be seen differently according to the shapes and reflectance distributions.

Reconstructed images with the background reflection were confirmed through optical reconstructed experiments.

7619-09, Session 2

Calculation of computer-generated hologram for 3D display using light-ray sampling plane

K. Wakunami, M. Yamaguchi, Tokyo Institute of Technology (Japan)

In this paper, we propose a new algorism for calculating computer-generated hologram (CGH) for 3D image display. The wavefront is calculated from light-ray information, that can be obtained by artificial computer graphics or image-based renderings using the data captured by a camera array. Thus the light-field data, integral imaging, or multi-viewpoint images can be utilized for CGH, and as well, it is possible to reproduce the angular reflection properties such as gloss or glitter, which is important for highly realistic 3D image but is difficult by conventional techniques based on the light propagation from point sources on the object surface. The method is similar to the CGH based on the principle of Holographic Stereogram (HS), but using HS-based CGH, the image far from the hologram plane is blurred due to the light-ray sampling and the diffraction at the hologram surface, so it is not suitable for the display of deep scene. Thus we propose the use of virtual "light-ray sampling (LS) plane" near by the object, and the wavefront at the LS plane is calculated from the light-rays. The wavefront propagation is then simulated based on Fresnel diffraction from the LS plane to the hologram. The hologram pattern is obtained from the complex amplitude distribution on the hologram plane. Even if the LS plane is distant from the hologram, the resolution of the reconstructed image is not degraded since the long-distance light propagation is calculated by diffraction theory.
In the experiment, we obtained high-resolution, deep 3D image with gloss appearance with using the image data generated by commercial rendering software.

7619-10, Session 3

Lens-less holographic microscope with high-resolving power

K. Sato, O. Murata, Univ. of Hyogo (Japan)

Digital holography has been applied to the various fields, and there is "the holographic microscope" in one of those. Holographic microscopes with lenses or microscope objectives have already been studied previously. But, these holographic microscopes lost the advantage of the holography of "3-D images with no distortion and with large depth can be recorded", because the object beam is recorded through the imaging lens.

A purpose of the present paper is to develop a lens-less holographic microscope with a high resolving power. A new technology is developed for recording and reconstruction of a microscopic high-resolution 3-D image. A wide off-axis hologram with a large viewing-zone angle is recorded with one CCD or with multi-CCDs by adopting a point-source reference light. Any imaging lens or any beam splitter is not located between the object and the CCD in our optical system to record the object light beam correctly. The in-line complex-amplitude hologram is extracted from the recorded off-axis hologram by applying the simple-shot digital holography which we have developed. The complex-amplitude hologram for the point-source reference light is transformed to one for the plane-wave reference light, and the high-resolution hologram is generated from the recorded wide hologram. A high-resolution image with a large depth is numerically reconstructed from the generated hologram at a short time by using the FFT. The resolving power of reconstructed image is improved up to the wave length as the viewing-zone angle becomes large.

7619-11, Session 3

Application of holographic interferometry to misalignment measurements in packaging applications

V. V. Nikulin, Z. Liu, Binghamton Univ. (United States)

Packaging of electronic and photonic components requires high accuracy, which has to be preserved not only in the process of manufacturing, but also in the process of operation. Therefore, products that are built using microelectronic components are subjected to extensive reliability testing. Shifts in alignment, both linear and rotational, could occur with time or simply because of the temperature variations and the associated expansion/contraction of the materials. Identifying where these problems occur and obtaining quantitative results with sub-micron accuracy could potentially be achieved by photometric measurements. Unfortunately, many conventional techniques are virtually useless when measurements are performed on diffuse objects, such as photonic packages. These limitations can be avoided using holography, which facilitates recording and reconstruction of the optical waves reflected from any surface. In the process of reconstruction it is possible to reproduce not only the amplitude of the reflected wave, but also its phase distribution, which carries information about the distance to each point illuminated with light. An optical technique developed by our group and presented in this paper is based on holographic interferometry. The main goal of the initial research was the proof-of-concept demonstration in the laboratory environment; however, to make this technique suitable for reliability testing, which provides vital information for modifications in the design or the packaging process, a number of outstanding issues are identified and potential solutions are presented.

7619-12, Session 3

Using photoconductivity for coherence domain imaging

X. Zhang, Univ. of Missouri, Columbia (United States) and Beijing Forestry Univ. (China); P. Yu, Univ. of Missouri, Columbia (United States)

We report a new method to detect coherent waves by using photoconductivity in semi-insulating semiconductors. The method is based on low coherence interferometry that uses a superluminescence diode as the light source. The interferograms are recorded by using a photorefractive multiple quantum wells (PRQW) device. When the signal and reference beams interfere in the PRQW, it forms a dynamic holographic grating. In a transverse geometry of the PRQW, photocarriers in the bright region move to the dark region. The space charge distribution causes changes of local electric field in the PRQW. It introduces the changes in absorption and index of refraction as well as photoconductivity. Conventional coherence domain imaging using PRQW is based on multi-wave mixing, such as two-wave mixing and four-wave mixing. Our innovation is to use the photoconductivity to detect coherent signals. We tested the concept by changing the optical delay and measuring the photocurrent. The change of the internal electric field causes the change of the photocurrent in the PRQW when the totally incident light density stays the same. We studied the photocurrent under various externally applied electric fields and incident light densities. The relative change of photocurrent is about 10 times higher than the relative change of two-wave mixing that has the highest diffraction efficiency in multi-wave mixing configurations. The changes of photocurrent are also proportional to the incident signal light density while the reference intensity is a constant. This method provides a potential solution of coherent detection for biomedical optical imaging applications.

7619-13, Session 3

Application of holographic optical elements in active interferometers for nondestructive testing

J. Kornis, R. Séfel, Budapest Univ. of Technology and Economics (Hungary)

The recent successes in the automatization of various optical measuring methods can postulate creation of new knowledge based systems. These active interferometers can continuously adapt themselves to the change of measuring conditions and environment even in industrial circumstances. Active interferometers, realized in speckle metrology and digital holography are presented in the article.

The measuring system can eliminate variable reflection or external disturbances e.g. unwanted vibrations. Using optoelectronic feedback loop any of chosen phase difference between the interfering beams in phase stepping interferometer can be stabilized. Active interferometers have also been developed for phase shifting interferometry in speckle metrology.

One of the main tasks was to develop methods to automatically select the sensitivity of the measurement. For this purpose the wave fronts of the interferometer are formed by different holographic optical elements. Using this technique the fringe density at highly deformed points can be decreased or different components of the complicated fringe pattern can be removed which results in increase of the sensitivity and leads to easier evaluation of the fringe pattern.

Selected applications in speckle metrology and digital holography are shown demonstrating applications of computer generated and classical types of HOE-s. Also the accuracy of the wavefront generation of the spatial light modulators is analyzed.

7619-14, Session 3

Optically compensating for degraded reconstructed images in phase-conjugate holographic data storage

T. Muroi, N. Kinoshita, N. Ishii, K. Kamijo, N. Shimidzu, NHK Science & Technology Research Labs. (Japan)

Holographic data storage has the potential to attain a large capacity and a high data-transfer-rate. An optical phase conjugation configuration can compensate for lens aberrations in the path of the signal beam, and it can also prevent deterioration of the reconstructed image. Even with this configuration, however, non-flatness of a medium surface easily affects the reconstructed image quality. In addition, the photopolymer material used in a medium shrinks due to photopolymerization, which results in hologram distortion and, consequently, degrades the reconstructed image quality. To improve the image quality, we used adaptive optics (AO) to optically compensate for both hologram distortion and non-flatness of a medium surface. In our form of AO, the wavefront of the reference beam as input is controlled by using a deformable mirror in the path of the reference beam for reproducing, and the reconstructed beam as output is captured with a charge coupled device. We used a genetic algorithm to optimize the wavefront; the evaluation coefficient in the algorithm was defined by the mean value and the variation of brightness in the reconstructed image. Testing showed that hologram distortion and non-flatness of a medium surface could be optically compensated for and the reconstructed image quality thus improved. The bit-error rates in the reproduced data decreased from 4.5 x 10-3 without compensation to 6.2 x 10-4 with compensation. This decrease is effective in reducing the error correction processing time. Our form of AO can be used to effectively compensate for non-flatness of a medium surface and hologram distortion in phase-conjugate holographic data storage.

7619-16, Session 3

Zonal wavefront sensing with improved dynamic range and resolution using a liquid crystal spatial light modulator

B. R. Boruah, Indian Institute of Technology Guwahati (India)

Zonal wavefront sensors of the Shack-Hartmann type have dynamic range and spatial resolution which are determined by the size of each micro lens and the total number of micros lenses. Increase in the spatial resolution requires reduction in the aperture size of each micro lens which effects the dynamic range. This paper proposes a zonal wavefront sensing scheme that can provide improved performance in regards to both the spatial resolution and the dynamic range. The scheme is implemented using a liquid crystal spatial light modulator (LCSLM) in lieu of the micro lens array and a CCD camera. A spatially coherent beam whose wavefront is to be estimated is incident on the LCSLM panel. The LCSLM panel is divided into a rectangular array of sub-apertures and a plane diffraction grating is written onto each of such sub-apertures. A lens following the LCSLM focuses the diffraction orders onto the CCD camera. By having an appropriate grating element and orientation of each of the gratings the diffraction orders of a particular order can be arranged on the CCD panel as a regular pattern of focal spots. The displacements of these focal spots for the test beam relative to an ideal beam give a measure of the local slopes required for the estimation of the test wavefront. Programmability of the grating elements and their orientations in the LCSLM panel facilitates improvement in both the dynamic range and spatial resolution. The paper will also present results obtained from an experimental implementation of the wavefront sensing scheme.

