Nonlinear waves in metamaterials: state of the art

A. D. Boardman, P. Egan, R. R. C. Mitchell-Thomas, Univ. of Salford (United Kingdom)

Nonlinear waves in optical structures offer the prospect of many applications but are limited for ordinary materials by power limitations and the availability of intrinsic or extrinsic nonlinearity. Many new options, in the context of guided waves, will lead to new forms of computing and light manipulation. A range of planar waveguides will be introduced, in which the nonlinearity originates within a metamaterial component or is supplied through special bounding media. The stopping of light by such structures will be investigated. This will be shown to be a beautiful feature that leads to even more dramatic outcomes as the complexity of the waveguides increases. The trapped rainbow will be taken into a nonlinear regime and overall control using magnetooptics will be developed into forms that could be the basis of many applications. The whole question of soliton formation and propagation will be addressed next and will include both spatial and temporal solitons, and their interactions. The advantages of using couplers will be stressed, and their natural characteristics, through the use of metamaterials, will be connected to the stopping of light. The role of symmetry will be introduced, and the possibility of second-harmonic generation will be admitted, and the extent of metamaterial influence will be quantified. Finally, nonlinear bulk material will be examined using vortices as suitable probes. Many new outcomes will be delivered on this topic, which will emphasize, once again, how a whole range of different metamaterials can be deployed to reveal the fascinating world of nonlinear waves.

Nonlinear meta-atoms for multi-functional metamaterials

J. F. O’Hara, Los Alamos National Lab. (United States) and Oklahoma State Univ. (United States); M. Reiten, L. M. Earley, D. Roy Chowdhury, J. Zhou, A. J. Taylor, Los Alamos National Lab. (United States)

Nonlinearity adds an unprecedented amount of design flexibility and functionality to technology and is becoming increasingly studied in the context of metamaterials. Nonlinearity is the key to gain, bistability, photon mixing, rectification, and myriad other phenomena. Nonlinear behavior in natural materials begins at the atomic structure. We present a brief survey of some of the fundamentals of nonlinearity in natural materials. Then, we present some recent progress in studying analogous behavior in metamaterials and meta-atoms, the fundamental building block of metamaterials. Specifically, we show microwave frequency meta-atoms that support self-sustained oscillations, harmonic generation, chaotic broadband generation, and injection locking and pulling. In this work, meta-atoms and metamaterials are created using either circuit board milling or microfabrication techniques. Nonlinearity is added through the incorporation of semiconductor inclusions in the meta-atoms, such as varactors and tunnel diodes. Simulations and experiments are performed to determine nonlinear behavior. Meta-atoms are found to respond nonlinearly to both free-space and directly connected electromagnetic stimulation. In addition, nonlinear activity is achieved through either electric or magnetic excitation of the meta-atom. Measured results indicate a strong propensity of nonlinear meta-atoms to achieve numerous and simultaneous nonlinear behaviors, with mixing being the most common. We present our measured or simulated results and discuss their implications in the broader metamaterial perspective.

We also discuss the demarcation between basic lumped circuits and effective media.

Nonlinearity in metatronics

N. Engheta, Univ. of Pennsylvania (United States)

In recent years we have introduced and been developing the concept of “metatronics”, i.e. metamaterial-inspired optical nanocircuitry, in which the three fields of “electronics”, “photonics” and “magnetic” can be brought together seamlessly under one umbrella - a paradigm which I call the “Unified Paradigm of Metatronics”. We have now expanded this paradigm by including and exploring the role of optical nonlinearity in such metatronic circuits. In the present work, we will discuss our theoretical results in combining nonlinearity with the lumped optical circuit elements when accompanied with the ENZ materials for the difference-frequency generation, and the role of optical nanoantennas in enhancing the nonlinearity in metatronics. The enhancement of difference-frequency signal generation using proper design of nanoantennas may lead to composites with unusually strong difference-frequency effects.

Nonlinear active and metamaterials

A. K. Popov, Univ. of Wisconsin-Stevens Point (United States); I. R. Gabitov, The Univ. of Arizona (United States); N. M. Litchinitser, Univ. at Buffalo (United States); A. V. Kildishev, V. M. Shalaev, Purdue Univ. (United States)

In this talk, recent progress in nonlinear and active metamaterials will be reviewed. The phenomenon of anomalous field enhancement in graded-index metamaterials in the vicinity of zero index transition will be described. Exotic properties of coherent nonlinear-optical energy exchange between the ordinary and backward electromagnetic waves in negative-index materials, such as harmonic generation, frequency-mixing and optical parametric amplification, will be reviewed. Optical properties of active metamaterials with embedded amplifying centers will be described. The possibilities of compensating strong losses inherent to plasmonic metamaterials and for design of optical sensor and unique photonic microdevices will be discussed and numerically simulated.

Nonlinear spectroscopy on photonic metamaterials

S. Linden, Univ. Bonn (Germany); F. Niesler, N. Feth, M. Wegener, Karlsruher Institut für Technologie (Germany)

So far, research on photonic metamaterials has mostly concentrated on linear optics. However, photonic metamaterials can offer also interesting nonlinear optical properties, e.g., strong second harmonic generation (SHG). Unfortunately, our understanding of the nonlinear properties of photonic metamaterials is not as developed as the corresponding linear theory. In particular, the nonlinear mechanism for SHG from metallic nanostructures is still under debate. Here, we report on our recent experiments on nonlinear optical spectroscopy of second SHG from split ring resonator (SRR) arrays. In our experiments, the laser frequency is tuned over the fundamental resonance of the SRRs. We find that the SHG process is governed by
the fundamental resonance while the SRR resonance at roughly twice the frequency does not further amplify the SHG but rather leads to reabsorption.

8093-07, Session 2
Nonlinear metamaterials
D. R. Smith, Duke Univ. (United States)

Artificially structured metamaterials have shown enormous promise for their ability to realize unique electromagnetic response that can be used to enable such exotic constructs as negative index or transformation optical media. But, as interesting are the passive materials that have resulted from the metamaterials concept, potentially even more interesting are nonlinear metamaterials, in which the nonlinear susceptibilities of a medium can be designed with considerable freedom simply not available-or not as readily available-in conventional materials. The resulting “metacrystals,” which can be thought of as the analog of conventional nonlinear crystals, can provide new opportunities for managing the propagation of harmonics, and can have the capability to enhance or suppress certain nonlinear processes. We will describe a host of recently developed techniques for the accurate design and characterization of nonlinear metacrystals, showing that artificially structured media can be accurately described in the language of conventional nonlinear optics. Using metamaterial elements containing diodes and other nonlinear inclusions, we show the feasibility of nonlinear metacrystals at microwave frequencies, and demonstrate such phenomena as harmonic generation, three- and four-wave mixing, intensity-dependent resonance tuning, and similar phenomena. In all cases, analytical results, numerical simulations and measurements are all in excellent agreement, and point the way to the development of much more complex and interesting media.

8093-08, Session 2
Powered and nonlinear RF metamaterials
S. A. Cummer, B. Popa, Duke Univ. (United States)

The electromagnetic properties of metamaterials can be engineered to achieve substantially more flexibility and variety than those available from conventional materials. Yet even metamaterials as commonly realized through passive self-resonant metallic inclusions have some limitations. Adding some degree of external control or power to metamaterials can remove some of these limitations and gives metamaterials another level of functionality. We describe our recent efforts to develop an approach for realizing powered and nonlinear metamaterials in which each unit cell contains embedded active or nonlinear elements. Using a directly powered cell architecture, we demonstrate experimentally the effective electromagnetic material properties and the overall behavior that can be achieved with this type of active RF metamaterials. Characteristics such as loss and reciprocity that are dramatically different from passive metamaterials can be realized, potentially increasing the suitability of electromagnetic metamaterials for a variety of applications. We also describe our recent experimental work with active nonlinear metamaterials to create a phase conjugating lens. Varactor diodes are embedded in each metamaterial element and, when parametrically pumped with an external signal, can be made to generate a phase conjugated version of an illuminating source at close to half the pump frequency. We then demonstrate experimentally that an array of these nonlinear metamaterial elements does indeed act as a phase conjugating, and thus time-reversing and negative refracting thin material slab.

8093-09, Session 2
Second harmonic generation in index near zero transmission lines
I. V. Shadrivov, W. R. C. Somerville, D. A. Powell, The Australian National Univ. (Australia)

Nonlinear parametric effects are substantially suppressed in natural materials, because of the so-called phase mismatch. Various techniques, such as quasi phase matching, are used in order to overcome this limitation for achieving, e.g., efficient second harmonic generation. The essence of phase matching is that the indices of refraction for the interacting waves should be equal. This is why it is hard to find in natural materials - which should be dispersionless over the whole octave. In this work we pursue the idea of achieving phase matching between the waves with zero phase velocity. Such waves appear, e.g. in plasma near the plasma frequency, or in the so-called epsilon-near zero metamaterials. Here, we use the composite right-left handed (CRLH) transmission line with different parameters in order to achieve the required properties. We analyze the dispersion properties of such a transmission line, and study in nonlinear effects experimentally. We observe second harmonic generation, and demonstrate that it is enhanced near the frequency of zero phase velocity. We also measure experimentally the field distribution in the structure in order to experimentally determine its dispersion properties. We expect that similar regimes of the phase matching can be achieved in dual-band index-near-zero metamaterials.

8093-10, Session 2
Magnetoelastic nonlinear metamaterials
M. Lapine, I. V. Shadrivov, Y. S. Kivshar, The Australian National Univ. (Australia)

*(Invited for the Special Session on Nonlinear Metamaterials)*

For more than ten years, metamaterials are in a super-lens focus of research attention in electrodynamics and materials science. Rapid progress drives increasing interest in applied fields ranging from microwave engineering to optics. In particular, the possibility of nonlinear phenomena in metamaterials was soon explored [1,2], having established a new research direction with numerous promising ideas on nonlinear, tunable and active metamaterials [3,4].

The initial way to provide strong nonlinearity to metamaterials was found in either employing a nonlinear host medium [1] or engineering the elements of a metamaterial to include a nonlinear component [2]. Both the approaches result in a nonlinear response on the level of single element, which is further enhanced in a metamaterial, offering tools for harmonic generation, parametric amplification, loss compensation, solitons, tunability, etc.

Notably, the very structure of metamaterials remained fixed in such studies. At the same time, we recently reported [5,6] that structural changes in metamaterials offer an excellent means to control their properties, remarkably affecting resonance position and thus providing enhanced tunability of transmission, reflection and absorption.

In this talk, we report a further step forward and analyse a novel type of nonlinearity in metamaterials, which is achieved through specific conformational changes of the structure, analogous to those we employed in structural tuning. This results in exceptionally efficient self-action mechanisms.

For a detailed illustration, we consider an artificial magnetic metamaterial and analyse the nonlinear phenomena resulting from the structural changes, which give rise to unusual patterns of nonlinearity and bistability, providing a road towards interesting nonlinear phenomena.

REFERENCES


Nonlinear optical metamaterials are likely to enable new reconfigurable, ultra-compact opto-plasmonic devices that would bridge existing gaps in electronic-photon integration. Some of the most important functionalities to be realized in future opto-electronics chips include: i) buffering of optical signals to allow to avoid congestion of information traffic, ii) bridging the gap between micro-scale photonic waveguides (e.g., optical fibers) and nano-scale optical and electronic devices, and iii) low input power nonlinear optical signal processing. Although several approaches to the realization of such functionalities have been proposed and demonstrated, many of them are not easily scalable to a chip-size footprint.

In this talk we discuss our recent results on linear and nonlinear optics in guided-wave optical metamaterials and their applications for novel nonlinear photonic devices. We present a comprehensive analytical model for light propagation in coupled nonlinear waveguides for the most general case of arbitrary phase mismatch between the waveguides and arbitrary values of nonlinear coefficients and demonstrate that such nonlinear optical guided-wave structures enable a number of new phenomena and degrees of design freedom as compared to conventional nonlinear directional couplers. These unusual properties of metamaterial-based couplers form a basis for the development of ultra-compact all-optical processing applications, including all-optical buffers, flip-flops, and mirrorless lasers. We also discuss nonlinear optical wave propagation and interactions in transition metamaterial structures with various engineered graded refractive index profiles and discuss their potential applications for nonlinear low-intensity optical signal processing and sensing. Practical designs for the proposed structures will also be discussed.

Nonlinear metamaterial design for enhanced wave mixing.

E. Poutrina, A. Rose, D. Huang, D. R. Smith, Duke Univ. (United States)

For practical applications, the design and optimization of nonlinear metamaterial-based devices requires a quantitative approach, one that relates the particular metamaterial geometry incorporating non-linear elements to the nonlinear properties of the composite, effective medium. In recent work by Poutrina et. al, an analytical approach was developed allowing the description of a nonlinear metamaterial in terms of effective nonlinear susceptibilities, in analogy with the standard representation common in nonlinear optics. The analytical model employs a perturbative solution to the nonlinear oscillator model that describes a metamaterial inclusion in terms of an effective RLC circuit. In the present work, we use the developed approach to design a metamaterial with the predictably enhanced effective nonlinear characteristics and verify the theory predictions by simulating the three- and four- wave mixing processes in the designed geometries and by performing experiments on a varactor-loaded split ring resonator-based medium. We also demonstrate the capability of designing the symmetry properties of the effective medium for suppressing or enhancing the even-orders nonlinear response. Finally, we illustrate the manner in which the developed nonlinear metamaterial medium could be used to demonstrate nonlinear imaging based on wave-front reversal with four wave mixing.

Nonreciprocal transmission and one-way slow light in plasmonic metamaterials

A. B. Khanikaev, C. Wu, S. H. Mousavi, G. Shvets, The Univ. of Texas at Austin (United States)

Nonreciprocity is associated with a special class of systems for which forward and backward propagation behave differently. We propose plasmonic metamaterials endowed with extraordinary nonreciprocal optical properties. The structures considered represent (i) a subwavelength array of holes in an optically thin metal film and (ii) a low-symmetry metamaterial composed of periodically arranged meta-atoms made of plasmonic antennas embedded into magneto-optical medium. We show that both structures behave as one-way photonic mirrors, transmitting light only in one direction while stopping it in the opposite direction. It is found that in the case of the perforated metal the structure supports surface plasmon modes with nonreciprocal dispersion. Coupling of the incident radiation to these modes gives rise to the nonreciprocal response of the metamaterial. In the case of metamaterial made of plasmonic antennas, the nonreciprocal response is stemming from the resonances of individual meta-atoms. This approach allows for more flexibility in the design of the structure; very diverse nonreciprocal effects can be attained with the topologically similar meta-atoms but with slightly different geometrical parameters. As an example we designed the structure exhibiting one-way slow-light behavior, i.e. delaying light propagating in one direction but not in the opposite.

The main advantage of the proposed metamaterials as compared to their contemporary photonic counterparts stems from a significant difference made of plasmonic antennas, the nonreciprocal response is stemming from the resonances of individual meta-atoms. This approach allows for more flexibility in the design of the structure; very diverse nonreciprocal effects can be attained with the topologically similar meta-atoms but with slightly different geometrical parameters. As an example we designed the structure exhibiting one-way slow-light behavior, i.e. delaying light propagating in one direction but not in the opposite.

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Ultrashort nonlinearities of plasmonic metamaterials

M. Ren, A. Nikolaenko, E. Plum, N. I. Zholudev, Univ. of Southampton (United Kingdom)

We report on extraordinary strong nonlinear properties and ultrafast
transient dynamics of gold-based plasmonic metamaterials and metamaterial nanostructures aggregated with semiconductor nanotubes in order to account for the underlying physical processes observed in the experiments. We apply a Finite Element Method (FEM) with radial symmetry to numerically solve for the Z-scan experiment of a MDS using the corresponding nonlinear Maxwell equations. The amplitude and the phase of the electromagnetic field at the exit interface of the MDS are used for transforming to the far-field regime.