7619-17, Session 4

Reaction-diffusion model applied to high-resolution Bayfol-HX® photopolymer

F. K. Bruder, F. O. Deuber, T. Fäcke, R. Hagen, D. Hönel, Bayer MaterialScience AG (Germany); D. Jurbergs, Bayer MaterialScience LLC (United States); T. Rölle, M. S. Weiser, Bayer MaterialScience AG (Germany)

We have been developing a new class of recording materials for volume holography, offering the advantages for full color recording and depth tuning without any chemical or thermal processing, combined with low shrinkage and detuning. These photopolymers are based on the two chemistry concept in which the writing chemistry is dissolved in a preformed polymeric network. This network gives the necessary mechanical stability to the material prior to recording. In this paper we show that the recording process in these materials can be successfully described within a reaction diffusion model. For the first time the combination of plane-wave recording data in transmission and reflection geometry was used to extract the model parameters. This was achieved via a master curve construction of the respective power density response functions of the photopolymer at saturation recording conditions. Within that model, power density response, spatial frequency response, non locality effects, beam ratio effects and even dosage response can be predicted and explained for a wide range of CW recording conditions which are important for various holographic applications of these new materials.

7619-18, Session 4

Fabrication of HOEs with enhanced characteristics

C. G. Stojanoff, Holotec GmbH (Germany)

Abstract

the subject matter of this paper is to present the results of several studies relating to the properties of holographic materials and to illustrate the developed procedures to enhance their performance. The desired optical properties of the holographic material are determined by the engineering problem at hand. There are several procedures that facilitated the achievement of the specific objectives, such as controlling the spectral characteristics of the HOE by inorganic and/or organic additives and filler material to enhance the UV or IR performance. Externally induced stress in a hologram by applied mechanical strain changes the performance characteristics of the HOE and is used in engineering applications. The optical characteristics of the HOE are also modified by internally induced stress, such as changing the water content of the polymer or by infusion of filler material and the generation of thermal gradients in the film during the coating of the holographic film or the hologram development. The method of conformational modification is used during the coating and the drying of gelatin films to set the relationship between coiled and helical structures that determine the mechanical properties of the gelatin matrix.

Film manufacturing information and properties will be given for:

Carboxylated PVA enhanced with metallic salt additives;

Dichromated gelatin with inorganic and/or organic additives;

Fine-grain silver halide panchromatic film, developed in the EU Silver Cross Project.

Multiple exposures technique is used to record up to four holograms in the same DCG film that are used to generate simultaneously several monochrome or RGB beams.

7619-19, Session 4

Holographic recording without a separate reference wave

M. Ozcan, M. Bayraktar, Sabanci Univ. (Turkey)

Here we describe a new holographic recording method in which a separate reference wave is not required. Object wave is split into two beams and one of them is spatially filtered to create a plane reference wave.

More specifically, part of the object wave is focused to a single mode optical fiber (at the operating wavelength of 632.8 nm) and the wave at the exit end of the fiber behave approximately like a point source. A positive lens converts this point source to a plane wave where it is used to interfere with the original object wave for holographic recording.

This methods allows use of low coherence light sources since path lengths of the interfering waves are matched automatically which will lead to holographic recording of objects at any distance rather easily. Optical setup will be discussed and the experimental results will be presented.

7619-21, Session 4

A fast analytical algorithm for generating CGH of 3D scene

Y. Liu, J. Dong, Y. Pu, B. Chen, H. He, Z. Deng, H. Wang, Sun Yat-sen Univ. (China)

A novel method for fast generating hologram of three-dimensional (3D) textured triangle -mesh-model is presented. This 3D model can be obtained from true-life scene or 3D design software. Our method provides a capability to analytically describe the diffraction field of the 3D model consisting of triangles. In contrast to other polygon based holographic algorithms, our full analytical method will avoid using the numerical algorithm- Fast Fourier Transform, which leads to a depth-of-field limitation by the Whittaker-Shannon sampling theorem. In order to further decrease the computation time, we employ the GPU platform that is remarkably superior to the CPU's. We found the GPU's parallel algorithm performs hundreds of times faster than those of CPU. We have rendered a true-life scene with colored textures as the first demo by our homemade software. The holographic reconstructed scene possesses high performances in many aspects such as depth cues, surface textures, shadings, and occlusions, etc.

7619-41, Session 4

Refreshable holographic 3D display using photorefractive polymer: progresses and prospectives

P. Blanche, R. Voorakaranam, C. Christenson, College of Optical Sciences, The Univ. of Arizona (United States); A. Bablumian, TIPD LLC (United States); J. Thomas, College of Optical Sciences, The Univ. of Arizona (United States); M. Yamamoto, Nitto Denko Technical Corp. (United States); R. A. Norwood, N. Peyghambarian, College of Optical Sciences, The Univ. of Arizona (United States)

The very first demonstration of our refreshable holographic display was published in Nature (S. Tay et al., "An updateable holographic 3D display", Nature 451, pp 694-698 (2008)). Based on the unique properties of a new organic photorefractive material and the holographic stereography technique, this display addresses a gap between large static holograms printed in permanent media (photopolymers) and small real time holographic systems like the MIT holovideo. Applications range from medical imaging to refreshable maps or advertisement. In this talk, we will discuss several technical solutions for improving the performance parameters of the initial display from an optical point of view. We will detail how the unique properties of the photorefractive material can be used to generate full color holograms, how to reduce the recording time form minutes to seconds and present the roadmap to having hundreds of cm^2 of recording surface area instead of ten cm^2.

7619-42, Session 4

Blends of azobenzene-containing polymers and molecular glasses as stable rewritable holographic storage materials

R. Walker, H. Audorff, L. Kador, H. Schmidt, Univ. Bayreuth (Germany)

In recent years the developments in computer technology have drastically accelerated. In order to handle the ever growing amount of data to be stored, an increase in the storage capacities of mass storage media is necessary. A promising approach is holography, where the storage capacity is greatly increased by using the entire volume instead of only the surface of the medium.

Writeonce media, which are mainly based on photopolymer systems, seem to be fairly advanced. For a rewriteable media, only few systems can meet the strict requirements for holographic data storage materials. Photoaddressable azobenzene-based polymer systems are the most promising candidates, however the photo-physical sensitivity of these materials has to be further increased.

Low molecular-weight organic glasses with azobenzene moieties can also be used for reversible inscription of holographic volume gratings. They exhibit a faster response time than a comparable photoaddressable polymer due to a lack of chain entanglements. A new series of these photochromic molecular glasses is investigated as blending materials to improve the photochromic response of photoaddressable polymers. In order to identify potential candidates for blending, a variety of molecular glasses are synthesized and screened with respect to their photo-physical response. The best combination of structural variations is chosen to tailor a photoaddressable material with optimized physical and photo-physical properties. By doping these photochromic molecular glasses into photoaddressable polymers we are able to combine the high stability of polymer systems with the fast response of molecular glasses, thus creating a system which has the advantages of both material classes.

This work was supported by the German Science Foundation in the framework of SFB 481 (projects B2 and Z4).

7619-43, Session 4

New thermoplastic-based photosensitive materials for holographic applications

M. Cheverton, S. Jain, M. Sinha, M. Takemori, A. Burns, J. Maxam, GE Global Research (United States); S. Chakravarti, M. Davis, C. Hein, B. Kiekens, M. Laurin, L. Markestein, M. Niemeyer, B. Patel, S. Tanizaki, M. Tjahjadi, J. Zhou, SABIC Innovative Plastics (United States); G. Kuriakose, S. Naik, P. Nadkarni, K. Puthamane, V. Vasudevan, GE John F. Welch Technology Ctr. (India)

GE Global Research and SABIC Innovative Plastics are developing new thermoplastic-based volume holographic materials for security, authenticity and aesthetic applications. The basic technology being leveraged is the ability to create a refractive index change in the volume of the material using photosensitive materials. These photosensitive materials undergo a chemical transformation under exposure to light and create a refractive index change that extends over a wide range of wavelengths, conforming to the Kramers-Kronig relationship. Early efforts are focused on developing these materials so that they can be processed using conventional processing techniques such as film extrusion and

Return to Contents

injection molding into thin films and thick parts, respectively.

Recently, significant progress has been made in developing novel optical techniques to record a variety of holographic features into these materials. The team has demonstrated animated holograms, multi-color holograms, true-color holograms, and ambient light viewable holograms in the new class of volume holographic materials. Current materials are sensitive to 532 nm and 405 nm wavelengths. Diffraction efficiencies in excess of 70% and sensitivities greater than 800 cm/J have been have been demonstrated in injection molded samples.

7619-22, Poster Session

Mobile phone color holography

S. J. Zacharovas, A. Nikolskij, E. A. Kuchin, Geola Digital uab (Lithuania)

Geola's digital holographic printer uses series of digital photographs taken from different angles to calculate an interference pattern for its future projection by printer's Spatial Light Modulator. Since our i-Lumograms are digital holograms created from sequence of images, it is possible to use conventional mobile phone as a source for such image sequence. Movie taken by modern mobile phone is an acceptable source or I-Lumograms in size of up to 30x40cm.

7619-23, Poster Session

Floating image display with high-resolution computer-generated hologram

T. Yamaguchi, T. Fujii, H. Yoshikawa, Nihon Univ. (Japan)

In this paper, we have investigated the floating image display with the computer-generated hologram (CGH). As the 3D display, the floating 3D image display gives strong dimensional impression to the viewer. However, there are few reports about the floating image display with the CGH. Since the required spatial frequency to the display is very high compared with the rear image display, it is difficult to output the CGH which display the floating image. Even if the CGH is output by the inadequate device, the viewing area and the image size of the CGH is not enough. Therefore, to reduce the required spatial frequency for the fringe pattern of the CGH, the position of the object is placed at the behind of the hologram plane. Also, the huge calculation amount of the fringe pattern is big problem.

In our resent work, since we developed our output device (named fringe printer) for the fringe pattern, the pixel pitch of the printed fringe pattern develops from 0.87 m to 0.44 m. By using the fringe printer, we have achieved over 40 Gpixel hologram. Therefore, we research to make the floating image display with the fringe printer. To realize the wider and bigger image display, the image is reconstructed by the conjugate of the original reference wave to reproduce the real image. Also, to solve the huge calculation amount, we employ the GPU to make parallel calculation and calculation faster.