8093-19, Session 4

Suppression of plasmon losses in metamaterials by means of parametric bichromatic irradiation

A. Kussow, A. Akryurtlu, Univ. of Massachusetts Lowell (United States)

Novel mechanism of suppression losses in plasmonic subsystem in metals and semiconductors is suggested. If two parametrically coupled fields are applied to a metal plasma, a non-linearity of the transport equation affects the electric response, or the permittivity. If the coupling constant between the probe wave and the support wave is small, the permittivity, at the frequency of the probe wave, is still Drude-like, with the re-normalized plasmon frequency. In the case of a strong coupling, unusual response effects are possible (the induced transparency and the considerable suppression of the plasmon losses), with profoundly non-Drude permittivity function.

8093-18, Session 4

Z-scan simulations on metallodielectric stacks with nonlinear absorption

N. C. Katte, J. Haus, P. Powers, J. Gao, A. M. Sarangan, Univ. of Dayton (United States); M. Scalora, U.S. Army Aviation and Missile Command (United States); R. Jakubiak, Air Force Research Lab. (United States)

Experimental investigations reveal significant nonlinear responses from metallodielectric stacks (MDSs) with constituent metal films of silver (Ag), gold (Au) or copper (Cu). In particular, the Cu dielectric MDS exhibited large non-linear absorption. Nevertheless, there is a need to investigate these materials with more faithful numerical techniques as superlens imaging without using actual NIMs which are typically lossy, narrow band, and require complicated fabrication processes.

8093-17, Session 4

Harmonic generation and energy transport in GaP At visible and UV wavelengths

M. Scalora, U.S. Army Aviation and Missile Command (United States); V. Roppo, Univ. Politecnica de Catalunya (Spain); M. A. Vincenti, D. de Ceglia, N. Akozbek, The AEGIS Technologies Group, Inc. (United States)

We study inhibition of absorption, optical transparency, energy and momentum transport of phase locked harmonic pulses in semiconductors like GaP, at visible and UV wavelengths. In these spectral regions semiconductors are characterized by large absorption, metallic behavior, or a combination of both. This phenomenon is attributed to phase locking between the fundamental and its harmonics that occurs under phase mismatched conditions, irrespective of material parameters, as long as the material is somewhat transparent to the pump. As a result of phase locking the pump impresses its dispersive properties to the generated harmonics which in turn experience no absorption or other de-phasing effects such as group velocity walk-off. The harmonics co-propagate phase- and velocity-locked to the pump, and any energy exchange between the pump and its harmonics ceases away from interfaces. We show experimental and theoretical evidence that phase locking causes the generated harmonics to propagate through GaP at 223nm, where the material displays metallic response, without being absorbed, and that the transport of electromagnetic energy and momentum is quite peculiar and seemingly anomalous. We also show that it is possible to exploit cavity environments to generate and enhance harmonic generation below 200nm in semiconductors like Silicon. These results make it clear that there are new opportunities in ultrafast nonlinear optics and nano-plasmonics in new wavelength ranges.

8093-16, Session 4

Optical negative refraction by four-wave mixing in thin metallic nanostructures

X. Zhang, Univ. of California, Berkeley (United States)

While all natural materials exhibit refraction in the positive direction, artificially engineered negative index metamaterials (NIM) have been shown capable of bending EM waves negatively. We report the experimentally observed nonlinear negative refraction at optical frequencies using four wave mixing (4WM), wherein the incident and negatively refracted beams are at different frequencies. The nonlinear negative refraction could potentially impact many important applications such as superlens imaging without using actual NIMs which are typically lossy, narrow band, and require complicated fabrication processes.

8093-21, Session 5

Spontaneous emission near hyperbolic metamaterials

Z. Jacob, Univ. of Alberta (Canada); I. I. Smolyaninov, Univ. of Maryland (United States); E. Narimanov, Purdue Univ. (United States)

Engineering the photonic density of states using microcavities or photonic crystals helps to control a plethora of phenomena associated with light. While the unique electromagnetic response of metamaterials and their capabilities have received widespread attention, the role of the PDOS in nanostructured metamaterials has been unexplored. Here, we unravel how a unique dielectric response can give rise to a divergence in the PDOS for bulk propagating waves within a medium and understand other intriguing properties and advantages of metamaterial based PDOS engineering especially in connection to the Purcell effect.

As opposed to conventional methods for enhanced and directional spontaneous emission based on closed cavity Purcell enhancement of spontaneous emission or open cavity approaches based on photonic crystal waveguides, our design relies on a completely new approach, namely the singularity in the density of states of a hyperbolic dispersion medium. The dielectric response of the medium surrounding the emitter is engineered to provide dramatically increased density of photonic states in a broad bandwidth as well as inherent directionality to the emitted photons. An increased density of photonic states immediately translates...
to a larger number of radiative decay channels available for an excited atom ensuring enhanced spontaneous emission, a necessary quality for single photon sources.

We use a green's function approach to calculate the local density of states. In the limit of zero losses, under the effective medium approximation, the LDOS near a hyperbolic dispersion medium is infinite. We use the semiclassical theory of spontaneous emission to analyze the divergence of the decay rate of an emitter near a metamaterial due to the singularity in the density of states. For a medium which has the dielectric permittivities of opposite signs in perpendicular directions and no losses, the decay rate of a point dipole diverges. This divergent behavior of the decay rate is in counterintuitive to the conventional response of materials where the decay rate and the LDOS goes to a constant value when losses are zero.

8093-22, Session 5

**Transition metamaterials in materials with hyperbolic dispersion**

A. Pandey, E. A. Gibson, N. M. Litchinitser, Univ. at Buffalo (United States)

Recently, we predicted new phenomena occurring due to the electromagnetic wave propagation in metamaterials with material parameters gradually changing from positive to negative values, transition metamaterials. At oblique incidence, we predicted the phenomenon of anomalous electromagnetic enhancement and resonant absorption in the vicinity of the point where the refractive index changes sign. In all previous studies, we considered an effective isotropic medium with assigned values for dielectric permittivity and magnetic permeability that give rise to an effective gradually changing refractive index. However, the particular mechanism of dissipation and the influence of the microscopic structure of metamaterials on the field enhancement phenomenon would be determined by a physical model of a metamaterial.

In this work, we design and investigate electromagnetic wave propagation in transition metamaterials based on two materials systems: metal/dielectric multilayered structures for optical frequency range and highly doped/undoped semiconductors for mid-infrared frequency range. In the latter case, the level of doping is carefully adjusted such that the effective refractive index gradually changes from positive to negative values. It was shown (Narimanov et al.) that strongly anisotropic materials that possess a negative permittivity component along the direction perpendicular to the interface and positive component along the interface, have hyperbolic dispersion relations. As a result, the component of the Poynting vector along the interface is opposite to the direction of the wavevector component along the interface, leading to the effective negative refractive index. We investigate how the dispersion relation changes when the refractive index gradually changes from positive to negative in these structures.

8093-23, Session 5

**Multilayered metamaterials with hyperbolic dispersion**

T. U. Tumkur, G. Zhu, P. J. Black, C. E. Bonner, M. A. Noginov, Norfolk State Univ. (United States)

We have developed and studied a family of hyperbolic metamaterials consisting of lamellar metal-dielectric structures which can be fabricated on flat, flexible and curvilinear substrates and functionalized by emitting dye molecules. Hyperbolic materials can accommodate waves with high wavevectors and hence possess broadband singularity in the density of photonic states [1]. Owing to this property, we demonstrate the reduction of radiative lifetimes of emitters. We have also shown that the spontaneous lifetime reduction is much stronger when emitters are placed inside a metamaterial rather than on its surface. Three different types of metal-dielectric lamellar structures, consisting of organic and inorganic dielectric components have been fabricated. The first type consisted of 20 alternating layers of silver and IR-140 dye-doped PMMA, which, in agreement with theoretical predictions [1], showed a strong reduction of the fluorescence lifetime, down to 286 ps when the sample was illuminated from the front and 217 ps when it was illuminated from the rear. For comparison, the emission lifetimes of the same dye deposited onto a glass substrate and silver film were equal 716 ps and 607 ps, respectively. Expectedly, the fluorescence lifetime reduction in films deposited on the top of other undoped metamaterials (including Ag-LiF, Ag-MgF2 and Ag-PMMA lamellar structures), was considerably smaller, as in the case of Ag-LiF which had a fluorescence lifetime equal to 499 ps. Our observation paves the road to many exciting applications including a single photon gun needed for quantum optics and information technology [1].


8093-24, Session 5

**Transfer matrix approach to propagation of angular plane wave spectra through metamaterial multilayer structures**

P. P. Banerjee, H. Li, R. Aylo, G. T. Nehmetallah, Univ. of Dayton (United States)

The development of electromagnetic (EM) metamaterials for perfect lensing and optical cloaking has given rise to novel multilayer bandgap structures using stacks of positive and negative index materials. Gaussian beam propagation through such structures have been analyzed using transfer matrix method (TMM) with paraxial approximation [1], and unidirectional and bidirectional beam propagation methods (BPMs) [2,3]. Since TMM is naturally a plane wave approach, we use this technique to analyze the non-paraxial propagation of a collection of TE or TM polarized plane waves having an initial Gaussian amplitude profile in 1 transverse dimension (x) through a stack containing layers of positive and negative index materials. The spatial variation of the electric field at any plane (z) during bidirectional propagation through the stack is found from the composite angular plane wave spectrum. Specifically for the TM case, the spatial variations of both the x and z polarization components are calculated. The numerical results from TMM are compared with numerical simulations using FEM and FDTD techniques. The TMM calculations are exact, less computationally demanding, and can be performed for arbitrary angular plane wave spectra. Finally, the TMM based angular plane wave spectrum approach can be readily applied to a wide variety of other cases, such as propagation through induced reflection gratings in nonlinear media.


8093-25, Session 5

**Fingerprinting metamaterial behavior in 2D periodic composites: Fundamentals and applications to THz optics.**

S. Foteinopoulou, The Univ. of Exeter (United Kingdom); M. Kafesaki, E. N. Economou, Foundation for Research and Technology-Hellas (Greece); C. M. Soukoulis, Iowa State Univ. (United States)

2D periodic composites can behave as uniaxial effective media, with the possibility of extra-ordinary hyperbolic dispersion, not available in natural materials. Such hyperbolic type of dispersion typically occurs when constituents with negative permittivity are present. Accordingly, 2D composites incorporating polar materials can act as uniaxial hyperbolic effective metamaterial. Thus, they become highly attractive structures, since they can enable extra-ordinary beam manipulation in the THz...
regime (0.1-10 THz) where traditional visible optics is not suitable. While often the metamaterial composites can be described by traditional effective medium theories, this is not always the case. A mere deviation between actual transmission/reflection and the values predicted by effective medium theory does not necessarily imply effective medium picture breakdown.

Here, we developed a new criterion that establishes an angular fingerprint of effective metamaterial behavior for two-dimensional (2D) composites. We apply such criterion to characterize different candidate polar-polar and polar-dielectric 2D composite structures as effective metamaterials. We found polar-polar metamaterial structures that are highly transmissive in cases where transmission through an identical slab made of either of the constituents would be next to none. In addition, our results suggest that pola-material based metamaterials demonstrate interesting and unusual angular transmission maps for the different polarization channels. We analyze and discuss the underpinning physics of such curious angular polarization-dependent transmission, and how to utilize it for the design of efficient polarization filters and converters.

8093-77, Poster Session

Toward curvilinear metamaterials based on silver filled alumina template

Y. A. Barnakov, P. J. Black, Norfolk State Univ. (United States); N. Kiriy, Cornell Univ. (United States); H. Li, A. V. Yakim, L. Gu, M. A. Noginov, Norfolk State Univ. (United States)

The advent of metamaterials and their continued development over the past decade has revolutionized the fields of electrodynamics and photonics, giving new perspective to the classical interaction of light with matter and enabling scores of unparalleled physical phenomena. Despite of recent tremendous progress in both theory and experiment, the research field is hindered by a lack of inexpensive large-size three-dimensional metamaterials. One way to overcome this problem is to utilize bulk dielectric templates, which nanoporous space can be filled with metals or other dielectrics. Recently, we have demonstrated that an array of silver nanowires embedded into a flat alumina membrane matrix with 35nm-diameter pores behaves as a metamaterial with hyperbolic dispersion, characterized by different signs of the electric permittivity tensor elements. It has been theoretically predicted that a metamaterial with hyperbolic dispersion realized in curvilinear coordinates (with radial or azimuthal anisotropy of metallic inclusions) has a property of a hyperlens - a device allowing for sub-diffraction imaging in the far field. The structure with a similar ‘hair brush’ morphology but different radial distribution of electric permittivity has been predicted to have a functionality of a non-magnetic optical cloak. In this work, we explore a family of novel curvilinear metamaterials fabricated via inexpensive non-lithographic means. This synthetic route opens a door to design and fabrication of large, three-dimensional bulk metamaterials for a number of practical applications ranging from optical cloaking to broadband sub-wavelength imaging.

8093-78, Poster Session

Microwave superlens with sloped faces

M. K. Khodzitskii, A. P. Slobodzanuk, D. S. Filonov, National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation); P. A. Belov, Queen Mary, Univ. of London (Russian Federation)

Over the last ten years, the various designs of superlens have been developed [1-3]. Some of them are based on the concept of canalization of sub-wavelength images [4]. These developments are widely used in the near-field microscopy and magnetic resonance imaging (MRI) [5-6]. In this paper, based on the existing designs of wire medium superlenses, a superlens with sloped faces has been designed. The superlens was developed to increase the resolution and sensitivity of the NMR tograph with a resonant frequency of 63.86 MHz and magnetic field induction of 1.5 T. The lens has length of 250 cm, the slope of faces is 30 degrees and the size of the working aperture is 40*20 cm2. It consists of a 20x20 array of brass wires with diameter of 2 mm and period of 10 mm. Due to sloped faces, the lens becomes more convenient device for NMR tomography of biological objects. Investigation of near-field transfer by the lens was carried out in the frequency range of 60-68 MHz. A wire antenna in the form of a flag was selected as the source. The flag was located on the distance of 2 cm from the surface of the lens. Numerical simulation in the CST Microwave Studio software package has shown the transmission of the image in the form of a flag with J/500 resolution to λ/5 distance.


8093-79, Poster Session

Polarization-insensitive and omnidirectional near perfect broadband metamaterial absorber in the near infrared regime

S. Chen, H. Cheng, J. Tian, Nankai Univ. (China)

We present a near perfect broadband metamaterial absorber in the near infrared regime. The electromagnetic response of mixed-size cut wires combined with thick metal layer is theoretically studied. The broadband absorber is polarization insensitive and the absorption remains high even at large incident angle for both transverse electric (TE) and transverse magnetic (TM) polarizations. By simply adding more loops of the cut wires, the bandwidth of the strong absorption can be effectively enhanced due to the hybridization of surface plasmons in different loops.

8093-80, Poster Session

Liquid crystal-metal nanorods composites with spatially distorted optic axis for transformation optics

J. Xiang, O. D. Lavrentovich, Kent State Univ. (United States)

Transformation optics uses materials with spatially varying optical properties to control the trajectories of light propagation. The concept is familiar to liquid crystals, in which the optic axis can adopt various configurations in space. For example, a cylindrical nematic LC sample with the optic axis arranged radially would form the light trajectories in such a way that they diverge, leaving a cylindrical wedge behind the axis of the structure un-illuminated, with the angle that depends on the optical anisotropy of the liquid crystal. In this work, we consider a hybrid system, representing a liquid crystal with dispersed metal nanorods, in which the effective refractive index depends on the volume fraction of the metal component. In this hybrid material, one can control not only the orientation of the local optic axis, but also the values of the effective refractive indices. We simulate propagation of light in three basic geometries, filling the composite material in the space between two concentric cylinders, with the optic axis represented in the cylindrical
coordinates as (a) or (b) where changes from 0 to when increases (b) or decreases (c) in the range. We demonstrate that the geometries (b) produce a non-magnetic optical cloaking effect, while (c) produces a condensing effect on light propagation. This work was supported by AFOSR FA9550-10-1-0527 grant.

8093-81, Poster Session

Modeling of nonlinear metamaterials
P. L. Colestock, M. Reiten, J. F. O'Hara, Los Alamos National Lab. (United States)

We report the results of a study to model the behavior of nonlinear metamaterials in the microwave frequency range composed of arrays of split-ring resonators combined with nonlinear circuit elements. The overall model consists of an array of coupled damped oscillators whose inter-element coupling is a function of signal amplitude, similar to that which exists in the Fermi-Pasta-Ulam system. [1] We note the potential occurrence of classical nonlinear effects including parametric coupling and FPU recurrence. These in turn lead to nonlinear waves on the array which are a type of soliton particular to the form of nonlinearity that has been incorporated. We have studied, in particular, the nonlinear effects that arise from tunnel diodes embedded in the resonant circuits. Whether or not the aforementioned nonlinear phenomena occur is a function of the details of the nonlinearity and the inherent circuit losses. We derive conditions for stable oscillations and carry out simulations of the resulting circuit frequency response. We shall present these modeling results along with preliminary experimental data from laboratory measurements of prototype nonlinear metamaterials.

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8093-82, Poster Session

Plasmonic toroidal response at optical frequencies
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Toroidal dipole is created by currents flowing on a surface of a doughnut-shaped structure along its meridians first considered by Zel’dovich in 1957 [1]. Toroidal metamaterials were first theoretically proposed in 2007 [2]. In 2010, the toroidal metamaterials consisted by four three-dimensional resonant split rings show toroidal response in microwave region [3].

In this paper, we study the optical responses by integrating four U-shaped split-ring resonators (SRRs) together. The resonances of the four U-shaped SRRs array with magnetic field of incident light passing through the resonant rings was numerically investigated by using commercial software COMSOL 3.5a based on finite-element method (FEM). The permittivity of gold was described by the Lorentz-Drude model [4]. The size of a single U-shaped SRR is 110 nm (arms) × 90 nm (bottom) and 30 nm line width wire loop. Simulation results shows toroidal and magnetic dipole resonance at free space wavelength 660 nm and 952 nm respectively. Incident light induced magnetic dipoles point in the same direction produced magnetic resonance. In contrast, four magnetic dipoles form a head-to-tail configuration which concentrates toroidal resonance.

References:

8093-84, Poster Session

infrared absorbance of wavelength-selection trapezoid grating
J. Sze, Instrument Technology Research Ctr. (Taiwan); A. Wei, Foxsemicom Integrated Technology Inc. (Taiwan); F. Chen, Instrument Technology Research Ctr. (Taiwan); K. Lee, Chinese Culture Univ. (Taiwan)

A trapezoid grating which improve the contrast of the wavelength-selection infrared absorbance is demonstrated. The absorbance of wavelength-selection trapezoid grating is studied by using the rigorous coupled-wave analysis (RCWA) numerical scheme. The side wall slope of the trapezoid silicon grating plays an important role in the infrared absorbance enhancement. According to the calculated spectral absorbance curves of the trapezoid gratings, it is found that the peak is located at the wavelength of 7.0 micrometer, which is equal to the period of the trapezoid grating. The analyzed results show that the maximum contrast absorbance of the trapezoid grating is given at the side wall slope of 18. The modified shape of the gratings side walls can be used for further tailoring thermal radiation properties which is useful for enhancing the performance of infrared detectors.

8093-85, Poster Session

Polarization effects in second harmonic generation from G-shaped nanostructures
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Planar chiral nanostructures are novel structures that attract attention first of all by their possibility to influence the polarization properties of the transmitted or reflected light by rotating its polarization plane or changing...
its ellipticity. In case of the second harmonic generation (SHG) the changes can be more significant. The high sensitivity of the SHG process to the symmetry and shape of the structures can lead to the appearance of new effects such as anisotropy of the rotation of the polarization plane or depolarization of the SHG response. In case of spiral structures one can expect different strength of the nonlinear interaction under the excitation by the left and right circularly polarized pump radiation. In this work, polarization properties of optical SHG from arrays of gold G-shaped nanostructures are studied.

Samples were formed as an array of 1x1 microns gold G-shaped nanostructures of 25 nm thickness on the silicon surface. The reflected SHG was studied using an output of the Ti:Sapphire laser at 780 nm. A strong anisotropy of the SHG intensity is observed, induced by the anisotropic amplification of the distribution of the SHG and fundamental fields under the excitation of the structure by linear or circular polarized fundamental beams. Stokes parameters and intensities of polarized and depolarized SHG components were estimated from the experimental data. The intensity of the depolarized SHG component is found to be comparable with the polarized one, both of them being anisotropic and has the symmetry though nor each nanostructure nor the whole array are symmetric. It was found, that one of SHG efficiency is strongly dependent of the type of the circularly polarization of the fundamental radiation.

**8093-86, Poster Session**

**Second and third harmonic generation at UV and soft x-ray wavelengths from semiconductor gratings**

M. A. A. Vincenti, D. de Ceglia, The AEgis Technologies Group, Inc. (United States); M. Scalora, U.S. Army Aviation and Missile Command (United States)

Extraordinary transmission properties are demonstrated in the UV range for GaAs gratings with sub-wavelength apertures under TM-polarization excitation. The metal-like response below 270nm, typical of several semiconductors such as GaAs or GaP, in fact may be used to excite surface waves that lead to enhanced transmission in the linear regime and to novel nonlinear optical phenomena in the UV and soft X-ray ranges. An investigation of the linear transmission as a function of geometrical parameters of the grating reveals the formation of surface waves and relatively high transmission values even in regimes where the nominal absorption is significant. Strong field localization in sub-wavelength cavities and on the surface of the grating can be achieved under proper excitation conditions leading to the enhancement of harmonic generation. Nonlinear contributions to harmonic generation arise from symmetry breaking and the nonlinear magnetic Lorentz force. Preliminary results show promising nonlinear conversion efficiencies at wavelengths below 100nm, and demonstrate cross-coupling of TE and TM polarizations for pump and harmonic signals. A down-conversion process that can re-generate pump photons of polarization orthogonal compared to the incident pump field is also demonstrated.

**8093-87, Poster Session**

**Enhanced nonlinear optics in resonant GaAs gratings: harmonic generation and optical bistability**

D. de Ceglia, G. D’Aguanno, N. Mattiucci, M. A. A. Vincenti, The AEgis Technologies Group, Inc. (United States); M. Bloemer, M. Scalora, U.S. Army Aviation and Missile Command (United States)

We present a study on nonlinear optical processes in GaAs gratings, made by perforating a single layer of GaAs with subwavelength slits. Large enhancement of conversion efficiency, for both second and third harmonic generation, is predicted when a TE-polarized pump field excites the guided mode resonances of the grating. When these modes are excited, the spectrum near the pump wavelength shows abrupt changes of linear transmission and reflection that follow a typical Fano-like shape. At the same time the grating provides dramatic enhancement of local fields and fosters favorable conditions for harmonic generation processes, even in regimes of strong linear absorption at the harmonic wavelengths. In particular, in a GaAs grating pumped at 1064nm, we predict second (632nm) and third (354nm) harmonic conversion efficiencies several orders of magnitude larger than conversion rates achievable in either bulk or etalon structures made of the same material. We demonstrate that these efficiencies are not influenced by linear absorption at the harmonic wavelengths, and they are unrelated to grating thickness or to the order of the guided mode excited. We also analyze the effects of self phase modulation on resonant gratings. In particular we will demonstrate the possibility of triggering optical bistability at relatively low switching intensities by exploiting the strong field localization provided by the grating at the guided mode resonances. Finally, we will discuss the influence of self-phase modulation on the harmonic generation conversion efficiencies.

**8093-88, Poster Session**

**Nonlinear optical couplers based on strongly anisotropic metamaterial waveguides**

G. Venugopal, N. M. Litchinitser, Univ. at Buffalo (United States)

Nonlinear waveguide couplers have attracted a lot of interests in the recent years. Combined with the unique properties of metamaterials, nonlinear directional couplers open fundamentally new opportunities for the development of ultra-compact signal processing functionalities for on-chip applications. Recently, we proposed a novel kind of nonlinear coupler with one channel filled with linear negative index material and another one filled with positive index material one or both of which could be nonlinear. The opposite directionality of phase and velocity in such systems lead to an effective feedback mechanism. We found exact analytical solutions and predicted that such systems can be bi- or multi-stable and support a family of gap solitons. However all previous studies were based on coupled-mode analysis assuming that effective medium parameters for dielectric permittivity and magnetic permeability of metamaterials.

In this work we discuss the design and simulation of nonlinear couplers based on strongly anisotropic metamaterial waveguides. Such waveguides were shown to support negative-index propagating modes (Podolskiy and Narimanov). For these modes, the wave propagation is in a direction opposite to the phase velocity. As a result, the waveguide behaves as a 2-dimensional counterpart of 3-dimensional negative index material. The waveguides in a coupler that we design consists of alternating metal and dielectric subwavelength layers with positive and negative permittivities, respectively. As a nonlinear optical material, we incorporate chalcogenide glass that was demonstrated to have relatively high nonlinear refractive index of ~ 10^-13 cm2/W. We will report numerical simulations demonstrating novel transmission properties of such couplers, including distributed feedback and bistability.

**8093-89, Poster Session**

**Optical negative refraction by four-wave mixing in metallic nanostructures**

S. Palomba, Univ. of California, Berkeley (United States); S. Zhang, The Univ. of Birmingham (United Kingdom); Y. Park, X. Yin, X. Zhang, Univ. of California, Berkeley (United States); G. Bartal, Technion-Israel Institute of Technology (Israel)

While all natural materials exhibit refraction in the positive direction, artificially engineered materials have been utilized in various ways to bend EM waves negatively. Bulk metamaterials and photonic crystals demonstrated negative refraction of the EM energy flux and wavevectors. A direct way to obtain negative refraction from very thin film has been
theoretically proposed by Tretyakov and Pendry.

Here, we demonstrate nonlinear negative refraction, by using degenerate four-wave mixing (FWM) process to show efficient frequency conversion by a 20nm thick gold film where the newly generated frequencies emerged at a negative angle comparing to the exciting wave. The ratio between the sines of the incident and nonlinearly refracted angles remains a negative constant and depends only on the wavelengths ratio hence rigorously fulfills Snell’s law, expanding the phenomenon of negative refraction into the nonlinear regime. Showing the ability for negative refraction by very thin slab, such nanosystems could constitute the building blocks for the implementation of a super lens in the visible region and possible further investigations.

Our approach can operate for all frequencies and polarizations and has no nonlocal effects typically present in metamaterials and it constitutes the first demonstration of negative refraction in ultrathin films.

8093-90, Poster Session

second order optical susceptibilities of ZnO(0001) and NiO(001) surfaces

A. V. Gavrilenko, V. I. Gavrilenko, Norfolk State Univ. (United States)

Direct fabrication of complex nanostructures with controlled crystalline morphology, orientation and surface architectures remains a significant challenge. Nonlinear optical spectroscopy of the second harmonic generation (SHG) is a tool that is extremely sensitive to a very thin surface layer (up to few atomic monolayers). This technology is therefore a very powerful tool for contact-less monitoring of the nanocrystal growth, as well as surface, and interface structural quality. In this work we study SHG spectra of hexagonal zinc oxide (0001) and nickel oxide (001) surfaces as materials extensively studied for different applications in nanophotonics. Electron energy structure and second order nonlinear optical susceptibilities have been studied from the first principles within the Density Functional Theory (DFT) using ab initio pseudopotentials. Equilibrium geometries of (001) surfaces are obtained by total energy minimization method using the Local Density Approximation (LDA). Optical functions are calculated within the independent particles picture. Analysis of the results is focused on understanding of the physics behind the formation of the second order optical response from the transition metal oxide surfaces, namely contributions of oxygen and metallic d-electron related excitations. Strong contribution to the nonlinear optical susceptibility functions of the high-density d-electrons below the Fermi energy in transition metals is demonstrated. Theoretical predictions are compared with available experimental data.

8093-91, Poster Session

Experimental harmonic generation in the metallic regime of GaP

V. Roppon, Univ. Politecnica de Catalunya (Spain) and Charles M. Bowden Research Ctr. (United States); J. V. Foreman, N. Akozbek, Charles M. Bowden Research Ctr. (United States); M. A. A. Vincenti, AEGis Technologies Group (United States); M. Scalora, Charles M. Bowden Research Ctr. (United States)

When a pump signal traverses an interface into a nonlinear medium it generates SH and/or TH fields, depending on the type of nonlinearity involved. Each harmonic consists in a homogeneous portion that walk-off from the pump field and in an inhomogeneous component phase- and velocity-locked to the pump. The key observation here is that the inhomogeneous component always experiences the same complex index of refraction identical to the index of the pump, which is tuned in a region of transparency. A detailed investigation of the propagation characteristics of the inhomogeneous component in different circumstances can bring about new interesting scenarios. For example, it has been shown that in a high-Q GaAs cavity the inhomogeneous SH signal (at 612nm) can achieve conversion efficiencies of the order of 1e-3 with pumping field intensities as low as 0.15MW/cm² inside the cavity.

Following the evolution of this topic, it now comes natural to ask the following question: does this phenomenon hold for harmonic fields tuned at frequencies in the metallic range? That is to say, if the pump field is tuned in the transparency region, will a harmonic field propagate if it happens to be tuned in a region where sign(ε)<0, where one expects no propagating solutions? The short answer to this question is yes and we provide experimental evidence that show how an electromagnetic field is generated and propagates in otherwise forbidden wavelength ranges.

8093-92, Poster Session

Wave propagation in lossy MTMs surrounded by linear and nonlinear media with arbitrary nonlinearity

Z. I. Al-Sahhar, Al-Aqsa Univ. (Palestinian Territory, Occupied); H. J. El-Khazondar, M. M. Shabat, Islamic Univ. of Gaza (Palestinian Territory, Occupied)

The dispersion relation in a system consists of a lossy metamaterials (MTMs) film surrounded by a linear substrate and a nonlinear cladding with an arbitrary nonlinearity is derived. The surface plasmonic (SP) wave at the interfaces between metamaterials (MTMs) and the nonlinear cover is recovered by taking certain limits. Lossy MTMs have simultaneously complex-negative permeability µ and complex-negative permittivity ε. Results are presented by plotting the SP frequency as a function of the nonlinearity at chosen damping factors. Both the real and imaginary parts are studied. Results also display the wave frequency as a function of plasma frequency. For comparison, the imaginary part is set to zero and curves are reproduced.

8093-93, Poster Session

Super Talbot effect in anisotropic metamaterial

W. Zhao, Z. Lu, Rochester Institute of Technology (United States)

Advances in metamaterial provide the possibilities to engineer the permittivity of a metamaterial to be almost any arbitrary value (positive, zero, or negative), In particular, if the real part of the permittivity component along the light propagation direction is negative, while the transverse ones positive, the dispersion curve is in hyperbolic form. The anisotropic metamaterial (or hyperbolic metamaterial) can convert the evanescent waves which would normally decay in the conventional materials into propagating waves. The anisotropic metamaterial can be realized by depositing thin, alternating metal-insulator layers.

In this paper, we re-visit the classical optical phenomenon, called Talbot effect and investigate this effect in such an anisotropic metamaterial. From 2D and 3D numerical simulation results, we show that the super Talbot effect can be observed in the metamaterial even the period of the object is much smaller than the incident wavelength. Deep subwavelength resolution of the super Talbot effect can be achieved as long as the attenuation of the metamaterial is small enough. As the incident wavelength is 630nm, the period of the input grating is 94nm and the duty cycle is 50%, for an Ag-SiO2 layered structure (dAg=50nm; dSiO2=5nm), the image size measured at the fourth Talbot imaging plane is about 55nm. The Talbot distance measured is around 152nm. The corresponding effective permittivity is calculated at 6.16+i0.31 (along propagation direction) and 4.94+i0.05 (along transverse directions).
The super Talbot effect may have the applications in the areas of nanolithography and optical storage.