7619-24, Poster Session

Superresolution digital holographic microscopy using multipoint light sources illumination

A. Phan, N. Kim, J. Park, Chungbuk National Univ. (Korea, Republic of); S. Jeon, Univ. of Incheon (Korea, Republic of)

Digital holography has many advantages in comparison with the conventional hologram. Digital holographic microscopy is an interesting application of the digital holography. 3D structure of the microscopy specimen can be captured and reconstructed by a digital holographic microscopy. One problem is the resolution limitation of the reconstruction. The size and the resolution of the captured holography are limited by the CCD, which finally restricts the reconstruction resolution. In order to increase the resolution of hologram, several synthesis methods have been proposed. Some method moves the CCD camera position, and some uses a complex system of mirror or grating to create a tilted beam illumination to capture more information of specimen. However, these previous methods require mechanical motion or complex system configurations.

In this paper, we present a simple way to capture more information of the object by using multi-point light sources which are created by a lens array. The use of the lens array makes the overall system simple and compact. First of all, the polarizing beam splitter (PBS) splits the coherent beam from the 532nm laser source to two beams, one is reference beam and the other is object beam. The object beam is then expanded and passes through a lens array to create the multi-point light sources. We use a movable aperture to select a point source that illuminates the specimen. By moving the aperture, the specimen is illuminated from many directions. The specimen is magnified by an objective lens. After objective lens, the other beam splitter (BS) is used to combine the reference beam and object beam. In reference beam part, we use a phase-shifting system to control the phase of the reference beam. The multiple holograms are captured by a CCD camera sequentially with different point light source, synthesized together, and then reconstructed by computer using phase-shifting method. By proposed method, we can increase the resolution by 9 times (3x3) in comparison with the resolution of the CCD camera.

7619-26, Poster Session

The electromagnetic wave diffraction on a dielectric multilayer coated Fourier grating in conical mounting

M. Ohki, K. Sato, Shonan Institute of Technology (Japan); S. Kozaki, Gunma Univ. (Japan)

We analyze the electromagnetic wave scattering problem for multilayer coated Fourier grating for a general angle of incidence and arbitrary polarization. This analysis is treated in quasi two dimensional problems with the scalar wave function where the incident wave vector is not perpendicular to the ruling direction of the gratings. The analytically procedure is applied to T-matrix method with R-matrix propagation algorithm. This formulation can be expressed in the closed form because R-matrix propagation is used avoiding a singularity in matrix elements for the evanescent mode. Numerical examples are also presented for diffraction efficiencies versus incident and azimuthal angle.

7619-27, Poster Session

Image enhancement in phase-shifting digital holographic microscopy using spiral-phase filter

M. Piao, N. Kim, J. Park, Chungbuk National Univ. (Korea, Republic of); S. Gil, Univ. of Suwon (Korea, Republic of)

Phase shifting algorithm in digital holographic microscopy provides many benefits. The algorithm offers the elimination of zero-order intensity and a twin image as well as the compensation of aberrations of the object wavefront versus the reference wave. However, the visualization of the reconstructed phase object or cell is not sharp and clear. In order to reconstruct the phase object or cell unambiguously in microscopy applications, we apply a spiral phase filter to phase shifting digital holographic microscopy system. The spiral phase manipulates the phase of the whole light field in the Fourier plane in the form of a spiral shape, and then height profile of the phase object can be distinguished immediately by the sense of the spiral fringes. Even though spiral phase has been already applied to optical microscopy, the observed image was restricted to two-dimension. Here, in our system, by the combination with holographic technique, we reconstruct the three-dimensional information

with enhanced quality.

In this paper, we demonstrate the application of the spiral phase filter for image enhancement in phase shifting digital holographic microscopy system. The method is based on Fourier plane filtering of the microscopic image with a spiral phase filter which is loaded at a computer controlled Spatial Light Modulator (SLM) in the optical imaging pathway of phase shift digital holographic microscopy system. The image carrying light wave is convolved with the spiral phase filter located in a Fourier plane, producing phase edges of an image. As a result, the reconstruction of phase object or cell is clear and sharp.

7619-28, Poster Session

Evolution of diffraction efficiency of holograms with monosaccharides

N. Y. Mejias-Brizuela, A. Olivares Pérez, Instituto Nacional de Astrofísica, Óptica y Electrónica (Mexico); A. Grande Grande, Instituto Tecnológico Superior de Atlixco (Mexico); I. Fuentes Tapia, Instituto Nacional de Astrofísica, Óptica y Electrónica (Mexico)

We present the behavior in the time of the diffraction efficiency of holographic gratings, it was recorded in two monosaccharides, glucose and fructose, and both were sensitized whit potassium dichromate and blue dye. There monosaccharides present a diffraction efficiency with a maximum of 7% approximately. After 24 hours the parameter of diffraction efficiency decays.

7619-29, Poster Session

Study of pH effect and aging of coating emulsions for hologram recording

R. C. Fontanilla-Urdaneta, A. Olivares-Pérez, I. Fuentes-Tapia, Instituto Nacional de Astrofísica, Óptica y Electrónica (Mexico)

The study was carried out during real time holographic gratings formation when the coating emulsions age as a function from the time. The experiments are studied by influence of hologram parameters to get the diffraction efficiency at room conditions through changes of electrical potential application and pH dependence on coating emulsions for hologram recording process.

7619-30, Poster Session

High-speed white-LED-light optical transmission for computer-generated hologram

K. Sato, Shonan Institute of Technology (Japan)

Transmission of hologram is very important to realizing the holographic 3D TV.

Transmission of Computer Generated Hologram(CGH) data using SSTV wire-less method is tried before and one frame with 76.8k bit data is transmitted by 2kbbs is reported.

In this research we consider to more high speed transmission and more high resolution hologram data transmission using white LED light.

We can get high contrast reconstructed 3D image after the transmission with white LED light.

7619-31, Poster Session

Experimental study on the influence of wavefront aberration for holographic data storage

N. Yoshida, Tokyo Univ. of Science (Japan)

The holographic data storage (HDS) is expected as a next generation's mass optical storage system. Recently HDS is studied as a high-speed and large capacity archival memory from the demand of the energy saving at the large-scale data center. These systems are planned to replace the hard disk drives.

In HDS, the wavefront aberration of the optical system causes the deterioration of the quality of the reconstructed signal. It is a very important subject to obtain the reliability and the interchangeability of the media or drive systems. In this paper, first, the influence of the aberration of the optical system on signal quality is studied by experiment. Especially an influence of 3rd-order astigmatism, coma, and spherical aberration on each point spread function of the two-dimensional digital bit pattern is examined. Second, the experimental results are compared with the simulation results. From the view points of tolerance analysis, the permitted range of the wavefront aberration is discussed.

Next, two-dimensional signal processing was studied to improve the signal quality. Two-dimensional FIR filter was applied to the reconstructed signal. The coefficient of FIR filter was optimized by the real-coded genetic algorithm. In our paper, these experiment and simulation results are discussed.

7619-32, Poster Session

Simulation study on the influence of wavefront aberration for holographic memory

Y. Ohuchi, Tokyo Univ. of Science (Japan)

The memory density of the optical disks is limited by the diameter of the focusing beam on the media which is determined by the wavelength of the laser used and the NA (number of apertures) of the focusing lens. To improve memory density, the research and development of a new breakthrough technology is deeded, which is based on a principle that is different from the conventional memory principle. In this environment, the holographic data storage (HDS) , which can expand the 2D memory space of the conventional optical disk into 3D memory space, seems to present a potential for realizing high capacity memory technology of the future. One of the characteristics of hologram memory is that it can create 2D reproduction image. This makes the data reproduction speed faster than the conventional optical disk systems. In HDS, the wavefront aberration causes the deterioraion of the signal quality. The analysis of the wavefront aberration is necessary to improve the reliability and the interchangeability of the hologram memory technology. Since different optical systems have been adopted in various types of recording methods in holographic memory, an assessment technique specific to each system is needed. In this paper, we report the results of simulations where wavefront aberrations were generated in the reference beam and signal beam that were different to those during recording, particularly with respect to off-axis recording/reproduction systems, and show the influence on signal quality.

7619-33, Poster Session

Pre-calculated object light-based fast calculation method for computer-generated hologram

H. Sakata, Y. Sakamoto, Hokkaido Univ. (Japan)

A computer generated hologram is an ideal display system which shows three-dimensional objects, however computation times for calculating

holograms are very enormous.

The fast calculation methods based on the Fast Fourier Transform using a patch model are proposed, but it requires two two-dimensional Fast Fourier Transforms per patch. Therefore, calculating a object light from a complex object including many patches takes much calculation time.

We have proposed a fast calculation method using the three-dimensional affine transformation in real space (i.e. does not require the Fast Fourier Transform per patch). This method performs twice as fast as a method using the Fast Fourier Transform. Fast calculation of this method is achieved by calculating object lights of variously-shaped patches from a pre-calculated object light of a fixed-shape patch. However, it is difficult to calculate the object light from complex object including large-angle tilted patches by using this method.

In this paper, we propose the three-dimensional affine transformation for a cylindrical pre-calculated object light. This allows for calculating object lights from complex objects including large-angle tilted patches by only one cylindrical pre-calculated object light at high speed. In addition, we show the effectiveness of our transformations and the computation time.

7619-34, Poster Session

Fresnel hologram generation by using HD resolution depth video camera

R. Oi, K. Yamamoto, T. Senoh, T. Mishina, T. Kurita, National Institute of Information and Communications Technology (Japan)

Holography is considered as an ideal 3D display method. However, conventional hologram must be developed in a dark room and under laser irradiation.

We attempted hologram generation under white light by adopting depth maps of real scenes. The infrared depth camera, which we used, captures the depth information as well as color video of the scene in 20mm of accuracy at 2m of object distance. The camera can be used for the moving objects.

In this research, we developed a software converter to convert the HD (1920 × 1080 pixels) resolution depth map to the Fresnel hologram by using linier interpolations.

In this conversion method, each elemental diffraction pattern on a hologram plane was calculated beforehand according to the object distance and the maximum diffraction angle determined by the reconstruction SLM device (6.8µm LCOS).

Transmission beam and conjugate beam are eliminated by sacrificing half of the vertical resolution of hologram.

For hologram size (SLM size) is smaller than the captured scenes in the experiment, we set the longitude magnification to the same ratio to the lateral magnification.

We observed the reconstructed 3D image of the scene. The image distortion caused by the depth errors will also be discussed.