8093-94, Poster Session

Numerical optimization for the plasmonic Raman sensor including periodic hole arrays and taping directions

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Metal nanostructures are interesting for achieving new types of biosensors because they can work as nanocavities that have high sensitivity when surface plasmons are used. This approach should let us detect the binding reactions of molecules in real time with high sensitivity. However, to achieve this, we must greatly enhance the electromagnetic field and Raman radiation.

Nanofocusing structures for surface plasmons could present a breakthrough in achieving both nanoscale confinement of electromagnetic energy and large, highly controlled local field enhancement required for efficient surface-enhanced Raman scattering.

We previously fabricated a nanofocusing (tapered) hole array in a metal film on a dielectric substrate by using focused ion beam (FIB) lithography and succeeded in observing localized surface plasmon resonances. The results of experiments using this array agreed with most of the calculation results for a tapered hole array obtained using the finite-difference time-domain (FDTD) method. Moreover we numerically determined structural design optimization at the dependencies of the expected local field enhancements on Au film thickness, focusing hole diameter, and hole period by the FDTD method in order to take into consideration the plasmonic resonance effects and we concentrated our efforts on periodic nanofocusing hole arrays at the metal-substrate interface.

In this paper, we analysed further structural parameters such as differ from tapered direction and incident direction with the theoretical predictions.

8093-26, Session 6

Metamaterials and plasmonics: improved material building blocks

G. V. Naik, J. Kim, P. R. West, A. Boltasseva, Purdue Univ. (United States)

Conventional metals like silver and gold that are used as building blocks for optical metamaterials exhibit excessive losses at optical frequencies. This seriously threats to restrict plasmonic and metamaterial devices in this frequency range to only the proof-of-concept stage. A recent approach that could unlock the technological potential of plasmonics and optical metamaterials is to look for better plasmonic materials (which must have a negative real part of dielectric permittivity). Here we provide an overview of two classes of alternative plasmonic materials - doped semiconductors and intermetallics - that could allow realization of novel transformation optics and metamaterial devices with greatly improved performance operating at near infrared and visible frequencies.

8093-27, Session 6

Understanding and reducing losses in metamaterials

C. M. Soukoulis, Iowa State Univ. (United States)

One of the most serious obstacles when increasing the frequency towards the visible regime is the problem of ohmic losses in the metallic elements and absorption losses in the substrate. By optimizing the overlap of the electromagnetic field and the metal, the metamaterial losses can be reduced by design to some extent. We will present a detailed study of developing the self-consistent calculations of gain with metallic nanostructures in 2D and 3D. The need for self-consistent calculations stems from the fact that by increasing the gain in the metamaterial, the metamaterial properties change, which, in turn, increasing the coupling to the gain medium until a steady state is reached. We will present theoretical and numerical studies has been demonstrated by optical pumping the effective gain coefficient of the combined system can be much higher than its bulk counterpart due to the strong local-field enhancement inside the metamaterial designs. Although optical pumping can compensate losses, it will not materialize to real world applications. We will review how one can reduce the losses with realistic applications; one needs to use semiconductors with gain (quantum dots and quantum wells), which can be pumped by electrical injection. This is compatible with semiconductor industry.

8093-28, Session 6

Effect of losses on nonlocal effects in metal-dielectric multilayered metamaterials

A. A. Orlov, P. M. Voroshilov, National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation); P. A. Belov, National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation) and Queen Mary Univ. of London (United Kingdom); Y. S. Kivshar, The Australian National Univ. (Australia) and National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation)

We study the effect of losses on spatial dispersion in metal-dielectric multilayered metamaterials. Previously we discovered that under certain conditions two waves instead of one can be excited in metamaterial under consideration by incident TM-polarized light beam. As was demonstrated earlier, under certain conditions such periodic structures demonstrate strong nonlocal effects manifested, e.g., in the appearance of the second extraordinary wave which can be excited in the metamaterial by an incident TM-polarized light beam and observed through the beam splitting. The existence of an additional light wave is a clear manifestation of the presence of spatial dispersion in the metamaterial, and it validates our earlier observation of strong nonlocal nature of metal-dielectric multilayered metamaterials. Our analysis of such structures with realistic losses demonstrate that losses naturally cause damping of the waves inside of the metamaterial and also reduce the frequency range where birefringence without splitting by polarization is observed. When we employ realistic losses for silver (Ag) as metal, we reveal that the typical losses of silver in the visible range are too high for our purposes. Hence, we consider an active medium with a gain in order to compensate losses.

8093-29, Session 6

Scaling of loss in metamaterials

J. B. Khurgin, The Johns Hopkins Univ. (United States)

It is important to distinguish two separate mechanisms of metamaterial loss increase with frequency: intrinsic material-related loss and purely size-dependent mechanism associated with inability of storing energy outside the metal at high frequencies when electro-static limit is being approached. By highlighting the above we establish the fact that fundamentally losses in the metamaterials with true sub-wavelength features cannot be improved for frequencies higher than 100’s of GHz and show that at optical frequencies roughly the same performance is obtained using magnetic (e.g. split rings) and non-magnetic (e.g. spherical and elliptical nanoparticles) metamaterials.
Graphene in metamaterials: What makes a material a good conductor?

P. Tassin, T. Koschny, Iowa State Univ. (United States); M. Kafesaki, Foundation for Research and Technology-Hellas (Greece); C. M. Soukoulis, Iowa State Univ. (United States)

Recent developments in the field of metamaterials—or engineered materials with novel electromagnetic properties—have promised a number of exciting applications, in particular at optical frequencies. Most metamaterials consist of carefully designed metallic structures that replace atoms in their role as the basic units of interaction with electromagnetic radiation. Unfortunately, the noble metals are not particularly good conductors at optical frequencies, resulting in significant absorptive loss in photonic metamaterials. Recently, several materials have been proposed to replace metals as the currently-carrying elements in metamaterials, such as graphene at optical frequencies and high-Tc superconductors at terahertz frequencies. In this communication, we first address the question of what is a good conductor for use in a metamaterial. We develop a model based on the quasistatic response of metamaterial constituents to an incident electromagnetic field in order to develop a figure of merit for conductors. The results lead to two conclusive ideas: (1) In determining the merits of a certain conducting material, its material properties cannot be uncoupled from certain geometric aspects, such as the layer thickness that can be experimentally obtained. (2) It is the resistivity of the material, rather than the conductivity or permittivity, that gives direct information on the absorptive loss in the metamaterial and on the frequency saturation caused by kinetic inductance. These considerations lead to a figure of merit for conducting materials. Finally, we apply the figure of merit to a number of materials, such as graphene and high-Tc superconductors.

All kinds of cloaks, all kinds of transformations

M. W. McCall, A. Favaro, P. Kinsler, Imperial College London (United Kingdom); A. D. Boardman, Univ. of Salford (United Kingdom)

Electromagnetic cloaking was the first example of so-called transformation optics where the invariance properties of Maxwell’s equations are used to determine how coordinate deformations can be actualized in an electromagnetic medium cite{Pendry2006}. The concept was experimentally realized cite{Schurig2006} and the improvement towards an ideal macroscopic wide-bandwidth cloak continues to be a major goal for the experimentalists. This has included carpet cloaking in 3D cite{Ergin2010}, and the use of polarization selectivity using calcite cite{Chen2011}. Most recently, a significant extension of the concept has been proposed in which the coordinate transformations embrace time as well as space cite{McCall2011}. The electromagnetic medium for realizing spacetime transformations must be dynamic as well as inhomogeneous, and by influencing the local speed of light we showed how it is possible for the light reaching a camera to record an edited version of the events it surveys. Regulating the local speed of light about an average value likely requires that the medium within which the coordinate transformation is carried out be one of uniform refractive index, rather than vacuum. Although this extends the original programme of transformation optics, by using quite abstract methods we have shown how such an extension can be embedded within a general theory of non-birefringent transformations cite{Favaro2011}. However, what if the initial medium is nonlinear or otherwise programmable? Influencing the initial medium will influence the functionality of the final medium in ways that have yet to be explored, with controllable cloaking an obvious goal. Beyond electromagnetics, transformation theory has been applied now to acoustics to produce a variety of interesting and experimentally realizable schemes cite{Zhang2011,Torrent2007}. Although acoustics is not mathematically equivalent to electromagnetics cite{Cummer2007}, the ideas of actualizing a coordinate transformation do carry over. Therefore, we ask what are the essential ingredients of any transformation theory, and to what other areas of physics can the scheme be applied? We explore the structure and relationship between propagation and constitutive equations towards a general theory.

A transforming device formed by metamaterials creating a visual result of a changed scattering cross section

C. Du, X. Dong, G. Yuan, Q. Deng, C. Liu, Institute of Optics and Electronics (China)

A device for transforming the scattering cross section’s shape of perfect electrical conductor (PEC) objects to other arbitrary shapes is presented based on transformation optics. The designed functional device covers the original PEC object with its electromagnetic parameters determined by the transformation expressions. Then, the virtual PEC objects with their definite shape of the scattering cross section will be produced visually. The validation of the device was made by means of finite-element method. Though the designed transformer is anisotropic and inhomogeneous, the development of metamaterials makes it more closely to practice. This device can find applications in many aspects like camouflage some objects from the radar or other target recognition systems.

Spaser action, loss compensation, and stability in plasmonic systems with gain

M. I. Stockman, Georgia State Univ. (United States)

We demonstrate analytically that the conditions of spaser generation and the full loss compensation in a dense resonant plasmonic-gain medium (metamaterial) are identical. Consequently, achieving the full compensation or overcompensation of losses by gain in such a medium
will lead to an instability and a transition to a spaser state. This will limit (clamp) the inversion and lead to the limitation on the maximum loss compensation achievable. The criterion of the loss overcompensation, leading to the instability and spasing, is given in an analytical and universal (independent from system’s geometry) form.

8093-35, Session 8

Design and analysis of metamaterials for the continuous wave terahertz laser
J. Luo, Huazhong Univ. of Science and Technology (China)

The artificially structured electromagnetic materials, which called metamaterials, has led to the realization of phenomena which cannot be obtained with natural materials. We have found many fundamental progress and applications of metamaterials in millimeter wave or microwave, and many usefully potential applications of terahertz as well, but still need considerable efforts to fill this “THz-gap” in future. Therefore, it is especially important to design the metamaterials device in the terahertz frequency regime. For the first, we analyze the split ring resonator (SRRs) model in theory, and many planar SRR arrays have been designed for later testing, the planar SRR arrays are fabricated using conventional photolithography and electron-beam deposition of gold on n-GaAs substrate, the metal array and n-GaAs together form a Schottky contact. Then the influences of background substrate and the shapes of the SRRs on the terahertz resonance are experimentally investigated at several terahertz frequencies of continuous wave terahertz laser in turn, such as 1.4THz, 2.52THz, 4.25THz, etc., and all the transmission properties are recoded and analyzed, especially, some SRR arrays can obtain about 80 percent absorption of THz amplitude transmission. In addition, computer simulations of the spectral response of the chosen planar metamaterials are performed to analyze the resonance frequency, surface current density and local electric field, which agree well with measured results. These metamaterials may be useful for future applications in the construction of various THz filters, THz antenna, or THz grid structures ideal for constructing THz switching devices.

8093-36, Session 8

Interference enhancement of photoluminescence of ultrathin layer with silicon nanocrystals
S. A. Dyakov, Trinity College Dublin (Ireland); D. M. Zhigunov, Lomonosov Moscow State Univ. (Russian Federation); T. S. Perova, Trinity College Dublin (Ireland); V. Y. Timoshenko, Lomonosov Moscow State Univ. (Russian Federation); A. Hartel, D. Hiller, M. Zacharias, Albert-Ludwigs-Univ. Freiburg (Germany)

Most of prospective applications of silicon nanocrystals (Si-NCs), such as active media for optical waveguides, amplifiers and lasers, or absorbing ultrathin layer for the third generation photovoltaic devices, imply utilization of thin films containing Si-NCs. Therefore, the control of optical properties of such films is of current importance. However, small optical thicknesses of the films and complicated multilayered structure make certain difficulties for the ordinary estimations using standard formulas. We present a model, which enables one to prognosticate the photoluminescence (PL) intensity of multilayered structure. Using theoretical predictions we experimentally observed PL intensity enhancement of 4 nm thick film with Si-NCs for optimally chosen silicon dioxide (SiO2) buffer layer thickness. Moreover, our model enables one to explain nonmonotonic dependence of PL intensity from Si-NCs layer on its thickness.

Alternating layers of stoichiometric SiO2 and silicon rich silicon oxynitride (SRON) were deposited on Si substrates using PECVD system. Subsequently, all samples were annealed for 1 h in high purity N2 atmosphere at 1100oc in order to form Si-NCs in SRON layers. Triple-layered structures consisting of buffer SiO2 layer, emitting SRON layer and capping SiO2 layer were fabricated. For the first set of samples the thickness of buffer layer was varied from 0 to 125 nm, while the thicknesses of emitting and capping layers were fixed. The second set of samples is characterized by variable thickness of emitting SRON layer, the thicknesses of other layers were constant. The PL process is approximated by radiation of chaotically oriented dipoles.

8093-37, Session 8

Interactions in planar metamaterials: from strong coupling to active tuning
I. Brener, Sandia National Labs. (United States)

The issue of interactions between different types of engineered metamaterial resonances has received considerable attention since it was shown that electromagnetically induced transparency behavior can be mimicked using coupling between metamaterials and/or plasmonic resonators. In this talk I will present some of our recent results on strong coupling between metamaterial resonators and other excitations such as phonons, free carriers and intersubband transitions in semiconductor heterostructures, and ways to exploit these for active tuning of metamaterial properties.

8093-38, Session 8

Octave-wide photonic band gap in three-dimensional plasmonic Bragg metamaterials
H. W. Giessen, R. Taubert, Univ. of Stuttgart (Germany)

Coupling between individual particle plasmon resonances (PPRs) has been a field of extensive research over the past few years. Most of the work was dedicated to near-field coupling with close spacing between the resonant particles. In this limit, retardation is negligible, but also the interesting properties of radiating PPRs are mostly neglected. In contrast, when particles are positioned at distances on the order of their emission wavelength, coupling can be mediated by the radiation fields of the PPRs.

We investigate far-field coupling in three-dimensional stacked plasmonic nanostructures. We show that a superradiant mode forms when particles are stacked at Bragg distance. Increasing the number N of stacked layers leads to the formation of a very broad photonic band gap of about 1 eV. Ivchenko et al. predicted that the radiative width of the superradiant mode in a structure of Bragg-stacked oscillators is proportional to the number of layers. This can be intuitively understood by the matching of the oscillator phase to their vertical distance, which leads to an increased, “collective” dipole moment of the coupled system. To demonstrate this, we extracted the FWHM from calculated spectra of Bragg stacked nanowires for one to ten layers. The FWHM of the coupled system increases strongly for increasing number of layers. The dependence of the stop gap width on the plasmonic oscillator strength is investigated by considering different wire geometries: w and h are changed, keeping a constant aspect ratio, in order to compensate for the spectral shift. Therefore the spectral position for the different geometries is constant and only the oscillator strength changes.

For the small wires with low oscillator strength, the width of the mode increases slowly but linearly up to approximately 7 layers and start to saturate for more layers. In contrast, the large wires, which exhibit a big oscillator strength, show a strong increase for the first two layers and almost no further change for higher N. This issue can be understood by taking into account that interaction is only possible within the coherence length of the oscillators. As the large wires couple more efficiently to the radiation field, their decay is on the order of only a few cycles of the light field. Interaction with oscillators beyond this range is not possible. This interpretation is supported by extracting the radiative lifetime for a single oscillator from the linewidth at N=1 and deducing the coherence length of propagation subsequently.
8093-13, Session 9

Linear and nonlinear properties of low spatial symmetry metamaterials

G. Shvets, C. Wu, A. B. Khanikaev, N. Arju, The Univ. of Texas at Austin (United States)

Plasmonic Low Spatial Symmetry Metamaterials (LSPMs) is a novel and exciting recent development in the area of electromagnetic metamaterials because they truly represent building blocks unavailable in Nature. Specifically, while most molecules and atoms possess at least some degree of spatial symmetry (e.g., a finite number of inversion planes), LSPMs can be designed to have none. This opens up exciting opportunities for making new optical devices that are based on both single-layer and multi-layers. For example, LSPM can be used for efficient polarization manipulation.

Three-dimensional LSPM whose properties slowly vary along the direction of light propagation can be used for making slow-light devices. LSPMs can be used for engineering the radiative lifetimes of metamaterials because they can be designed to support both “bright” (radiant) and “dark” (sub-radiant) resonances. The interference between the two results in the so-called Fano resonance. One attractive feature of LSPMs is that, depending on the light polarization, the same resonance can give rise a Fano-like or Lorentzian line shapes. We will describe the fundamental theory explaining these resonant shapes and present experimental results for the pi-shaped plasmonic antennas. Field enhancement predicted by the simulations will be used to evaluate the potential of LSPM-based devices for nonlinear applications.

8093-40, Session 9

Temporally shaping ultrafast light with metamaterials

D. P. Brown, UES, Inc. (United States); A. M. Urbas, Air Force Research Lab. (United States)

Coherent excitation in optical spectroscopy and control of photo-induced processes like second harmonic generation depend on the temporal properties of ultrafast pulses. In this work, we demonstrate that metamaterials can be fabricated to have very large spectral dispersion properties that can affect both the temporal envelope and phase of each spectral component of an ultrafast pulse in useful ways. Values for the group delay dispersion found were to be as large as plus or minus 4000 fs2. We simulated the effect these materials would have on an ultrafast pulse with a full width half max (FWHM) time duration between 12 and 15fs, and then experimentally tested the pulse shape by transmitting or reflecting off of the metamaterials an ultrafast pulse from an oscillator capable of the same pulse as the simulations. The pulse envelope was determined using fringe resolved autocorrelation (FRAC). Finally, we explored the effects on second harmonic generation and two photon fluorescence both numerically and experimentally, and we examined how the structure orientation of the metamaterial changes these effects.

8093-41, Session 9

Robust optical delay lines via topological protection

M. Hafezi, Joint Quantum Institute (United States); E. A. Demler, M. D. Lukin, Harvard Univ. (United States); J. M. Taloyo, Joint Quantum Institute (United States)

Optical signals might be a promising alternative to electronic signals in future circuits. One key requirement is the ability to filter and delay light on-chip over a large bandwidth (several Gbps) for various time-domain processing such as optical buffering and multiplexing. However, disorder in fabrication rapidly degrades performance, leading to effects such as unwanted signal modulation in transmission. Here we show theoretically how exploiting topological properties of optical systems forms a basis for robust optical devices which are immune to disorder.

Our method for realization of topological protected photonic devices makes use of two dimensional arrays of coupled resonator optical waveguides (CROW) to simulate a 2D magnetic tight-binding Hamiltonian with degenerate clockwise and counter-clockwise modes. This approach does not require explicit time-reversal symmetry breaking, but the degenerate modes — time-reversed pairs — behave analogously to spins with spin-orbit coupling in the electronic quantum spin Hall effect (OSHE), and experience a spin-dependent magnetic field. When the clockwise and counter-clockwise modes are decoupled, we can selectively drive each mode and observe quantum Hall behaviors without breaking the time-reversal symmetry in the tight binding Hamiltonian. In a direct analogy to the electronic integer quantum Hall effect, we show that photonic edge states carry light at the perimeter of the system, while being insensitive to disorder, and thereby forms a basis for robust photonic devices. In particular, in comparison to state-of-the-art 1-D CROW systems, our approach can be dramatically more resistant to scattering disorders and fabrication errors.

8093-42, Session 10

Layer-by-layer metamaterials using membrane projection lithography

D. B. Burckel, J. R. Wendt, I. Brener, A. R. Ellis, M. B. Sinclair, Sandia National Labs. (United States)

The lack of a suitable fabrication technique of bulk-like metamaterials containing 3D isotropic unit cells for operation in the IR and optical wavelength ranges continues to present a significant barrier to exploration of potential metamaterial solutions and applications. Recently we have introduced membrane projection lithography (MPL) a fabrication technique capable of creating truly 3D micron-scale metamaterial unit cells. The basic premise behind MPL is creating a patterned membrane suspended over a cavity (the unit cell). Directional evaporation(s) through the patterned membrane results in deposition of a replica of the membrane pattern on the interior face(s) of the cavity.

In this talk we report our recent progress extending MPL to 3D bulk-like materials in a layer-by-layer process. We will present fabrication details addressing complications associated with multi-layer processing as well as optical characterization data showing the impact of moving from a single layer of 3 dimensionally oriented resonators dominated by surface effects to one with resonators embedded in a medium with bulk-like behavior. These micron-scale 3D metamaterials demonstrate that MPL enables exploration into the viability of metamaterial concepts to applications in the thermal IR wavelength range.

Supported by the Laboratory Directed Research and Development program at Sandia National Laboratories. This work was performed, in part, at the Center for Integrated Nanotechnologies, a U.S. Department of Energy, Office of Basic Energy Sciences user facility Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy’s National Nuclear Security Administration under Contract DE-AC04-94AL85000.
well as on doping dielectric materials with plasmonic nanoparticles. The investigated methods allow for manufacturing of bulk 2 and 3 D micro and nanostructured materials with various geometries (rodlike, lamellar, spiral) as well as various component materials (oxides, metals, semiconductors). Recently even split-ring resonator geometry has been achieved.

8093-44, Session 10

All dielectric infrared metamaterial


Metamaterials comprising metallic inclusions such as split ring resonators have been utilized for numerous device demonstrations at microwave frequencies. Unfortunately, the increased impact of ohmic losses renders metal-based metamaterials too lossy for devices at optical wavelengths (infrared and shorter). A possible strategy to overcome this fundamental limitation is to replace the metallic inclusions with high permittivity dielectric resonators, thereby replacing lossy conduction currents with displacement currents. A further advantage of the utilization of dielectric resonators is the isotropic metamaterial response that arises due to the high degree of symmetry exhibited by typical resonator shapes (i.e. spheres and cubes). In this presentation, we will describe the design, fabrication, and characterization of all dielectric metamaterials operating in the thermal infrared. The dielectric metamaterials are based on cubic dielectric resonators fabricated from Tellurium and arrayed on a Barium Fluoride substrate. As predicted by analytical and numerical simulation, the metamaterial exhibits a magnetic resonance near 10 um wavelength, as well as an electric resonance at a slightly shorter wavelength. The retrieved effective parameters indicate a negative permeability (permittivity) in the vicinity of the magnetic (electric) resonance. This work represents a first step toward the development of low loss infrared metamaterials suitable for device applications. This work was supported by the Laboratory Directed Research and Development program at Sandia National Laboratories. Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

8093-45, Session 10

Nanorod metamaterials as a new plasmonic platform

A. V. Zayats, King's College London (United Kingdom)

Guiding and manipulating light on length scales below the diffraction limit requires structural elements with dimensions much smaller than the wavelength. Recently, novel plasmonic metamaterial has been developed based on arrays of aligned gold nanorods grown in self-assembled anodic aluminium oxide templates. This metamaterial provides a flexible platform with tuneable resonant optical properties across the visible spectral range, that can be specifically designed by changing the length, diameter and separation between the nanorods. Such metamaterials, with a controllable and engineered plasmonic response, can be used instead of conventional plasmonic metals for designing plasmonic waveguides, plasmonic crystals, label-free bio- and chemo-sensors and for development nonlinear plasmonic structures with the enhanced nonlinearities. The high electromagnetic field confinement and hence enhancement makes these systems ideally suited to the creation of active plasmonic devices by hybridization with nonlinear optical materials or sensing applications which benefit from the large effective surface area in such self-assembled, template based materials.

In this talk we will overview applications of plasmonic plasmonic nanorod metamaterial for designing new types of nanoscale waveguides, biosensing platforms and nonlinear optical devices with improved properties.

8093-46, Session 10

Enhanced transmission from a 2-D complementary metallic square array decorated with gold nanoparticles

M. J. Birnkrant, Air Force Research Lab. (United States); D. P. Brown, UES, Inc. (United States) and Air Force Research Lab. (United States); V. P. Tondiglia, SAIC (United States) and Air Force Research Lab. (United States); T. J. Bunning, A. M. Urbas, Air Force Research Lab. (United States)

Enhanced transmission from metallic hole arrays show promise as filters and environmental sensors. Recently, a subset of structures known as Metallic Complementary Arrays (MCA) have been studied. MCA are sandwich type structures that have a metal-insulator-metal (MIM) morphology. The MIM feature of MCA has one metal layer with complementary features to the other metal layer. These materials achieve selective transmission by matching plasmonic modes in the top and bottom layers. Understanding what influences the coupling between the two metal layers is not well understood. In this presentation we explore through simulation and experimentation a method for coupling the two metal complementary layers using nanoparticles. The MCA was fabricated using a modified interference-lithography technique to construct the insulator layer out of photoresist. Subsequently the metal layers were deposited through evaporation of gold. Finally nanoparticles were deposited on top of the MCA. The transmission spectra from a complementary array with nanoparticles showed enhanced transmission of light at wavelengths below the diffraction limit. Enhanced transmission below the diffraction limit is mediated by surface plasmon resonances. In the present case, the nanoparticles may act to impede surfaces plasmons on the MCA allowing for a number of surface plasmon modes to interact between the two metal layers. The influence of the impedance on the coupling between the two metal layers is investigated via nanoparticle coverage and separation distance.

8093-47, Session 10

Planar gradient index photonic metamaterials

Z. Wu, Toyota Technical Ctr., USA (United States)

Metamaterials operating at optical frequencies, referred to as optical or photonic metamaterials, require features fabricated at a subwavelength scale from 50 nm to 1000nm. In this work a planar gradient index metamaterial is designed and demonstrated at optical frequencies by numerical simulation through a finite-difference time domain method in conjunction with an electromagnetic retrieval technique. We confirm the gradient by simulating the deflection of a light beam passing through a multilayer silver (Ag) and magnesium fluoride (MgF2) slab featured with specially designed nano-rectangular holes. The planar gradient index photonic metamaterials we propose can be fabricated by available nano-fabrication technologies. Optical tests can be performed once the designs are also based on the consideration of the frequency range available for evaluation. In this paper, we combined the graded index concept with the fishnet structure for the purpose of extending gradient index metamaterials into optical frequencies. We designed the fishnet unit cell with optimum refractive index range by tuning the unit cell dimensions. A commercial finite-difference time domain software package (CST MICROWAVE STUDIO), was used to calculate transmission and reflection coefficients, also known as S-parameters. A standard material parameter retrieval algorithm was developed to determine effective refractive index from transmission and reflection coefficients. Refractive indices as a function of unit cell geometry were used to map the index profile to the variation of unit cells. The electric field mapping simulations were utilized to show the beam forming mechanism. The light beam deflection was demonstrated by introducing the light passing through planar gradient metamaterial consisting of a multilayer Ag-MgF2-Ag sandwich slab featured with specially designed and arranged fishnet unit cells. Unlike most of previous metamaterial gradient index designs, first, this was designed to operate in positive
index regime away from resonance to minimize losses; second, all of the patterned elements were planar which did not require volumetric unit cell; third, it was for optical frequencies.

8093-48, Session 10

Three-dimensional resonant guided wave networks

S. P. Burgos, E. Feigenbaum, H. A. Atwater, California Institute of Technology (United States)

It has recently been shown that resonant guided wave networks (RGWNs) are an artificial material class where the wave dispersion is controlled through strong coupling of local resonances throughout the waveguide network. In this work, we implement the RGWN concept at \( \lambda = 1100-1600 \) nm in three dimensions with a Cartesian mesh of regularly-spaced cylindrical plasmonic waveguides in a metallic mesh. The RGWN concept is based on two basic types of elements: isolated waveguides, where the waves accumulate phase, and power-splitting junctions at the waveguide intersections. Due to the simplicity of these two basic network operations, it is possible to comprehensively describe the full network dynamics with a reduced numerical code, which greatly reduces computation time in comparison to full wave simulations and allows for an insightful study of the network dynamics.

The conditions required for designing three-dimensional plasmonic cavities as well as their dependence on wavelength and network layout will be presented. Furthermore, using the Q-factor analysis, we map the eigenmodes of finite-size networks, and we categorize their symmetry and degeneracy based on the steady-state time evolution of the energy density within the network. Lastly, by implementing Bloch boundary conditions instead of PMLs, the numerical code is also used to calculate the bandstructure of infinite 3D network layouts. This method of analysis illustrates the design potential of 3D-RGWNs, which can ultimately be used to program complex network dynamics and functions.

8093-49, Session 11

Optical forces in metamaterials

P. Tassin, R. Zhao, T. Koschny, C. M. Soukoulis, Iowa State Univ. (United States)

Since a few years, it has been proposed to harness optical forces, i.e., the forces that arise when linear momentum is transferred from photons to matter, in micro- and nanophotonic systems. Most attention was focused on optical forces in waveguides, where resonant waveguide modes enable forces on the space scale of the wavelength of light. Recently, we have extended such research to subwavelength structures.

We start this communication with a study of optical forces in a prototype of metamaterial constituents—the nanowire pair. We show how the electric and magnetic dipole resonances lead to repulsive and attractive forces, respectively. However, the stacking of nanowire pairs in an array as in metamaterials may dramatically change the nature of optical forces, e.g., changing the forces associated with the electric dipole resonance from repulsive to attractive. In the second part of this communication, we show how the optical force can be exploited for the creation of nonlinear metamaterials. By optimizing a split-ring resonator structure for the enhanced interaction between the elastic and the electromagnetic modes mediated by the optical force, we demonstrate metamaterials with a transmission spectrum that depends on the power of the incident electromagnetic wave. This metamaterial thus allows for the switching of its transmittance by simply changing the incident beam power.

8093-50, Session 11

Electromagnetic forces on parallel plates cavity

J. Ng, Hong Kong Univ. of Science and Technology (Hong Kong, China); H. Liu, Nanjing Univ. (China); Z. Lin, Fudan Univ. (China); Z. Hang, C. Chan, Hong Kong Univ. of Science and Technology (Hong Kong, China); S. Zhu, Nanjing Univ. (China)

Metamaterials are man-made materials which possess unusual optical properties. These materials are often made from sub-wavelength metallic resonators. Most of the studies on these materials are focused on their optical properties, and the effect of optical forces associated with the excitation of resonances in these materials are much less discussed. In this talk, we will study the electromagnetic forces acting on resonating units comprising a simple parallel plate resonator made from gold. This simple system may serve as a prototypical building block of metamaterials. We first understand the physics using a qualitative Lagrangian model, and then full wave numerical simulation (CST microwave studio) is performed.

In microwave scale, gold behaves as perfect electric conductors. The two plates experience a repulsive force due to the leakage of electric fields at the edges. Even with a conventional microwave source (power ~15 mW), it is shown that the microwave force is significantly enhanced at resonance and it can lead to experimentally measurable forces. In near infrared scale, we need to consider gold as a plasmonic material as the field can penetrate the plates. The two plates attract each other owing to a novel mechanism - the plasmon-induced kinetic energy of the conduction electron reduces the Faraday magnetic energy which induces attraction. We show that the optical forces in near infrared can be enhanced by orders of magnitude write respect to the usual photon pressure and it can be deployed to the manipulation of the cavity itself.