7619-36, Poster Session

An electro holography using reflective LCD for enlarging visual field and viewing zone with the Fourier transform optical system in CGH

A. Katou, Y. Sakamoto, Hokkaido Univ. (Japan)

An electro holography outputting CGH (Computer Generated Hologram) data into the reflective LCDs is expected as 3-D movie display technology for realizing a Hologram-TV in the future. However, the resolutions of current LCDs are not high for practical use. This causes that narrow visual field and viewing zone, and conjugate images, ghost images, 0th-order light prevent as viewing.

In order to improve these problems, we have studied the Fourier transform optical system using a reflective LCD and a lens. The system is a simple and compact Hologram display. As reconstructing light spreads by a lens, we can see reconstructed images in-the-air nearly. Additionally, a barrier set in focus removes conjugate image and 0-th order light physically.

Moreover, we propose a method for enlarging visual field and viewing zone by changing distance reconstructing light source. When distance of light source keeps away from the lens, reconstructed image becomes small and is imaged at closer to the hologram comparing original position (enlarging viewing zone). Meanwhile, when light source approaches to the lens, reconstructed images are imaged far from the lens and become large (enlarging visual field). However, the shapes of 3-D images are distorted because each object-point magnification is different in depth. We have solved the problem by correcting CGH data according to the depth of the object point, when object light is calculated. The method produces 3D images with various sizes at various positions without any rearrangement of the optical system. We confirmed effectiveness of our method in the optical experiments.

7619-37, Poster Session

Efficient CGH generation of three-dimensional objects using line-redundancy and novel-look-up table method

S. Kim, W. Choe, E. Kim, Kwangwoon Univ. (Korea, Republic of)

In general, adjacent pixels of a 3-D image have very similar values of intensity and depth and some of them even have the exactly same values of them each other. In other words, a 3-D image has a spatial redundancy in intensity and depth data. This spatial redundancy can be represented with the run-length encoding method, which has been used for data reduction of the conventional 2-D images. Also, when these redundancies are expanded by line scale, the values of the line have similar value of the previous line.

Recently, N-LUT method to dramatically reduce the number of pre-calculated interference patterns required for generation of digital holograms was proposed. In this method, the fringe patterns for other object points on each image plane can be obtained by simply shifting this pre-calculated PFP according to the displaced location values from the center to those points and adding them together. Accordingly, CGH pattern for arbitrary line is shifted with amount of discretization step for the direction of next line, same images for arbitrary line are generated in the next line. And then differences between two lines are occurred, these differences are compensated in CGH pattern using the N-LUT method.

Accordingly, in this paper, a new approach for fast computation of CGH patterns for the 3-D image by taking into account of the line-redundancy between lines of the 3-D image is proposed. Some experiments with a test 3-D object are carried out and the results are compared to those of the conventional methods.

7619-38, Poster Session

Efficient generation of 3D hologram for American Sign Language using look-up table

S. Kim, J. Park, E. Kim, Kwangwoon Univ. (Korea, Republic of)

American Sign Language (ASL) is one of the languages giving the greatest help for communication of the hearing impaired person. Current 2-D broadcasting, 2-D movies are used the ASL to give some information, help understand the situation of the scene and translate the foreign language. These ASL will not be disappeared in future three-dimensional (3-D) broadcasting or 3-D movies because the usefulness of the ASL.

On the other hands, some approaches for generation of CGH patterns have been suggested like the ray-tracing method and look-up table (LUT) method. However, these methods have some drawbacks that needs much time or needs huge memory size for look-up table. Recently, a novel LUT (N-LUT) method for fast generation of CGH patterns of 3-D objects with a dramatically reduced LUT without the loss of computational speed was proposed.

Therefore, we proposed the method to efficiently generate the holographic ASL in holographic 3DTV or 3-D movies using look-up table method. The proposed method is largely consisted of five steps: construction of the LUT for each ASL images, extraction of characters in scripts or situation, call the fringe patterns for characters in the LUT for each ASL, composition of hologram pattern for 3-D video and hologram pattern for ASL and reconstruct the holographic 3D video with ASL.

Some simulation results confirmed the feasibility of the proposed method in efficient generation of CGH patterns for ASL.

7619-39, Poster Session

High-definition full-parallax CGHs created by using the polygon-based method and the shifted angular spectrum method

K. Matsushima, S. Nakahara, Kansai Univ. (Japan)

We proposed the segmentation method for computing large-scaled full-parallax CGHs by using the polygon-based method and demonstrated a CGH with 4 G pixels named “The Venus” in the last meeting. The CGH reconstructs a true fine 3D image accompanied by a strong sensation of depth. In this method, the occlusion in the 3D scene is handled by the silhouette method that makes it possible to shield light behind the object. This light shielding is achieved by multi-stage numerical propagation. The segmented frame buffer and the shifted Fresnel method was used for the numerical propagation in such the large-scale wave field. However, the shifted Fresnel method imposed restriction on design of the 3D scene, because severe aliasing errors are produced in the wave field propagated by using the method if the propagation distance is shorter than a specific value. In this paper, we propose the shifted angular spectrum method for short distance propagation in segmented frame buffers. This novel method removes the restriction on design of 3D scenes. High-definition CGHs are demonstrated for verifying improvement in the degree of freedom to design 3D scenes.

7619-40, Poster Session

Integration of holograms into designer objects: preliminary results

J. P. Eichler, S. Chruszicki, C. Schneeweiss, G. K. Ackermann, Technische Fachhochschule Berlin (Germany)

A small holographic laboratory and a designer studio are cooperating with the aim to develop prototypes for integration of holograms into different designer objects. Due to the high diffraction efficiency mainly dichromate gelatine holograms were produced. In this poster we present several preliminary prototypes: 1) application of holograms in designer lamps, 2) integration of small holograms into tiles and mirrors, and 3) the implementation of holograms in fine jewellery. Similar attempts to use holograms have been reported over the last decades. Further studies and discussions are necessary to improve the illumination and the visibility of the holograms under changing environment. In addition, further development is necessary with respect to a more arty selection of objects for designer holograms. It is desirable that designers increase their focus on a better integration of holograms into their work.

We thank AiF (German organization for cooperation between industrial research and Universities) for financial support.

Conference 7620: Broadband Access Communication Technologies IV

Wednesday 27 January 2010 • Part of Proceedings of SPIE Vol. 7620

Broadband Access Communication Technologies IV

7620-01, Session 1

Pricing broadband access

M. Chiang, Princeton Univ. (United States)

The economics of broadband access interact with the technologies in important ways. In this talk, we discuss the possibility of using pricing mechanisms as a lever to increase broadband access coverage, especially through two-sided pricing and adaptive access charging. Mathematical models are developed to clarify some of the controversial issues in these timely topics. Implications to ISP pricing and the content-pipe divide are presented.

7620-03, Session 2

Introduction and comparison of next-generation mobile wireless technologies

S. R. Zaidi, S. Hussain, M. A. Ali, The City College of New York (United States); A. Sana, S. Saddawi, Bronx Community College (United States); A. Carranza, New York City College of Technology (United States)

Mobile networks and services have gone further than voice-only communication services and are rapidly developing towards data-centric services. Emerging mobile data services are expected to see the same explosive growth in demand that Internet and wireless voice services have seen in recent years. To support such a rapid increase in traffic, active users, and advanced multimedia services implied by this growth rate along with the diverse quality of service (QoS) and rate requirements set by these services, mobile operator need to rapidly transition to a simple and cost-effective, flat, all IP-network. This has accelerated the development and deployment of new wireless broadband access technologies including fourth-generation (4G) mobile WiMAX and cellular Long-Term Evolution (LTE). Mobile WiMAX and LTE are two different (but not necessarily competing) technologies that will eventually be used to achieve data speeds of up to 100 Mbps. Speeds that are fast enough to potentially replace wired broadband connections with wireless. This paper introduces both of these next generation technologies and then compares them in the end.

7620-04, Session 2

Smooth migration technologies towards next-generation access systems

N. Yoshimoto, NTT Access Network Service Systems Labs. (Japan)

We describe technical issues of the next generation PON system regarding as smooth migration from the current PON systems, and also introduce recent hot topics of R&D such as 1G/10G dual-rate PON technologies.

7620-05, Session 2

Integration of PON and 4G mobile WiMAX networks to provide broadband integrated services to end users

S. Hussain, S. R. Zaidi, M. A. Ali, The City College of New York (United States); A. Sana, Bronx Community College (United States)

PON and Mobile WiMAX are two emerging broadband technologies for the next-generation (NG) access networks. Integration of PON and Mobile WiMAX might be an efficient solution to broadband network access that can take advantage of the bandwidth benefit of fiber communications, and the mobile and non-line-of-sight features of wireless communications. By leveraging the advantages of both of these access technologies combined on an integrated architecture platform, NG converged-access solutions can meet the demand for mobility, bandwidth, reliability, security, and flexibility. By combining the practically unlimited capacity of optical fiber networks with the ubiquity and mobility of wireless networks, NG Fiber-Wireless (FiWi) networks will enable the support of a wide range of emerging and unforeseen fixed-mobile applications and services independent of the access infrastructure. PON and 4G Mobile WiMAX integrated architecture enables differentiated bandwidth allocation to end users that can provide more network capacity at reduced operational cost as compared to other existing technologies.

7620-16, Session 2

A case for cross-layer traffic management in 4G networks

S. Parekh, Alcatel-Lucent Bell Labs. (United States)

To fulfill the promise of extensive QoS support in an efficient manner, 4G networks would need to implement application aware traffic management. We will illustrate this point by presenting our recent studies on video streaming in WiMAX networks. We will also review the QoS architecture of LTE and WiMAX networks.

7620-06, Session 3

Fiber-radio solutions for in-building high speed wireless networks

M. Sauer, Corning Inc. (United States)

No abstract available.