8093-51, Session 11

Electromagnetic radiation pressure on left- and right-handed dissipative media

H. Lezec, A. K. Agrawal, M. Abashin, S. Rajaouria, National Institute of Standards and Technology (United States); K. J. Chau, The Univ. of British Columbia (Canada)

We investigate both experimentally and theoretically the radiation pressure exerted by a plane wave of visible-frequency light on a flat slab of dissipative material which is either left handed [1] or right handed (i.e. having electric permittivity and magnetic permeability which are both negative or both positive, respectively). We characterize the radiation-pressure response of an optical-frequency, broadband, left-handed metamaterial based on stacked Ag/Si/Ag plasmonic waveguides, each designed to be left-handed over most of the visible spectrum. A fully-absorbing flat slab of this metamaterial integrated onto a low-stiffness cantilever is shown to experience a pull when illuminated at normal incidence by a plane-wave of free-space wavelength in the range 460 nm to 600 nm. Radiation-induced pull is further confirmed by observation of levitation of free-standing slabs of the metamaterial under illumination at 532nm. An analytic model is proposed which is consistent with the spectral dependence of the measured pressure response. In this model, the real part of the effective refractive index of the metamaterial contributes to a proportionately-large, negative absorption force, which, when it exceeds the positive Lorentz force, yields in a net negative pressure on the object. The origin of the implied momentum-transfer non-equivalence between Lorentz and dissipative forces, related respectively to the wave and particle nature of the photon, is investigated through finite-difference-time-domain simulations of optomechanical pulse-slab interactions, as well as via interferometric measurements of the radiation-pressure response of thin films of high-index, dissipative, right-handed materials on silicon-nitride membranes. [1] V. Veselago, Sov. Phys. Usp. 10, 509-514 (1968).
Grating-assisted subwavelength far field imaging
V. A. Podolskiy, Univ. of Massachusetts Lowell (United States); S. Thongrattanasiri, N. A. Kuhta, Oregon State Univ. (United States)

High-resolution imaging is of interest for a broad class of applications spanning all parts of the electromagnetic spectrum. Unfortunately, conventional far-field imaging is fundamentally limited by the free-space wavelength. The diffraction limit can be halved with structured illumination microscopy where the spectrum of the incident light is effectively doubled via interference. Alternatively, in the far-field superlens, part of the evanescent radiation emitted by an object is resonantly enhanced via surface plasmon polaritons, and is subsequently converted into propagating waves with a subwavelength diffraction grating, again doubling the resolution. Here we present an approach capable of non-resonant imaging with resolution on the order of 1/20 of the wavelength with far-field measurements.

The spectrum of a subwavelength focal spot is dominated by high-wavenumber components that exponentially decay away from the focal spot. The grating, that plays the role of image-reconstructing structure, located at the image plane, and translates the spectrum of the source by the multiple of inverse grating periods. This way, the diffraction gratings can convert the originally evanescent information into propagating waves which can be measured in the far field. Provided that the far-field measurements of the same object are performed for different values of incident angle, the contributions of different diffraction orders to the final intensity distribution can be separated from each other, and the original field distribution can be calculated.

Here we present a class of algorithms capable of recovering the subwavelength details of the objects and analyze the effect of imaging grating on image recovery.

Gradient index metalenses for extraordinary light focusing
C. Ma, M. A. Escobar, Z. Liu, Univ. of California, San Diego (United States)

The lens is the most commonly used element in optical systems, which however can achieve only diffraction limited resolution at the scale of λ/2, with λ being the working wavelength. Because of the versatile and exceptional designability of metamaterials, various superlenses have been proposed and demonstrated with resolving power beyond the conventional diffraction limit in the past decade. However, such superlenses behave remarkably different from their conventional counterpart. For instance, they cannot focus a plane wave due to the lack of phase compensation mechanism. We have recently proposed two types of phase compensated metamaterial lenses, i.e., the metamaterial immersion lens (MIL) and the metalens, which have super resolving power and are able to focus a plane wave to a spot. In this work, we proposed another type of phase compensated metalenses based on planar gradient-index (GRIN) or inhomogeneous permittivity metamaterials, which we refer to as GRIN metalenses. Using a generalized discretization method to analyze both the elliptically and hyperbolically dispersive GRIN metalenses, we investigate all the conditions of anisotropic GRIN material profiles required for both internal and external focusing. Simulation results show that the GRIN metalenses can achieve super resolution focusing and have ordinary or extraordinary Fourier transform functions. The extraordinary focusing behavior may enable exotic imaging applications.

Studies of plasmonic hot-spot translation by a metal-dielectric layered superlens
M. D. Thoreson, Purdue Univ. (United States) and rangen Graduate School in Advanced Optical Technologies (Germany); R. B. Nielsen, Technical Univ. of Denmark (Denmark); P. R. West, Purdue Univ. (United States); A. Kriesch, Max-Planck-Institut für die Physik des Lichts (Germany) and Erlangen Graduate School of Advanced Optical Technologies (Germany) and Cluster of Excellence Engineering of Advanced Materials (Germany); Z. Liu, Institute of High Performance Computing (Singapore); J. Fang, Purdue Univ. (United States); U. Peschel, Erlangen Graduate School in Advanced Optical Technologies (Germany) and Cluster of Excellence Engineering of Advanced Materials (Germany); A. Boltasseva, Purdue Univ. (United States) and Erlangen Graduate School of Advanced Optical Technologies (Germany) and Technical Univ. of Denmark (Denmark); V. M. Shalaev, Purdue Univ. (United States)

Single-layer and multilayer superlenses have been studied by a number of researchers in recent years. Most experimental studies have focused on the plasmonic operational regime that is limited to the near-UV range. Numerical studies have also predicted the existence of a canalization regime where superlensing occurs in a layered metal-dielectric system at wavelengths away from the plasmon resonance and into the visible range. This canalization regime has been experimentally observed in the microwave range. In this work, we have experimentally and numerically investigated superlensing in the visible range. By using the resonant hot-spot enhancements from optical nanoantennas as sources, we investigated the translation of these sources to the far side of a layered silver-silica superlens operating in the canalization regime. Using near-field scanning optical microscopy (NSOM), we have observed evidence of superlens-enabled enhanced-field translation at a wavelength of about 680 nm. Specifically, we discuss our recent experimental and simulation results on the translation of hot spots using a silver-silica layered superlens design. In this presentation we will compare experimental results with respective numerical simulations and discuss the perspectives and limitations of our approach.

Sub-wavelength imaging using stacks of metallic meander structures with different periodicities
P. Schau, K. Frenner, W. Osten, L. Fu, H. C. Schweizer, H. W. Giessen, Univ. Stuttgart (Germany)

Recently it has been questioned if bulk negative index materials (NIM) are really necessary for sub-wavelength imaging since it might not be possible to reduce losses in these materials to an acceptable degree. We suggest an alternative approach, which replaces a bulk NIM with two identical resonant surfaces that allow surface plasmon polariton propagation. The metallic meander structure, which is a thin metal film, corrugated periodically on both sides, acts as such a resonant surface. A direct resonant tunneling transmission of plasmons / photons is observed when two or more meander structures are stacked onto each other [1]. Recently, we have also found that stacks of meander structures with different periodicities show the same resonant tunneling transmission behavior when proper geometry parameters are used for each layer [2]. With respect to physical mechanisms we will explain in detail how changing structural parameters influences the optical properties of resonantly coupled surfaces. Furthermore, we will report on how the variation of the meander periodicity from layer to layer enables sub-wavelength imaging.


2) P. Schau, K. Frenner, L. Fu, H. Schweizer, H. Giessen, W. Osten, “Design of high-temperature metallic meander stacks with different grading periodicities for subwavelength-imaging applications”, assigned to: Optics Express, Vol. 19, No. 4, 2011

8093-58, Session 13
Metamaterial models of exotic spacetimes
I. I. Smolyaninov, BAE Systems (United States)
We demonstrate that optical space in metamaterials may be engineered to mimic physics of various exotic spacetimes.

8093-59, Session 13
Frequency conversion by the transformation-optical analogue of the cosmological redshift
V. Ginis, Vrije Univ. Brussel (Belgium); P. Tassin, Iowa State Univ. (United States) and Vrije Univ. Brussel (Belgium); B. Craps, I. Veretennicoff, Vrije Univ. Brussel (Belgium)
Recently, there has been a lot of interest in electromagnetic analogues of general relativistic effects. Using the techniques of transformation optics, the material parameters of table-top devices have been calculated such that they implement several effects that occur in outer space, e.g., the implementation of an artificial event horizon inside an optical fiber, an inhomogeneous refractive index profile to mimic celestial mechanics, or an omnidirectional absorber based on an equivalence with black holes. In this communication, we show how we have extended the framework of transformation optics to a time-dependent metric - the Robertson-Walker metric, a popular model for our universe describing the cosmological redshift. This redshift occurs due to the expansion of the universe, where a photon of frequency $\omega_{em}$, emitted at instance $t_{em}$, will be measured at a different frequency $\omega_{obs}$ at time $t_{obs}$. The relation between these two frequencies is given by $\omega_{obs}(t_{obs}) = \omega_{em}(t_{em})$, where $a(t)$ is the time-dependent scale factor of the expanding universe. Our results show that the transformation-optical analogue of the Robertson-Walker metric is a medium with linear, isotropic, and homogeneous material parameters that evolve as a given function of time. The electromagnetic solutions inside such a medium are frequency shifted according to the cosmological redshift formula. Furthermore, we have demonstrated that a finite slab of such a material allows for the frequency conversion of an optical signal without the creation of unwanted sidebands. Because the medium is linear, the superposition principle remains applicable and arbitrary wavepackets can be converted.

8093-60, Session 13
Geometric-optical studies for metamaterial representations of curved spacetime
T. H. Anderson, T. G. Mackay, The Univ. of Edinburgh (United Kingdom); A. Lakhtakia, The Pennsylvania State Univ. (United States)
Metamaterials offer opportunities to explore curved-spacetime scenarios which would otherwise be impractical or impossible to study. These opportunities arise from the formal analogy that exists between light propagation in vacuous curved spacetime and in a certain nonhomogeneous bianisotropic medium, called a Tamm medium. As the science and technology of nanostructured metamaterials continues its rapid development, the practical realization of Tamm mediums is edging ever closer. We considered two particular curved spacetimes associated with: (a) spinning cosmic strings, and (b) the Alcubierre drive. For both examples, a Tamm medium formulation was developed which is asymptotically identical to vacuum and is therefore amenable to physical realization. A study of ray trajectories for both Tamm mediums was undertaken, within the geometric optics regime. For the spinning cosmic string, it was observed that: (i) rays do not cross the string's boundary; (ii) evanescent waves are supported in regions of phase space that correspond to those regions of the string's spacetime wherein closed timelike curves may arise; and (iii) a non-spinning string is nearly invisible whereas a spinning string may be rather more visible. For the Alcubierre drive, it was observed that: (i) ray trajectories are highly sensitive to the magnitude and direction of the warp bubble’s velocity, but less sensitive to the thickness of the transition zone between the warp bubble and its background; and (ii) the warp bubble acts as a focusing lens for rays which travel in the same direction as the bubble, especially at high speeds.

8093-61, Session 14
Collinear meta-acousto-optics and its application to tunable filters
P. P. Banerjee, G. T. Nehmetalab, Univ. of Dayton (United States)
Acousto-optics (AO) or diffraction of light by ultrasound, is used in numerous applications in signal processing, filtering, and image processing. In conventional AO (CAO), the acoustic group velocity has the same direction as the phase velocity, and hence, the acoustic propagation vector. However, in an acoustic metamaterial, dispersion may allow for negative phase velocity but positive group velocity. Therefore, interaction between light and ultrasound wave-vectors is different for noncollinear meta-AO (MAO), implying a new interpretation for upshifted and downshifted interactions [Banerjee, SPIE 7754 (2010)]. In this work, we investigate nominally collinear AO interaction in an acoustic metamaterial. We show that phase matching between the undiffracted and diffracted orders, not normally achievable in collinear CAO, can be satisfied using the dispersive acoustic behavior in MAO. For example, with zero acoustic refractive index, phase-matching between incident and diffracted orders is achievable in optically isotropic materials. Also, using negative acoustic refractive index, phase-matching can be achieved using co-propagating incident optical field (e-polarized), diffracted optical (o-polarized) field, and pulsed ultrasound in positive uniaxial media. We develop heuristic theory and detailed model for collinear MAO for CW and multi-frequency (pulsed) ultrasound. Application of collinear MAO to spectroscopy using AO tunable filters is also investigated.

8093-62, Session 14
Plasmonic Bloch-Zener oscillations in metal-dielectric waveguide arrays
Y. Lan, R. Shiu, National Cheng Kung Univ. (Taiwan)
Plasmonic Bloch oscillations, an analog of electron Bloch oscillations in lattice, are periodic oscillations of optical beams that propagate in metal-dielectric waveguide arrays (MDWAs), which is caused by the alternating total internal reflection and Bragg reflection between the two boundaries of the waveguide arrays. When the electric field imposed on the lattice is increased, electron Zener tunneling will occur at the Brillouin zone boundary. However, plasmonic Zener tunneling has been never observed in MDWAs. Neither has the possibility that the optical beam tunneling into the next band will experience another Bloch oscillation been investigated. In this study, plasmonic Zener tunneling and the succeeding plasmonic Bloch oscillation in MDWAs are explored by performing both FDTD simulations and theoretical analyses. The MDWAs consists of alternative silver layers and dielectric layers. The relative permittivities of the dielectric layers have a constant gradient across the waveguide arrays. The plasmonic Zener tunneling is observed at the position of total reflection (Bloch wavevector $k_{z}$=0), which is caused by that the gap between the first and second equal-kz (longitudinal wavevector) bands is minimum at $k_{z}$=0, originated from the effectively (transverse) negative refraction index of the MDWAs. The relation between tunneling rate and...
permittivity gradient is elucidated. The FDTD-simulated contours of magnetic field intensity correlate well with the predicted ray trajectory using Hamiltonian optics. Furthermore, the tunneling beam is also observed to undergo Bloch oscillation in the FDTD simulation. This Bloch oscillation leads to the beam’s curling due to change of the direction of the energy flow. Depending on the geometry parameter, the curling beam will move backward, move forward, or even remain unmoved.

8093-63, Session 14

The Goos-Hänchen effect at the non periodic surface of a negative index metamaterial

V. Grünhut, M. A. Cuevas, R. A. Depine, Univ. de Buenos Aires (Argentina)

We present a rigorous analysis about the excitation of surface polaritons at a non periodic, rough interface between a conventional dielectric and a metamaterial with a negative index of refraction. In particular, we study the reflection of a Gaussian beam from a corrugated surface of finite length. We analyze the strong impact that surface polaritons have in the field reflected from this type of metamaterial rough surface and find new features of the well known Goos-Hänchen effect due to the resonant excitation of these surface waves. The dependence of the Goos-Hänchen lateral shift on the incident beam parameters is examined in detail and discussed in different situations among which is the total reflection case. We compare these characteristics with the limiting case of reflection of a beam from an infinitely periodic grating.

8093-64, Session 14

Anderson localization in one-dimension: quasiperiodic photonic bandgap structures

G. J. Kissel, Univ. of Southern Indiana (United States)

Existing in the “gray area” between perfectly periodic photonic bandgap structures and purely randomized photonic bandgap structures are the so-called “quasiperiodic” structures whose layers are chosen according to some deterministic rule rendering them aperiodic. We consider here a one-dimensional photonic bandgap structure, a quarter-wave stack, with the layer thickness of one of the bilayers subject to being either thin or thick according to various deterministic sequence rules. To produce these “quasiperiodic” structures we examine the following sequences: Fibonacci, Thue-Morse, Double Period, Rudin-Shapiro, as well as the transverse-magnetic polarizations with reduced loss.