7620-07, Session 3

Analysis of the spectrum characteristics of a super linear optical modulator

A. J. Prescod, Corning Inc. (United States); B. Dingel, Nasfine Photonics, Inc. (United States); N. Madamopoulos, The City College of New York (United States)

We demonstrate the superior spectrum characteristics of a previously-introduced ultra-linear modulator. This modulator exhibits excellent linearity (Spurious Free Dynamic Range, SFDR ~ 133 dB at 1Hz

bandwidth), wider linearization bandwidth (an order of magnitude wider), and flatter RF modulation frequency dependence characteristics (linearized 3dB bandwidth ~ 20% of central RF frequency) when compared with Resonator-Assisted Mach Zehnder (RAMZ) modulators. The modulator is based on a traveling-wave electrode design, in which a phase modulator (PM) is on the upper arm of a Mach Zehnder (MZ) interferometer and a ring resonator (RR) is located on the lower arm. This modulator design is also shown to have flexible control of the power split ratio of an RF input to both the PM and the RR, in addition to the RF phase bias between the RR and PM - which enables better manufacturing tolerance. Applications that require the use of ultra-linear modulators include Radio-over-Fiber, Radio-over-Free Space and ultra-dense (cable television) CATV.

7620-08, Session 3

Optical heterodyne technique for generating and distributing microwave signals

A. García Juárez, Univ. de Sonora (Mexico); I. E. Zaldivar Huerta, G. Aguayo Rodríguez, Instituto Nacional de Astrofísica Óptica y Electrónica (Mexico); J. Rodríguez-Asomoza, Univ. de las Américas Puebla (Mexico); R. R. Gómez Colín, A. Vera Marquina, M. d. C. Acosta Enriquez, A. Rojas Hernández, Univ. de Sonora (Mexico)

ABSTRACT. Optical generation of microwave and millimeter-wave signals is of great interest for many applications such as broad-band wireless access, sensor networks, software-defined radio, radar, satellite communication systems and recently in microwave photonic filters. The key advantage for generating microwave or millimeter-wave signals by optical means is that very high-frequency signals with very low phase noise can be generated by beating two optical signals with a wavelength spacing corresponding to the desired microwave or millimeter-wave frequency. In addition, the signals can be used as information carriers for transmitting both analog and digital information signals by using not only RF schemes but also through an optical fiber. For many applications, such as communication systems, the microwave signals would be used as a local oscillator, if the reference source there is not available. In this context, we propose the photonic generation of microwave signals for distributing point to point analog TV signals by using microstrip antennas. The experimental setup used in this work is based on optical heterodyne technique where two optical waves from different wavelength are combined and applied to a photodetector which acts as an optical mixer. Then a beat signal with a frequency equivalent to the spacing of the two wavelengths is obtained at the output of the photodetector. Finally we show a potential application which consists in to demonstrate that microwave signals generated by optical heterodyne can be used as information carrier and local oscilator in a wireless comunication system for transmitting and receiving analog TV signals.

7620-09, Session 3

Cancellation of the IMD3 and IMD5 using opto-electrical predistortion optical transmitter for radio-over-fiber systems

T. Lee, Y. Moon, Y. Choi, Chung-Ang Univ. (Korea, Republic of)

The radio-over-fiber (RoF) system has been studied for many years as a promising technique for providing wireless broad-band service. The advantages of analog RoF system are low cost, transparency for modulation techniques, and large capacity in the access network. Also, the complicated signal processing can be localized at the central station, rather than allocated to a number of remote base stations. Such a system can provide simple base station and thereby is suitable for in-building wired and wireless access network. In typical RoF systems, sub-carrier multiplexing is achieved by using directly modulated laser diode. However, the conventional laser diode for optical communication system has non-linear characteristics, which degrade overall analog RoF system performance. These limitations can be overcome by linearization techniques such as feedforward and predistortion methods. The optoelectrical predistortion method is robust on change of external environment, and can operate on broad bandwidth. Especially the optoelectrical predistortion method has much less dispersion dependency compared to the feedforward method. However, the method has limitation on size of overall system because of electrical and optical delay for error signals extraction. In this work, we design an integrated optical module for the compact optoelectrical predistorter. Then, the compact predistortion optical transmitter has been developed for in-building RoF systems. The proposed optical module consists of a TO-packed DFB-LD with aspheric lens, TO-packaged p-i-n photodiode, and CAN typed metal housing. More detailed experimental results and discussions will be presented.

7620-10, Session 3

Modeling and performance analysis of an all-optical photonic microwave filter in the frequency range of 0.01-15 GHz

G. Aguayo Rodríguez, I. E. Zaldívar-Huerta, Instituto Nacional de Astrofísica, Óptica y Electrónica (Mexico); J. Rodríguez Asomoza, Univ. de las Américas Puebla (Mexico); A. García Juárez, Univ. de Sonora (Mexico); P. Alonso Rubio, Instituto Nacional de Astrofísica, Óptica y Electrónica (Mexico)

The generation, distribution and processing of microwave signals in the optical domain is topic of research thanks to many advantages such as low loss, light weight, broadband width, and immunity to electromagnetic interference. In this sense, a novel all-optical photonic microwave filter scheme is proposed and experimentally demonstrated in the frequency range of 0.01-15.0 GHz. A microwave signal generated by optical mixing drives the microwave photonic filter. Basically, photonic filter is composed of a multimode laser diode, an integrated Mach-Zehnder intensity modulator, and 28.3-Km of single-mode standard fiber. Frequency response of the photonic microwave filter depends on the emission spectral characteristics of the multimode laser diode, the physical length of the single-mode standard fiber, and the chromatic dispersion factor associated to this type of fiber. Frequency response of the photonic filter is composed of a low-pass band centered at zero frequency, and several band-pass lobes located periodically on the microwave frequency range. Experimental results are compared by means of numerical simulations in Matlab showing a small deviation in the frequency range of 0.01-5.0 GHz. However, this deviation is more evident when higher frequencies are reached. In this paper, we evaluate the causes of this deviation in the range of 5.0-15.0 GHz analyzing the parameters involved in the frequency response. This analysis allows for an improved performance of the photonic microwave filter to higher frequencies. A potential application of this all-optical microwave photonic filter scheme resides in high-speed optical transmission systems.

7620-11, Session 4

Application and technical issues of WDM-PON

K. Iwatsuki, NTT Access Network Service Systems Labs. (Japan)

We describe the technical issues of broadband optical access system based on wavelength division multiplexing (WDM) technologies, some solutions, and their applications, including the technical convergence with photonics and wireless.

7620-12, Session 4

A novel PON-based mobile distributed cluster of antennas approach to provide impartial and broadband services to end users

A. Sana, S. Saddawi, Bronx Community College/CUNY (United States); S. Hussain, S. R. Zaidi, The City College of New York (United States)

In this research paper we propose a novel Ethernet Passive Optical Network (PON) based distributed cluster of antennas approach to provide broadband integrated services to mobile WiMAX users. Passive Optical Networks (PON) networks do not require powered equipment; hence they cost lower and need less network management. WiMAX technology emerges as a viable candidate for the last mile solution. In the conventional WiMAX access networks, the base stations and Multiple Input Multiple Output (MIMO) antennas are connected by point to point lines. Ideally in theory, the Maximum WiMAX bandwidth is assumed to be 70 Mbit/s over 31 miles. In reality, WiMAX can only provide one or the other as when operating over maximum range, bit error rate increases and therefore it is required to use lower bit rate. Lowering the range allows a device to operate at higher bit rates. Our focus in this research paper is to increase both range and bit rate by utilizing distributed cluster of MIMO antennas connected to WiMAX base stations with EPON based topologies. A novel quality of service (QoS) algorithm is also proposed to provide admission control and scheduling to serve classified traffic. The proposed architecture presents flexible and scalable system design with different performance requirements and complexity.

7620-13, Session 4

Wideband optical propagation measurement system for characterization of indoor optical wireless channels

M. Kavehrad, J. Fadlullah, The Pennsylvania State Univ. (United States)

The main objective of the research to be presented is to characterize an indoor wireless optical communication channel. Until recently, there has not been any comprehensive attempt to characterize this channel over a large bandwidth, e.g. 1 GHz. To this end, a measurement setup is implemented, with a high-power laser diode acting as the optical transmitter and an avalanche photodiode acting as the receiver.

Using a network analyzer, the laser is modulated by CW frequencies up to 1 GHz, which is the bandwidth of the receiver, as limited by the capacitance and the transit-time of the avalanche photodiode. Several optical configurations are tested including single collimated spot and diffuse spot. The impacts of receiver orientation and configuration on the channel frequency response are investigated. These measurements will enable us to explore the possibility of higher data transmission rates, potentially up to 1 Gbps, on indoor optical wireless channels. These channels can be a viable alternative to inherently insecure and interference-prone RF wireless channels, and therefore, could be the basis of next-generation high data rate wireless local area networks.

7620-14, Session 4

Efficiency of MIMO configuration and adaptive optics corrections in free space optical fading channels

Z. Hajjarian Kashani, M. Kavehrad, The Pennsylvania State Univ. (United States)

Free Space Optical (FSO) communications is the only practical candidate for realizing universal network coverage between ground and airborne nodes, satellites, and even spatial objects such as moon and nearby planets. When atmosphere (be it the earth or Mars) is a part of the optical channel, attributes of scattering and turbulence bring about amplitude attenuation, and scintillation, as well as beam wander and phase aberrations at the receiving aperture. Phase screens are usually used in order to simulate the atmospheric fading channel and phase fluctuations. In this paper, different methods of generating phase screens are compared based on their computational complexity, as in most computer simulations, a large ensemble of phase screens are required for averaging purposes.

To combat the focal plane intensity fading, caused by amplitude and phase variations in the received wave-front, it is possible to replace the Single Input-Single Output (SISO) communications system with its Multiple Input Multiple Output (MIMO) equivalent, which has the same total transmit power and receiving aperture area. Another alternative is to equip the receiver with a state of the art Adaptive Optics (AO) Correction system. Using average Bit Error Rate (BER), as a performance metric, effectiveness of these two approaches are compared and it is shown that while a MIMO configuration outperforms a basic AO system capable of only tilt corrections, an ideal AO system, which is able to remove higher orders of Zernike modes can asymptotically perform as well as an equivalent MIMO configuration.

7620-15, Poster Session

Statistical analysis on the optical fading in free space optical channel for RoFSO link design

K. Kim, T. Higashino, K. Tsukamoto, S. Komaki, Osaka Univ. (Japan); K. Kazaura, M. Matsumoto, Waseda Univ. (Japan)

Signal transmission qualities of various high frequency band radio services over a radio on free space optics (RoFSO) link are affected by not only a radio channel environment but also free space optical channel situation. A laser beam propagating through the free space such as the atmosphere undergoes the cumulative effect of a large number of refractive inhomogeneities. Hence, It may lead to multipath fading in laser beam intensity, called scintillation.