8093-66, Session 14

Waveguide characteristics for arbitrary permittivity and permeability including for metamaterials

B. R. Lavoie, P. M. Leung, B. C. Sanders, Univ. of Calgary (Canada)

We calculate dispersion, absorption, power flow, and effective width vs input-field frequency for 3-layer slab and circular waveguides wherein the dielectric permittivity and magnetic permeability can both be arbitrary response functions for each of the media. Either permittivity or permeability is also allowed to be identically zero. We study the electromagnetic field behaviour at interfaces between these media and consider, as examples, heterogeneous waveguides based on a dielectric medium enclosed by metal or a metamaterial (including a negative-index metamaterial), i.e. dielectric-metal or dielectric-metallic-waveguide. Our analysis provides a seamless model that accounts for dielectric-dielectric, dielectric-metallic, and dielectric-metallic-waveguides, and our results highlight that dielectric-metallic waveguides show reduced attenuation.

We treat metallic media according to the Drude model and metamaterial media with a modified Drude model that effectively models the magnetic response of the metamaterial. The modified Drude model is appropriate because its predictions are compatible with existing empirical results on metamaterials. Using these models we are then able to model the expected surface modes for metal or metamaterial waveguides; this surface mode is absent in the dielectric-dielectric waveguide. We show that, unlike the lossy surface mode for the dielectric-metallic waveguide, which allows only the transverse-electric polarization, the dielectric-metallic waveguide can sustain either transverse-electric or transverse-magnetic polarizations with reduced loss.

8093-65, Session 14

Near-field energy density enhancement in planar metamaterials

J. H. Shi, Harbin Engineering Univ. (China); C. Guan, Harbin Institute of Technology (China)

We theoretically investigate the positive/negative metamaterials with/without substrate built by asymmetrically split rings (ASRs) or asymmetrically split ring apertures (ASRAs) based on a full three-dimensional Maxwell finite element method. The asymmetry provides an easy and practical way to tune the electromagnetic response of metamaterials. The positive metamaterials on quartz glass and freestanding real metallic metamaterials show the quality factor of about 1000 and 1500, respectively. The near-field energy density enhancement 0.1 mm above the ASR metamaterial on glass substrate reaches at the ultra-high value of 150000, 500 times stronger than that of fundamental dipole resonance. The energy density enhanced factor attenuates to be one tenth only increasing the distance above the meta-surface to 0.5mm. The ultrahigh-Q trapped-mode resonances excited by broken structures confine most energy to a very small region of the surface of metamaterials. The freestanding metallic metamaterial will be good candidate to practical applications in microwave and terahertz range while increasing the thickness of quartz and choosing appropriate fabrication may pave to the practical design of the metamaterials on glass substrate. The low-loss trapped-mode metamaterials will be expected further and this tunable trapping of electromagnetic energy is of interest for new non-linear and switchable metamaterials, ultrasensitive media for chemical or biosensing and new types of optical switches.

8093-67, Session 15

Exotic properties of spinning particles metamaterials

A. ASENJO-GARCIA, A. MANJAVACAS, CONSEJO SUPERIOR DE INVESTIGACIONES CIENTIFICAS (SPAIN); J. GARCIA DE ABAJO, CONSEJO SUPERIOR DE INVESTIGACIONES CIENTIFICAS (SPAIN) and UNIV. OF SOUTHAMPTON (UNITED KINGDOM)

We will present exotic electromagnetic properties of assemblies of spinning particles, including light amplification and extreme optical properties.
Density functional study of spin polarization on a carbon material induced by iron atoms

M. M. Rahman, Univ. Putra Malaysia (Malaysia)

We investigate the spin polarization of a non magnetic material, e.g., a carbon material made from ten C atoms forming a hexagonal structure with total spin S=0, induced by a ferromagnetic material, e.g., two Fe atoms with a total spin S=4. Based on the density functional theory, we calculate the total spin density of the system. Our preliminary results show that the total spin for the ten C atoms changes from S=0 to S=2, while the total spin of the two Fe atoms changes from S=4 to S=0. These results seem to indicate that there is a promising possibility to induce spin polarization on a carbon material by Fe atoms.

References:

Applied metamaterials

A. M. Urban, Air Force Research Lab. (United States)

Metamaterials redefine the fundamental properties of systems by creating artificial, meso-scale meta-atoms which dictate the system response to external fields. When assembled into complex, structured materials, these meta-atoms and their mutual interactions can yield effective property sets not found in conventional materials and response tailored to specific application needs. The concept of defining the material properties with structure extends beyond electromagnetics to mechanical and thermal characteristics as well. Significant interest lies in the development of novel metamaterials structures and designs for electromagnetic and mechanical systems that possess properties optimized for selected applications. Key challenges are to develop capabilities to fully analyze the properties of these systems computationally and experimentally, to extract truly representative effective properties, and to understand the effectiveness of materials in an applications context. In the midst of this rapidly evolving field, AFRL is conducting a program to determine the utility of metamaterials in applications, evaluate their technological relevance and identify areas where focused efforts can enable rapid technological insertion. An overview of current research and application potential will be presented.

Highly sensitive nanostructured SnO2-based sensors for hydrogen sensing

L. A. Patil, Pratap College (India)

Nanostructured SnO2 thin films were prepared by ultrasonic spray pyrolysis technique. Aqueous solution (0.05 M) of SnCl4-SH2O in double distilled water was chosen as the starting solution for the preparation of the films. The stock solution was delivered to nozzle with constant and uniform flow rate of 70 ml/h by Syringe pump SK5001. Sono-tek spray nozzle, driven by ultrasonic frequency of 120 kHz, converts the solution into fine spray. The aerosol produced by nozzle was sprayed on glass substrate heated at 150 oC. The sensing performance of the films was tested for various gases such as LPG, hydrogen, ethanol, carbon dioxide and ammonia. The sensor (30 min) showed high gas response (S = 3040 at 350 oC) on exposure of 1000 ppm of hydrogen and high selectivity against other gases. Its response time was short (2 s) and recovery was also fast (12 s). To understand reasons behind this uncommon gas sensing performance of the films, their structural, microstructural, and optical properties were studied using X-ray diffraction, electron microscopy (SEM and TEM) respectively. The results are interpreted.
Design and fabrication of a chitosan based integrated optical device for humidity sensing

A. Mironenko, Institute of Chemistry (Russian Federation)

Recently, polymers and polymer/inorganic hybrids have become of great interest for development of optical waveguides with tailored optical properties. Due to high availability, relatively low cost and good film-forming properties of some of the natural polymers, their use can be considered as an alternative to molecular design of synthetic polymers for optoelectronic applications. Aminopoly saccharide chitosan is one of the most promising biopolymer-candidates for development of optical waveguides and sensor [1, 2]. Advantages of chitosan are not limited to its easy processability. Refractive index of chitosan film can be tailored via metal ions binding, in-situ reduction and stabilization of metal nanoparticles [3] or incorporation of optically active inorganic nanocrystals into the polymer thin film. Moreover, interactions of chitosan, as a hydrophilic polybase, with organic solvents, water vapor, mineral and organic acids change level of polymer hydration and/or protonation degree, and thus, optical properties of the film that is beneficial for sensing application.

Here we report on preparation of optical waveguides and humidity sensors based on chitosan in different salt forms, chitosan/gold nanoparticles and chitosan/gold nanoparticles/silica hybrides with layered structure. Chitosan-based optical waveguides were obtained on quartz, glass and MgF2 substrates by spin-coating and dip-coating. For investigation of optical properties, the light (wavelength 632 or 532 nm) was coupled into the planar waveguide via the flint glass prism using goniometer. A number of modes, effective refractive index, waveguide propagation losses were determined for all samples in the range of relative humidity 10-99%. It was demonstrated that chitosan-based thin films could be used as humidity sensors with fast response time (0.3-1 s), and highest sensitivity was found for chitosan/gold nanoparticles/silica hybrides with layered structure.

References


Bridging fiber optics with metamagnetics

X. Wang, G. Venugopal, J. Zeng, D. Lee, N. M. Litchinitser, A. N. Cartwright, Univ. at Buffalo (United States)

A majority of naturally existing optical materials are non-magnetic. In the past few years, it was shown that metamaterials can fundamentally change light-matter interactions by bringing the magnetic component of the field into play. Magnetism at optical frequencies may lead to new fundamental physics and novel applications, including negative index of refraction, super-resolution, and unprecedented opportunities for manipulating light trajectories in space (e.g., cloaking). Recently, Cai et al. demonstrated that coupled nano-strips with varying dimensions enable optical magnetic responses across the whole visible frequency range. To date, optical metamaterals were primarily demonstrated in a form of thin films with thicknesses on the order of or less than the optical wavelength on a substrate. In order to use them in applications such as photonic integrated circuits or on-chip sensing devices the light in- and out-coupling issue should be solved. Thus, waveguide-coupled metamaterials would be desirable. Fiber optics is a mature technology that enables long-distance, low-loss light delivery. Therefore, merging this mature fiber optics technology with the emerging metamaterials technology would likely enable a plethora of novel applications.

In this talk, we propose and experimentally demonstrate for the first time a fiber-coupled magnetic metamaterial structure. As an example, we demonstrate coupled nano-strip structures developed directly on the face of optical fiber that can serve as building blocks for more complex components such as multi-modality sensors (capable of measuring several properties of the sample at once), sensor arrays, imaging devices, ultra-compact components for photonic integrated circuits, and more.
Silanization of PECVD-grown silicon quantum dots for optoelectronics applications

I. E. Anderson, R. Shircliff, B. N. Jariwala, S. Agarwal, Colorado School of Mines (United States); P. S. Stradins, National Renewable Energy Lab. (United States); R. T. Collins, Colorado School of Mines (United States)

Semiconductor quantum dots have been the subject of intense research interest due to novel experimentally observed properties, such as tunable bandgap, phonon bottleneck, and a variety of surface effects. The control of these properties makes quantum dots a candidate for revolutionizing a variety of fields, including photovoltaics, optoelectronics, and biological imaging, labeling and sensing. Silicon, a material that is well characterized in its bulk form, may be most relevant to the fields that considered as a promising candidate for the low cost and high quantum dots embedded in the hydrogenated amorphous silicon matrix and interdot coupling. In addition, ultra-small Au clusters have molecular-like discrete energy structure, which induces distinctive features such as strong photoluminescence(PL) and ferromagnetism, etc. Therefore it is interesting to study a correlation between inter-dot space and collective properties of Au clusters. However it is difficult to control the inter-dot spacing with sub-nanometer resolution. In this study, we report on a development of precise tuning method of quantum-dot spacing and investigate fluorescence resonant energy transfer in Au clusters. The tuning device consists of a DC motor and capacitance-positioning sensor. After Au nano-clusters, which include Au_{6}, Au_{8} and Au_{13} clusters, were deposited on poly(dimethylsiloxane) film, the film was gently and continuously stretched by the DC motor. The degree of stretching was monitored by the capacitance-positioning sensor. We investigated the PL spectra of Au clusters and we found the blue shift of the PL peak with stretching the film. This peak shift caused by the emission enhancement and quenching from smaller clusters and the larger clusters, respectively. So the stretching the film means an increase the inter-dot spacing, the result can be explained as fluorescence resonant energy transfer from smaller cluster to larger one.

Si quantum dots and different aspects of applications.

T. V. Torchynska, Instituto Politécnico Nacional (Mexico)

This presentation will discuss the different aspects of the application of Si quantum dots in quantum electronics, such as: light emitting and photonic devices, solar cells and memory structures, one electron transistors and spintronics [1]. The special attention will be paid to the comparison of optical parameters of crystalline and amorphous Si quantum dots embedded in the hydrogenated amorphous silicon (a-Si:H). Nanocrystalline silicon films (nc-Si:H) that are silicon nanocrystals or quantum dots embedded in the hydrogenated amorphous silicon matrix that considered as a promising candidate for the low cost and high efficiency solar cells have been analyzed as well.

Engineering aperiodic order for optical devices with photonic-plasmonic nanostructures

L. Dal Negro, Boston Univ. (United States)

Deterministic Aperiodic Structures (DAS) are generated by the mathematical rules of L-systems and number theory, manifest unique light localization and transport properties associated with a great structural complexity, and can be fabricated on-chips using conventional nano-lithographic techniques. When combined with metal-dielectric nanostructures, they give rise to large energy gaps like periodic media (i.e. photonic-plasmonic crystals) and highly localized, enhanced field states like disordered random media, including the formation of Anderson-localized modes, forbidden in periodic scattering media. Contrary to random media, DAS possess controllable transport properties from ballistic to anomalous diffusion (slower diffusion than classical random walks) and strongly localized field states with large fluctuations of the photonic mode density - essential attributes to achieve spatio-temporal energy localization and enhanced light-matter coupling, i.e. radiative rates of fluorescent molecules, absorption cross-sections, non-linear optical processes on the nanoscale. In particular, DAS fabricated using metal-dielectric nanoparticles are suitable to engineer efficient nanoplasmonic structures for Surface Enhanced Raman (SERS) sensing, optical detectors, and enhanced light-emitting and nonlinear components.

In this talk, by combining dark-field scattering characterization, micro-photoluminescence and Raman measurements with accurate electrodynamic calculations based on semi-analytical multiple-scattering theories, I will discuss electromagnetic coupling1,2, resonant scattering3, colorimetric biosensing4, light emission5 and surface enhanced Raman sensing6,7 in two-dimensional metal-dielectric photonic-plasmonic arrays based on deterministic aperiodic sequences. In particular, I will survey the optical properties, and assess the device performances, of different aperiodic systems ranging from quasi-periodic crystals to pseudo-random nanoparticle arrays8 fabricated by Electron-Beam Lithography (EBL) on transparent quartz substrates. Finally, I will present novel aperiodic optical nano-antennas structures that can provide strong field localization at multiple frequencies over a broad spectral range9.

References:

Plasmonic light trapping in nanostructured metal surfaces

A. Polyakov, Lawrence Berkeley National Lab. (United States) and Univ. of California, Berkeley (United States); H. A. Padmore, S. Cabrini, S. D. Dhuey, B. D. Harteneck, X. Liang, P. J. Schuck, Lawrence Berkeley National Lab. (United States)

Metals are commonly used as ultra-fast photoemitters for Free Electron Lasers[1] and as field concentrators for generation of harmonics in a laser-driven plasma. In these applications high optical reflectivity is problematic[1]. This is especially true of gold, silver, and aluminum, which are all efficient reflectors due to their free-electron like behavior. However, by collective excitation of electrons in the form of a plasmon, free-electron metals can completely absorb light[2]. In this work, we demonstrate a practical realization of a new method recently proposed theoretically[2] where light is converted into plasmons, which are trapped in metal-insulator-grooves (MIGs).

The typical dimensions for the MIGs are 10-15nm in width and 30-40nm in depth spaced few hundred nanometers apart. The fabrication steps are: (a) the initial template is made by electron beam lithography from the HSO resist on the Si substrate (b) gold is evaporated on the template, (c) the template is removed from the gold structure in the KOH bath. The cross section analysis of the resulting gold structure revealed the slanted walls of the NG, which contributed to the reduced sample absorption efficiency (measured absorption is 80% of the theoretical model with perfect NG geometry). Comparison of the experimental data to the Finite Difference Time Domain (FDTD) modeling-based on the profile measurements-is a good agreement.