The scintillation effect is usually described in terms of optical loss according to optical fluctuation variance. For the design of practical RoFSO link, however, fluctuation speed of scintillation is the very important factor as well as its variance, because a long- period fading of optical intensity causes long fade duration. It is closely related to error bursts.

This paper presents empirical probability density functions (p.d.fs) of variance and fluctuation speed of scintillation, through analyzing a number of experimental data measured in Japan by a statistical model. The model enables us to treat scintillation speed by one parameter of cut-off frequency in the power spectral density (PDS). By using the model and based on the two p.d.fs, we also present simulation results on the level crossing rate (LCR) and average fade duration (AFD). Combined the two results, an outage probabilities corresponding to a threshold optical intensity can be derived.

Conference 7621: Optical Metro Networks and Short-Haul Systems II

Wednesday-Thursday 27-28 January 2010• Part of Proceedings of SPIE Vol. 7621

Optical Metro Networks and Short-Haul Systems II

7621-01, Session 1

Active and tunable waveguide devices based on silicon and silica for use in optical communication systems

E. Brinkmeyer, Technische Univ. Hamburg-Harburg (Germany)

A variety of waveguide devices are in use or could be used for improving or enabling optical communication systems, including on the one hand fiber optical components such as fiber Bragg gratings (FBGs), and on the other hand planar waveguide devices - in particular silica-on-silicon structures - such as arrayed waveguide gratings (AWGs). Some of the devices under consideration are quite mature while others could be called up-and-coming and may be useful in the future. The latter applies to waveguide devices in silicon-on-insulator (SOI) which offer tremendous prospects, in particular regarding compactness and a seamless interface to electronics. From yet another perspective the devices may be either passive or active and tunable. Active, for example, are amplifying, lasing or switchable devices based on stimulated Raman scattering in silicon, tunability can arise from free carriers, from the thermo-optic effect or the electro-optic effect in the waveguide itself or in polymers combined with it (e.g. using slotted waveguides). Aspects of design, applications and characterization of such devices will be reviewed in this paper with focus on planar waveguide components for adaptive dispersion compensation, active devices in silicon and measurement techniques.

7621-02, Session 1

Optical transceivers for short and medium reach optical networks

B. Huebner, Finisar Corp (United States)

Optical transceivers are the dominating technology for the optical front end of short and medium reach optical communication systems.

They are very diverse, ranging from extremely low cost and high volume applications to extreme performance and relatively high cost products. Very different technical solutions for the optical components are used and this paper will give an overview of these enabling technologies.

Furthermore we will discuss the challenges (Density, Power consumption, Cost) that optical transceivers face today and which technologies may be used to solve these challenges in the future.

7621-41, Session 1

Evolution of optical access network technologies

T. Pfeiffer, Alcatel-Lucent Deutschland AG (Germany)

Photonic technologies have found widespread applications in high-speed longhaul and metro transmission networks for decades. Introducing similarly advanced optical technologies into access networks must respect the strict requirements for simple deployment and operations as well as ease of system migration and network maintenance. The large number of optical ports and fiber links to be provided and operated at lowest cost make access networks special as compared to their longhaul and metro networks counterparts. The presentation will provide a view on the status and future evolution of optical access networks and the photonic technologies applied therein.

7621-42, Session 1

Optical fiber interconnects: physical design for reliability

E. Suhir, Univ. of California, Santa Cruz (United States) and Univ. of Maryland, College Park (United States) and ERS Co. (United States); A. M. Earman, Arasor (United States)

We address a number of practically important problems of the mechanical behavior and structural mechanics of bare or coated optical fiber interconnects (OFIs), experiencing thermal and/or mechanical loading. The emphasis is on analytical (“mathematical”) modeling. Possible failure modes are indicated and recommendations for a rational mechanical (“physical”) design and improved reliability of OFI structures are suggested. We determine the loading conditions, evaluate the stresses and strains, and provide recommendations of what should be done to ensure that the OFI response to thermal and/or mechanical loading is acceptable from the standpoint of structural integrity, elastic stability, dependability, and normal operation (both optical and mechanical) of the system. We show how methods of Engineering Mechanics and Materials Engineering can be effectively applied to obtain closed form solutions to various practical problems of the mechanical behavior, physical design and reliability of photonics materials and structures experiencing thermally induced and/or “mechanical” loading. We discuss how to choose the appropriate material(s) for a particular package design and how to change, if necessary, the geometrical characteristics of the design to create a viable and reliable FOI structure. The major topics discussed include, but might not be limited to: bending of bare and coated OFIs, OFIs under the combined action of bending and tension, role of silica material nonlinearity, stresses in coated and partially coated fibers, interaction of “global” and “local” thermally induced stresses, elastic stability and microbending of OFIs, solder materials and joints in OFI structures, dynamic response of OFI structures to shocks and vibrations.

7621-03, Session 2

Changing the network structure: leaving the past behind

R. Herber, T-Systems Enterprise Services GmbH (Germany)

The infrastructure of the existing network is determined by the old copper access technology. Not only the copper access itself, also the number of central offices and their geographical distribution are results of the copper network and its physical limitations.

Today, in Germany 8000 active locations cater for the delivery of plain old telephony services as well as for the delivery of new fiber based broadband services. Due to the fact that the attenuation of the fiber is relatively low, new concepts for the design of the network structure can be discussed. A reach of - let’s say 40 km - on an optical transport system is no problem. Longer possible link lengths can result in a reduced number of central offices, leading to reduced expenditures for the building, power supply and air conditioning. In the case of Germany a number of roughly 900 central offices is envisaged.

However, a significant drawback of today’s existing optical access technologies is the very limited number of customers on a single fiber. For instance, GPON provides typically a 32-way split and a distance of 20 km.

This paper discusses some new ideas to introduce higher splitting ratios and longer access lengths into the network. With WDM and/or coherent optical receivers new options for a future proof access network are available.

7621-04, Session 2

Optical metro networks 2.0

J. Elbers, ADVA AG Optical Networking (Germany)

Fueled by the rapid traffic increase in access and enterprise networks, optical metro networks represent a major growth area for system vendors and component manufacturers. This presentation reviews new developments from a technical and economic point of view. Topics such as network and node architectures, high-speed transmission, integrated optical/electronic switching as well as system automation and network/service management will be discussed.

7621-05, Session 2

Recent development and future prospects of optical metro networks and their technologies

T. Inui, A. Sahara, T. Takahashi, NTT Network Innovation Labs. (Japan)

Fiber to the home (FTTH) is widely spreading in Japan as a high-speed access infrastructure. Based on the broadband access, internet traffic is constantly increasing due to various types of services such as data communications, VoIP, IPTV, video sharing and P2P.

To respond the traffic increase, reconfigurable optical add drop multiplexer (ROADM) ring systems have been developed and widely deployed as metro networks. ROADM system has the advantages such as elimination of costly transponders, flexibility using optical switches, and remote-controllability.

The standardization of high-speed Ethernet interfaces, 100GE and 40GE, is going to be completed in IEEE in the forthcoming 2010. ITU-T is also going to complete the standardization of next generation OTN interface which can accommodate the high-speed Ethernet interfaces and transport 100Gbit/s-class signals. 100GE users may be small in the early stage, but network operators have to provide 100Gbit/s links for such aggressive users. Thus, metro networks should have optical transmission lines which channel data rate is up to 100Gbit/s. Service providers have to construct such high-capacity optical metro networks economically. From the operational point of view, optical metro networks would be desirable to have advanced functionalities such as A to Z fast provisioning, unified OAM&P (operation, administration, management and provisioning), colorless operation and quick delivery of transport services with broad bandwidth in the metro region.

This paper overviews the broadband situation in Japan and the recent development and future prospects of optical metro networks and their technologies. Firstly, the situation of broadband infrastructure and internet traffic in Japan is overviewed. Then, the recent development of optical metro networks and their enabling technologies is reviewed. Finally, the future prospects of optical metro networks are described.

7621-07, Session 2

All optical grooming for 100G ethernet

J. Leuthold, W. Freude, Univ. Karlsruhe (Germany)

No abstract available.

7621-25, Poster Session

Investigation of dense dispersion management optical links with non-perfect dispersion maps

V. A. Burdin, V. A. Andreev, M. V. Dashkov, K. A. Volkov, Povolzhskaya State Academy of Telecommunications and Informatics (Russian Federation)

There is no doubt that dispersion management soliton systems (DDMS) are the most applicable for the short-haul transport. However on practice it is unbelievable to realize an ideal coincidence between projected and installed lengths of dispersion map fibers, which can be explained, for example, by business problems or an optical closure placement. Here we present results of numerical simulations of optical pulse propagation and following bit-error-ratio estimation in a dense dispersion manage optical link with non-perfect dispersion maps.

7621-26, Poster Session

Optical link upgrade by DDMS technique with compensating fiber in optical cable closure

V. A. Burdin, A. V. Bourdine, M. V. Dashkov, K. A. Volkov, Povolzhskaya State Academy of Telecommunications and Informatics (Russian Federation)

A well-known dense dispersion management soliton (DDMS) technique is applied to increase bandwidth of metropolitan area network fiber optic links. This technique requires an installation of optical cables with dispersion compensating fibers (DCFs), which leads to high costs for upgrading of installed fiber optic links. To become the DDMS more applicable, we propose to place DCFs in optical fiber closures. Here results of numerical simulations of optical pulse propagation and following bit-error-ratio estimation in fiber optic link with DCFs in optical closures are represented.

7621-06, Session 3

In-service characterization of optical links and signals with respect to PMD

H. Rosenfeldt, Agilent Technologies Deutschland GmbH (Germany)

Tackling PMD has turned out to be one of the most puzzling problems during the advent of high speed optical transmission systems. It still seems far more attractive to avoid links with high PMD than to install an expensive PMD-compensator. Measuring the PMD of an installed fiber link can answer the question if this link can be operated with or without a PMD-compensator. Common test methods require exclusive access to the fiber link. This is considered to be a major limitation since it is not easy to reroute the traffic of a WDM system with many channels. This contribution discusses techniques to measure the PMD of a fiber link while it is in service. Approaches using a single transparent channel are discussed as well as methods utilizing the whole received WDM signal. The latter method seems particularly attractive since only single end access is needed. However, there are principal limitations which need to be understood in order to qualify a link. Performing these measurements while the link is in service will help network operators to smoothly upgrade to higher bit rates in their backbone networks.

7621-08, Session 3

Phase preserving amplitude noise suppression using an attenuation imbalanced NOLM

E. R. Parsons, College of Optical Sciences, The Univ. of Arizona (United States); C. Stephan, K. Sponsel, T. Roethlingshoefer, Max Planck Institute for the Science of Light (Germany); F. Küppers, College of Optical Sciences, The Univ. of Arizona (United States); G. Onishchukov, Max Planck Institute for the Science of Light (Germany); B. Schmauss, University of Erlangen-Nuremberg (Germany); G. Leuchs, Max Planck Institute for the Science of Light (Germany)

A nonlinear optical loop mirror with a bidirectional attenuator has been used for regeneration of return to zero differential phase shift keyed (RZ-DPSK) signals.

A 2.5 ps, 10 Gb/s signal with amplitude fluctuations of ~15% was regenerated with a negative power penalty of ~1.5 dB practically back to the quality of the undistorted reference signal.

Parameters limiting system performance and optimization possibilities will be discussed.

7621-09, Session 3

Photonic balancing and its application in optical receivers and regenerators for fiber optic systems

F. Küppers, E. R. Parsons, H. Chaouch, College of Optical Sciences, The Univ. of Arizona (United States); W. Weiershausen, M. Mattila, A. Tervonen, T. von Lerber, Luxdyne Ltd. (Finland)

We present an optical receiver and an optical regenerator for RZ-DPSK signals that use photonic balancing. Photonic balancing is achieved through pulse counter-propagation and collision in a saturated SOA. We explain the principles of photonic balancing and show how it can lead to an improvement in RZ-DPSK detection by 3 dB, similar to electrical balancing. We also show how this scheme can be used as a Mamyshev-type regenerator. Finally we investigate the suitability of using this scheme with a periodic group delay device (PGDD) to allow multi-channel functionality.

7621-10, Session 3

Challenges and opportunities for optical amplifiers in metro optical networks

G. J. Cowle, JDSU (United States)

No abstract available.

7621-11, Session 3

All-optical 2x2 switch by exploiting optical nonlinearities in a single semiconductor optical amplifier

C. Porzi, Scuola Superiore Sant'Anna (Italy); L. Ma, Tsinghua Univ. (China); M. Scaffardi, CNIT (Italy); M. Yao, Tsinghua Univ. (China); L. Potì, A. Bogoni, CNIT (Italy)

A 2x2 cross/bar optically-driven switch is implemented with a single semiconductor optical amplifier (SOA). The two input signals enter the gate through opposite SOA facets, whereas a pump signal is applied to both the amplifier facets. Optical circulators (OCs), placed before each SOA facet, are used to retrieve the input signals at the amplifier output, and polarization beam splitters (PBSs) are placed after the OCs output paths. Each output branch of a single PBS is coupled to one output branch of the other PBS to form the two switch outputs. Polarization controllers (PCs) are inserted in the input/output paths. In absence of control light, the low-power signals traveling inside the amplifier do not experience any nonlinear effect, and the PCs are adjusted so that each input signal exits the PBS output port which is not coupled to the other PBS output port for the second input signal. Each input signal is then retrieved only at one output gate port. This situation describes one of the two possible cross/bar configurations of the gate. When the pump light is injected into the amplifier with appropriate polarization state, both the input signals inside the amplifier experience nonlinear polarization rotation due to strong carrier/phase modulation. The amount of polarization rotation can be controlled with the pump level in such a way that each signal leaving the amplifier moves to the other PBS exit, setting the switch in the other possible cross/bar configuration. Bit error rate measurements demonstrate error-free operation for both the possible configurations.

7621-12, Session 4

NG-PON: Enabling technologies for metro-access convergence

F. J. Effenberger, Huawei Technologies Co., Ltd. (United States)

It has long been a goal of network planners to restructure their networks to reduce or eliminate fixed installations and all the operational difficulties and concerns that go along with them. Optical access networks have been a part of that goal because of their intrinsic long-distance capabilities. In practice, however, the demand for bandwidth has outpaced the supply offered by cost-effective passive optical systems. This has kept most PON deployments at a relatively modest reach (<20km) and split ratio (<32 way).

Currently, NG-PON technologies such as 10 Gbit/s systems, TDM, WDM, and their hybrids are coming on the scene. These potentially could increase the bandwidth capabilities on a single access fiber to many times what is practical now. The distance capabilities of these systems are also significantly improved, reaching to 60km. This may be the trigger for serious convergence of the inter-office/metro and access networks. This paper will examine the current trends in NG-PON technology, and extrapolate how these will impact the overall telecom network.

7621-13, Session 4

Challenges of future converged access and metro networks

D. Breuer, R. Hülsermann, C. Lange, E. Weis, Deutsche Telekom Labs. (Germany)

Steadily increasing customer demand for more and more bandwidth in excess of 100 Mb/s per subscriber, new technical options and a strong competitive environment drive the evolution of today's telecommunication networks, particularly in the access network. The physical properties of fibers such as very low loss and almost unlimited bandwidth allow for high bit rate long distance transmission in future access networks compared to the conventional copper based access networks in place today. In future this will lead to much larger service areas which are served from one central office and to a significant reduction of central offices of today's infrastructure facilitating a converged metro-access architecture. One driver for this network consolidation is the need for significant operational expenditure (OPEX) savings which are expected due to reduction of active equipment and footprint. But also the changes from today's "service oriented" network design, where each service is almost realized on a new platform, towards an open standardized multi-layer Next Generation Network where all services will be delivered over a common infrastructure will lead to significant challenges in the network

infrastructure.

This paper will review drivers and challenges in future enlarged access networks from an architectural, technological and economical point of view.

7621-14, Session 4

Effects of network node consolidation in optical access and aggregation networks on costs and power consumption

C. Lange, R. Hülsermann, D. Kosiankowski, F. Geilhardt, A. Gladisch, Deutsche Telekom AG (Germany)

The increasing demand for higher access bit rates requires fibre deployment in access networks closer to the subscriber since the copper wire characteristics are the major limiting factor. Besides higher access bit rates, optical access network technologies enable extended distances between the network terminal at the customer premise and the access node's line port due to the low attenuation and high bandwidth of optical fibres: Access and aggregation networks tend to merge and the network operator is able to establish larger service areas. The resulting simplified network structure with a smaller number of network nodes is expected to lead to a more cost-efficient operation of the redesigned network compared with today's access network structures inherited from the copper-based telephone networks.

It can be expected that concentration effects - fewer but larger network sites - will also help to increase the energy efficiency of the access/aggregation network operation. In this paper network node consolidation scenarios basing on different architectures for optical access networks will be analyzed with respect to power and energy consumption contributing to operational expenditures. Based on simplified device models and power consumption values from data sheets and measurements power and energy consumption results are calculated.

7621-15, Session 5

40G/100G DWDM transmission in metro optical networks

A. Lemus, R. Saunders, Opnext, Inc. (United States)

No abstract available

7621-16, Session 5

Serial 100 Gbit/s PM-RZ-DQPSK transmission in the presence of perturbations from lower data rate neighboring channels

H. Chaouch, F. Küppers, College of Optical Sciences, The Univ. of Arizona (United States); S. Vorbeck, M. Schneiders, Deutsche Telekom (Germany)

This paper investigates serial 100 Gbit/s PM-RZ-DQPSK transmission in the presence of perturbations from neighboring 10 Gbit/s NRZ, 40 Gbit/s RZ-DPSK, and 40 Gbit/s RZ-DQPSK DWDM channels. It addresses the need to outline upgrade paths of current hybrid DWDM systems equipped with 10 and 40 Gbit/s line cards towards 100 Gbit/s for remaining channels. A numerical simulation approach is used to evaluate the signal quality of the central probe for various DWDM channel constellations and power levels.

7621-17, Session 5

Non-binary LDPC-coded modulation for high-speed optical metro networks with back propagation

M. ARABACI, I. B. Djordjevic, The University of Arizona (United States); R. Saunders, R. M. Marcoccia, Opnext, Inc. (United States)

Network operators already consider 100 Gb/s transmission per dense wavelength division multiplexing (DWDM) channel; however, at such speeds, channel impairments severely degrade the system performance. By using multilevel modulation, all related coding, signal processing and transmission can be performed at lower symbol rates, where dealing with fiber nonlinearities and PMD is more manageable, while the aggregate rate is kept at 100 Gb/s and above. We have shown recently that the low-density parity-check (LDPC)-coded turbo equalizer is an excellent candidate to mitigate linear and nonlinear impairments simultaneously. However, the complexity of the equalizer's dynamic trellis channel description grows exponentially as the channel memory increases and signal constellation size grows.

An interesting approach to reduce the channel memory is the backpropagation method. Namely, in point-to-point links, the receiver knows the dispersion map and can propagate the received signal through a dispersion map with fiber parameters (group velocity dispersion (GVD), second-order GVD and nonlinearity coefficient) of opposite signs to that used in the original map. However, using backpropagation, the nonlinear interaction of ASE noise and Kerr nonlinearities cannot be compensated for, and the complexity is about two orders of magnitude higher than that of a linear equalizer. In this paper, we propose to use a coarse backpropagation (with reasonably small number of coefficients) to reduce the channel memory, and compensate for the remaining channel distortions by non-binary LDPC-coded turbo equalization. We propose non-binary LDPC codes because they offer lower decoding complexity and latency while providing larger coding gains compared to their binary counterparts.

7621-18, Session 5

Quaternary modulation formats for 100-Gbps optical links

T. F. Detwiler, S. M. Searcy, Georgia Institute of Technology (United States); R. Lingle, Jr., OFS Fitel, LLC (United States); E. B. Basch, Verizon Labs., Inc. (United States); S. E. Ralph, Georgia Institute of Technology (United States)

100 Gbps and greater optical links will experience increased deployment particularly in metro-core and regional network environments. Indeed, the upcoming IEEE standard (IEEE P802.3ba 40Gb/s and 100Gb/s Ethernet Task Force) seeks 100Gbps over 40km for access. Furthermore metro-core/regional architectures also require reach of several hundred km and the ability to pass through ten or more ROADMs. However, a number of fundamental challenges remain including i) selection of an appropriate modulation format that is robust to a variety of nonlinearities and sufficiently spectrally efficient and robust to withstand the strong optical filtering of the cascaded ROADMS, and ii) selection of an optimum dispersion management strategy. Spectral efficiencies of at least 4 bits/symbol/Hz are anticipated. We present a comprehensive comparison of a variety of single-carrier quaternary modulation formats, each providing 2 bits/symbol and assuming a polarization multiplexed format. Although prior studies of such formats have either not extended to 100Gbps or have focused entirely on QPSK, we consider QPSK, offset QPSK, 2-level MSK, and quaternary CPFSK. Each format is presented with an appropriate MZM-based transmitter, and constrained by practical signal fidelity limitations that also enable comparison to experimental results from our 100G testbed. Direct detection receivers are best suited for cost-sensitive metro networks. We therefore primarily examine direct detection however we also quantify the performance of coherent

receivers, where applicable. Simulation results demonstrate the relative OSNR penalty (at a non-FEC BER of 10-3) for a range of dispersion maps, launch powers, and adjacent channel formats.

7621-19, Session 6

Ultimate information capacity of fiber optic networks

I. B. Djordjevic, The Univ. of Arizona (United States)

There have been numerous attempts to determine the channel capacity of a nonlinear fiber optics communication channel. The main approach, until recently, was to consider ASE noise as a predominant effect and to observe the fiber nonlinearities as the perturbation of linear case or as the multiplicative noise.

In this invited paper, we describe how to determine the true fiber-optics channel capacity. Because in most of practical applications the channel input distribution is uniform, we also describe how to determine the uniform information capacity, which represent the lower bound on channel capacity. This method consists of two steps: 1) approximating probability density functions (PDFs) for energy of pulses, which is done by: (a) evaluation of histograms, (b) instanton approach or (c) edgeworth expansion, and

2) estimating information capacities by applying a method originally proposed by Arnold and Pfitser.

To calculate the information capacity, we model the whole optical transmission system as the dynamic nonlinear channel with memory, in which m previous and m next symbols influence the observed symbol.

The optical communication system is characterized by the conditional PDF of the output complex vector of samples y=(y1,...,yn,..), given the source sequence of M-ary symbols x=(x1,..,xn,..). The information rate can be calculated by I(Y;X) = H(Y) - H(Y|X), where H(U) = E(logP(U)) denotes the entropy of a random variable U and E(.) denotes the mathematical expectation operator. To evaluate the first term we use the transition PDFs, and to evaluate the second term we use the forward step of BCJR algorithm. The information capacity is obtained by maximizing the information rate over all possible input distributions.

To reduce the computational complexity, we use the backpropagation approach.

7621-20, Session 6

DQPSK for metro networks

A. J. Stark, Y. Hsueh, C. Liu, Georgia Institute of Technology (United States); A. McCurdy, R. Lingle, Jr., OFS Fitel, LLC (United States); S. Tibuleac, ADVA Optical Networking (United States); G. Chang, S. E. Ralph, Georgia Institute of Technology (United States)

Optical metro networks are likely to experience wide deployment of 100Gbps line rates to support storage, voice and video applications. These deployments will require new modulation formats that must coexist with existing 10Gbps rates in networks with a variety of dispersion management methods that were originally engineered for 10Gbps line rates. Modulation formats that can support 100Gbps within a 50GHz channel spacing are invariably phase-based and have different optimization compared to traditional OOK formats. Furthermore, direct detection receivers are best suited for cost-sensitive metro networks. We therefore examine DQPSK transport on our 100G testbed that allows 112 Gbps POL-MUX RZ-DQPSK with 12 Gbps OOK channels and a variety of dispersion management methods using standard single mode fiber. Although a number of studies of 40Gbps line rates within a 10Gbps network have been reported, there has been little with respect to 28Gbaud DQPSK formats. We quantify the OSNR penalty due to nonlinearities of these hybrid optical links by examination of nominal span loss of 20dB, and vary the length of span while keeping the dispersion compensation per span constant and the loss per span constant. This allows a direct examination of the impact of the residual dispersion per span (RDPS) on the nonlinear penalty in the DQPSK channel. We vary compensation from 80%-100% (of total dispersion) across 6 spans (348.5 ps/nm - 0ps/nm). We report the required OSNR to achieve a non-FEC BER of 10^-3 versus RDPS for both single- and dual-pol RZ-DQPSK. Additionally, we show the effects of changing the 12 Gbps channel launch powers. Experimental data is validated against RSoft OptSim simulations.

7621-21, Session 6

Capacity achieving modulation format for high-speed optical networks

H. G. Batshon, I. B. Djordjevic, The Univ. of Arizona (United States)

In recent years, we have witnessed an increased demand on optical networks transmission capacities due to the growing popularity of the Internet and multimedia in everyday life. According to industry expert estimates, 1 Tb/s Ethernet should be standardized by the year 2012-2013, and the fiber capacity will reach its limits near the year 2025. To this end, we propose a non-uniform coded modulation format based on iterative polar quantization that achieves the channel capacity for SNRs of up to 25 dB. The optimization for this modulation format is based on quantization mean error squared. The proposed modulation scheme is optimized for ASE-noise dominated channels and can achieve 500 Gb/s data rate per polarization utilizing the currently available components operating at 50 GSymbols/s. This coded-modulation scheme outperforms the QAM counterpart by 0.7 dB for 64-point constellation at bit error ratio of 10^-6, while the improvement increases as the constellation size increases. The FEC codes of choice for the simulations presented in this proposal are structured LDPC codes, due to the improved performance and less complex encoder and decoder design. One major benefit of the current scheme is that it is an affordable upgrade to the current systems where the transmission system itself remains intact except for the transmitter and the receiver.

7621-22, Session 6

1-µm waveband and C-band, 10-Gbps error-free operation of ultra-broadband photonic transport system with holey fiber

N. Yamamoto, K. Akahane, T. Kawanishi, National Institute of Information and Communications Technology (Japan); Y. Omigawa, Aoyama Gakuin Univ. (Japan); H. Sotobayashi, Aoyama Gakuin Univ. (Japan) and National Institute of Information and Communications Technology (Japan)

An ever-growing demand for high data transmission capacities necessitates the use of alternative wavebands to enhance the transmission capacities of photonic networks. Recently, we have focused on a development of an ultra-broadband photonic transport system by using a novel transmission line and attractive photonic devices. Additionally, we have focused on an use of 1-µm waveband as a novel optical communications band.

In this presentation, 10-Gbps error-free multi-band photonic transmissions in a 1-µm waveband and C-band are successfully demonstrated over a single transmission line of an ultra-wideband and single-mode 4.5-km long holey-fiber. Semiconductor-lasers of 1060- and 1549-nm wavelengths are used for the 1-µm and C-band light-sources. Ytterbium- and Erbium-doped fiber amplifiers are respectively carried out for the 1-R repeaters. 10-Gbps data-streams in each band are generated simultaneously by using LiNbO3 modulators. A semiconductor optical amplifier and clock data recovery are also used in a data-receiver. By using the ultra-broadband photonic transport system with the holey-fiber, it is expected that wideband optical frequency resources can be employed for future optical communication networks.

7621-23, Session 6

Experimental demonstration of simultaneous compensation of polarization mode dispersion and fiber nonlinearities by LDPC-coded turbo equalization

L. L. Minkov, I. B. Djordjevic, The Univ. of Arizona (United States)

In recent years LDPC codes have gained significant interest in the area of optical communication systems due to their capacity-approaching performance, high coding gain and low decoding complexity for structured codes. We describe the construction principles of high-rate, high-girth, quasi-cyclic LDPC codes and present an LDPC-coded turbo equalization scheme designed to operate on a dynamic description of the optical channel that is suitable for simultaneous mitigation of multiple transmission impairments. The equalization scheme is based on the maximum a-posteriori Bahl Cocke Jelinek Raviv (BCJR) algorithm which uses the conditional density probability functions of the channel and calculates the initial likelihood ratios for the LDPC decoder. To optimize the code performance extrinsic information transfer charts are used.

We also investigate and evaluate the performance of the proposed scheme in the presence of polarization pode dispersion (PMD), fiber nonlinearities and chromatic dispersion for 10Gb/s transmission system and various modulation formats including NRZ, carrier suppressed RZ and polarization multiplexed BPSK for different transmission distances. LDPC codes of rates 0.8, 0.9 and 0.95 are evaluated. The experimental setup includes a recirculating loop of 80km single mode fiber (SMF). Experiments with and without chromatic dispersion compensation are conducted. We further determine the channel capacity for the used modulation formats and codes. We experimentally demonstrate that the proposed equalization scheme closely approaches the theoretical Shannon limit.

7621-24, Session 6

NLMS-based PMD equalization with improved adaption speed

D. Goelz, P. Meissner, Technische Univ. Darmstadt (Germany)

The still increasing demand for data bandwidth in short-haul transmission as well as in long-haul transmission implicates the development of optical high-speed communication systems that carry 40 Gbit/s and higher. This step is limited mainly by the polarization mode dispersion (PMD) of the fiber infrastructure. Direct detection (DD) transmission systems are state of the art. At this the square-law detection of the photo diode transforms linear distortions into nonlinear effects, which makes linear equalization principles less effective. Coherent detection on the other hand delivers amplitude, phase and polarization information of the field and thus enables advanced PMD-compensation in the electrical domain. We realize PMD-compensation by means of least mean squares (LMS) based adaptive electronic equalizers. The drawback of adaptive equalization principles is the setting of the adaption step-size. Small step-sizes lead to very accurate results, but are very time-consuming. By contrast large step-sizes can accelerate the adaption process but lead to inaccurate equalizer settings. Accordingly, it is desirable to resize the step-size during the adaption process. For these reasons different step-size control (SSC) algorithms are implemented, analyzed and adapted to the requirements of an optical PMD affected transmission system. It shows that SSC algorithms are able to accelerate the adaption-process significantly.