All-inorganic quantum-dot light-emitting diodes with metal oxide as charge transport/ injection layers

Y. Zheng, L. Qian, R. Zhou, P. H. Holloway, J. Xue, Univ. of Florida (United States)

Light-emitting diodes (LEDs) employing colloidal semiconductor quantum dots (QDs) as emitting layers (EML) have received significant scientific and technological interests. Currently, charge injection/transport layers comprised of conjugated polymers or thermal evaporated small organic molecules are widely used in QD-LEDs in order to achieve high efficiency emission. However, these organic charge transport/injection layers suffer from inferior thermal stability and low charge mobility compared to inorganic materials, and are more susceptible to degradation induced by oxygen and/or water. Here, we have demonstrated two different types of all-inorganic QD-LEDs using metal oxides as charge injection/transport layers. By using thermal evaporated MoO3 as a hole transport layer and ZnO nanoparticles as an electron transport layer, we have demonstrated red, green, and blue light-emitting QD-LEDs with performance approaching those of conventional quantum-dot LEDs with organic charge transport layers. For example, the green QD-LEDs we fabricated show a maximum luminance of 9,000 cd/m2, a peak luminance power efficiency of 1.74 lm/W, and an external quantum efficiency of 1.3. We also demonstrated a novel all-solution processable inorganic QD-LEDs in which the vacuum deposited oxide layer was replaced with a solution deposited oxide nanoparticle layer. Our data show that superior device performance can be achieved by improving hole injection from the oxide layer into the QD EML, which requires engineering of the heterojunction formed between the QDs and the hole transport oxide layer. All-inorganic QD-LEDs have the potential to serve as low-cost, efficient and stable light sources for display and solid-state lighting applications.
Stability of organic nanowires
F. Balzer, M. Schiek, Univ. of Southern Denmark (Denmark); I. Wallmann, A. Schäfer, A. Lützen, Rheinische Friedrich-Wilhelms-Univ. Bonn (Germany); H. Rubahn, Univ. of Southern Denmark (Denmark)

Organic nanowires from light-emitting conjugated oligomers might become the key ingredient for organics based optoelectronic devices. Different methods for nanowire growth have been pursued in the past such as filling of nanoporous templates, organic molecular beam deposition, and precipitation from solution. The morphological stability of such nanowires with time, in the presence of various gases, and under thermal load is of major importance for their use in any device. In this study the stability of organic nanowires from para-phenylenes, thiophenes, and from naphthyl end-capped thiophenes grown by organic molecular beam epitaxy is investigated via atomic force microscopy and optical spectroscopy. Simple aging experiments under ambient conditions already show substantial changes. Nanoscopic organic clusters, which initially coexist with the nanowires, vanish within hours, whereas wires develop facets and even break up into smaller ones within days. The influence of various gases such as water vapor, oxygen, and nitrogen is investigated to clarify the underlying mechanisms. Thermal annealing of nanowire samples leads to even more pronounced morphology changes, such as a strong decrease in nanowire number density, a strong increase in nanowire height, and the formation of new types of crystallites. This happens even before sublimation of organic material starts. These experiments also shine new light on the formation process of the nanowires.

Light collimation and resonance in composite negative/positive index photonic crystals
J. Zhang, S. Dhuey, B. D. Harteneck, Y. Wu, D. Olynick, X. Liang, S. Cabrini, Lawrence Berkeley National Lab. (United States)

The negative refraction in photonic crystals (PC) is due to the negatively sloped band folding effect of a strongly modulated PC. However, a negative index PC cannot fulfill some physical functions alone because light diverges after self-focusing. We report two structures composed of super lattice Bragg media of both negative and positive refraction index on SOI wafer for confining light in collimation or resonance. The first structure is composed of positive index air slab (n=1) and negative index PC slab (r=180 nm, a=470 nm, n=-1) periodically. Each PC strip has a length of isolated by an air slab with a length of . The structure shows the zero-average-index condition at the communication wavelength and allows light propagation in collimation. The two termination interfaces of each PC slab assist electromagnetic wave coupling into the waveguide with maximum transmission. Laser at 1.55 µm propagates 2 mm long without diffraction as our measurements. The second structure is a periodical arrangement of negative index PC (n=-1) and positive index air (n=1) both in equal-lateral triangle shape. By choosing of the symmetric equal-lateral triangle shape, light can fold back at the interface of opposite index media and resonant within this structure. The simulation of 1.55 µm wavelength propagation in TM polarization has been done by Rssoft. In conclusion, we are going to report light manipulating by two photonic crystal structures composed of opposite index media. The latest fabrication, simulation and optical measurement results will be presented in the conference.

Photonic crystal patterning of luminescent sol-gel films for light extraction
A. Revaux, G. Dantelle, Ecole Polytechnique (France); D. Decanini, Ctr. National de la Recherche Scientifique (France); F. Guillomet, Ecole Polytechnique (France); A. Haghiri-Gosnet, Ctr. National de la Recherche Scientifique (France); C. Weisbuch, J. Boilot, T. Gacoin, Ecole Polytechnique (France); H. Benisty, Institut d’Optique Graduate School (France)

For enhanced light extraction, the surface of sol-gel layers containing luminescent centers is patterned by nano-imprint lithography with a square photonic crystal (PhC). Light has to be guided in the slab rather than emitted toward the substrate to be efficiently extracted by the PhC. To increase the light fraction guided in the sol-gel layer, titania sol-gel films (n=1.7) are chosen rather than usual silicones (n=1.5) and a low-index layer of porous latex-templated silica is inserted between the substrate and the TiO2 film (nporous down to 1.16).

To study the effect of the structure of the film itself, we developed model sol-gel waveguides including europium chelates as emitters, which do not induce any microstructure effects (no light scattering). Furthermore, the large Stokes shift and the small absorption cross-section of the chelate at its emission peaks discard reabsorption losses and ensure long propagation distances. Chelates are spectrally and spatially coupled to the resonant modes of the PhC and the guided light is extracted via leaky modes to free space. We investigate the interaction between the guided mode and the PhC and the role of the porous underlayer with angle-resolved luminescence measurement and complementary simple simulations. This study gives access to the structure and the extraction strength of the guided modes, as well as the cladding influence on them. The role of an underlying porous layer that avoids leakage to the glass substrate has notably been revealed, with critical porous fraction thresholds identified for allowing guided modes to be seen, notably TM modes.
have prepared Mg doped ZnO alloy nanostructures and studied the structural and vibrational properties. Structural studies are performed through X ray diffraction technique, confirms that the prepared particles are in hexagonal wurzite structure and the lattice parameters change considerably due to doping. Vibrational properties are done with Fourier Transform Infrared red spectroscopy (FTIR).

All the samples show the IR active optical phonon modes of ZnO show a characteristic broad restrahlen band in the spectral range of 300-600 cm⁻¹. Gaussian fitted band show each band is composition of three different one. These fitted bands are named as B1, B2 and B3. The band centered at 427cm⁻¹ corresponds to E1(TO) mode. It is observed that the intensity decreases with the increase of Mg concentration, apart from that the surface phonon modes are appeared at 460 and 521cm⁻¹. Compare to the undoped sample all the normal modes show red shift. We completely analysed the structural and phonon properties of mg doped ZnO particles.

8094-13, Session 4

Structural fluorescence in the butterfly Morpho sulkowski (Nymphalidae)

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Evolution and natural selection have generated complexity and efficiency in all living families. Morpho sulkowski - a butterfly from Neotropic ecoccupy (South America) and belonging to the Nymphalidae family - concentrates on its wings distinct but complementary features contributing to its exceptional visual attraction: i) the wings are predominantly white but ii) present a bright blue metallic flash due to a iridescence process; iii) the presence of fluorescent molecules producing a violet-blue coloration when irradiated by ultraviolet light and finally iv) the particular ultrastructure of the scales presenting a three-dimensions natural photonic crystal.

Due to the confinement of the fluorescent sources in a photonic crystal, the emission is preferably directed in space and its efficiency is enhanced for particular detection angles. Furthermore, a clear correlation is observed between the reflection and the fluorescent processes that control the surface optical response, So, collecting and analyzing data over every emerging direction is shown to be crucial. To quantify these observations and characterize these optical effects, three types of measurements were carried out. First of all, the morphology of the butterfly was examined by means of scanning electron microscopes. In addition, the angular distribution of the reflected light was measured with a high performance viewing angle instrument, providing BRDF data (Bidirectional Reflectance Distribution Function). Finally, an automatic method coupling an ultraviolet source to a gonio-spectrophotometer allows fluorescent emission characterization. This set-up, developed on purpose, is composed of various excitation and analysis modules and provides angular emission maps. Tentative explanation for the measured correlation is presented.

8094-14, Session 4

Photo-induced self-organized dynamic pattern formation in bio-synthesized nanomaterials

N. V. Kukhtarev, T. Kukhtareva, F. Okaro, A. Johnson, Alabama A&M Univ. (United States)

We have observed a dynamic self-organization of laser scattering from the biosynthesized nanofluids with silver and gold nanoparticles. Various procedures for nanofluid synthesis suitable for different applications are under constant investigation. In our present research the green biosynthesis process has been used for noble nanoparticles production. The aqueous solution of Magnolia Grandiflora leaves has been used as a reductant for silver and gold nanofluids. We have applied the UV-visible spectroscopy method to control reaction process, fluorescent spectroscopy and nonlinear interferometric imaging experiments for characterization of nanofluids. From the experiments with laser-induced photothermal scattering it is possible to estimate the value of nonlinear refractive index coefficient. The kinetics observed in the pump-probe experiments with blue and red CW laser allowed us to estimate a timescale (~ 1s) of photothermal lens formation and dissipation.

Moreover, we have observed the phenomena of self-organization of the non-linear laser scattering reflected from the fluid’s surface. The diverse regular diffraction patterns (hexagons, rolls, squares etc), resembling diffraction of X-rays on crystal structures, were observed in the solutions of biosynthesized nanoparticles.

From the angular size of the observed hexagonal diffraction patterns it was possible to estimate the diameter of diffracting nanoclusters as 18 microns for silver and gold nanofluids and 9 microns for the Magnolia broth. The kinetics of the hexagonal scattering shows a quasiperiodic patterns (resembling heart beats), with a period of about 12 seconds with the slow build-up and sharp disappearance of scattering.

8094-15, Session 4

Multi-color reflection from chiral thin-film stacks

D. J. Brink, Univ. of Pretoria (South Africa)

Iridescence from nano-structured biological materials is fairly well known. Usually the process is based on simple multi-layer interference effects from thin-film stack typically found in butterfly wings, bird feathers, insects and sea shells. Recently a more interesting and sophisticated nano-structure was found in the exocuticle of scarab beetles, which interacts specifically with circularly polarized light and produces strong resonant reflections of narrow wavelength bands. These structures consist of many hundreds of ultra-thin (~ 5 nm) transparent birefringent layers sandwiched together in such a way that the fast- and slow axes form a (usually left handed) spiral as you look deeper into the material.

In the work presented here we studied the optical reflection from the outer parts of the scarab beetle Proagasoderus brucei, which is unusual in the sense that it is one of a very small group of species exhibiting different colors on different parts of its body. The optics of this insect has not been studied before.

Scanning electron microscopy and reflection spectroscopy were used to analyze the structure and optical properties of the exocuticle of this insect. Measurements were compared with a computer model of the optics of the nano structure. In this way observations could be explained, some unknown parameters could be quantified and the properties of similar artificial structures with possible practical applications can be predicted.

8094-16, Session 4

Nanoarchitecture in the black wings of the Troides magellanus: a natural case of absorption enhancement in photonic materials

A. Herman, C. Vandenbem, O. Deparis, P. Simonis, J. Vigneron, Facultes Univ. Notre Dame de la Paix (Belgium)

The birdwings butterfly Troides magellanus possess interesting properties for photonics. The black wings of the male exhibit strong (95%) absorption of the visible light as well as two strong peaks in the infrared (3 μm and 6 μm) both due to melanin. The study of absorption enhancement in this butterfly could be helpful, for instance to realize highly absorbent biomimetic materials. Observations of the wings
using a scanning electron microscope (SEM) revealed that the scales covering them were deeply nanostructured. From these observations, a periodic three-dimensional (3D) model of the scale nanoarchitecture was established and used in numerical simulations in order to calculate the absorption spectrum by means of a 3D transfer matrix electromagnetic method. In order to study separately the effect of the structure on the absorption, the complex refractive index, n+i*k, was first taken spectrally constant (n=1.56, k=0.0358). A broad absorption was observed in the visible range as well as two peaks in the infrared, which were not present for a homogeneous layer. This result clearly demonstrated a structural effect on the absorption. A Lorentz dispersion model was then used to account for the spectral dependence of the complex refractive index. The infrared absorption peaks were enhanced in this case. Therefore a combination of nanostructure and material resonances led to enhancement of the absorption. Finally, in order to quantify this enhancement, a comparison with a planar layer with identical refractive index and identical volume led us to conclude that the absorption was 30% higher with nanostructures.

8094-22, Poster Session

Tuning Surface plasmon absorption in Au-Ag alloy polymer nanocomposite free standing films
B. Karthikeyan, National Institute of Technology, Tiruchirappalli (India)

Nano composite polymers gains interest because of its enhanced physical and chemical properties are depends on the nanofillers like noble metallic clusters and semiconductor quantum dots. In situ synthesis is a good way of synthesis for the incorporation of nanofillers in to the polymer host. Noble metal nanoparticles show absorption due to surface plasmon resonance (SPR) in the visible region where the delocalized conduction band electrons oscillate with the frequency of applied optical field. The resonance bandwidth and peak maximum depends on parameters such as nanoparticle size, morphology, and dielectric constant of the host where the nanoparticles are embedded. Alloying is also one of the potential parameter to tune the SPR band. In the present work we prepared Au-Ag bimetallic and alloy nanoparticles. Particles are synthesized through polyol method where Poly vinyl alcohol is employed as a reducing and capping agent as well. Optical absorption measurements show the strong band at 410 nm and 532 nm is due to SPR of Au and Au nanoparticles respectively. When the bimetallic structure is formed, there are both the bands in the polymer. Thermal annealing induced the alloy nanostructures makes the absorption band becomes broad and it is between 410 to 532 nm. Increase in annealing time makes more broadened SPR band. Results are discussed based on Mie and Maxwell-Garnet theory.

8094-23, Poster Session

Optical, phonon and structural analysis of Na doped ZnO nanostructures
T. Pandiyarajan, B. Karthikeyan, National Institute of Technology, Tiruchirappalli (India)

Semiconductor nanoparticles gained much attention due to its novel physical and chemical properties, its potential applications in biology and medicine make scientific community to understand the insight of these particles. Doping metal ions in to it will alter its electronic structure and control its band gap. In the present work we report, synthesis, linear optical properties and x ray peak broadening analysis of the Na doped ZnO nanostructure. To prepare Na doped ZnO, simple room temperature wet chemical method was adopted. X ray pattern shows prepared particles are in hexagonal wurtzite structure. The individual contributions of small crystallite sizes and lattice strain to the peak broadening in undoped and Na doped ZnO nanoparticles were studied using Williamson-Hall (W-H) analysis. Analysis shows decrease in stress and strain value when sodium is doped in ZnO nanoparticles. Morphological studies were investigated through Scanning Electron Microscopic (SEM). Optical absorption measurements show an exciton absorption peak around ~ 360 nm. When doping concentration increases exciton peak maximum shift towards the higher wavelength. Photoluminescence measurements were done by exciting at 335 nm, when doping concentration increases the intensity of exciton peak maximum is decrease, reveal an exciton peak emission and oxygen vacancy band emissions. All the three bands depend on sodium concentration. Vibrational studies were done by Fourier Transform Infrared Spectroscopy (FTIR), it shows band at 433 cm-1 is attributed to Zn-O bond and in Na doped samples shows red shift. Apart from Zn-O bond surface phonon modes are observed.

8094-24, Poster Session

Synthesis of tin oxide, indium oxide and tin-doped indium oxide nanowires by chemical vapor deposition
K. K. Wong, M. K. Fung, Y. C. Sun, Y. C. Chen, A. M. C. Ng, B. Djuri?i?i?, W. K. Chan, The Univ. of Hong Kong (Hong Kong, China)

Nanostructures of tin oxide (SnO2), indium oxide (In2O3) and tin-doped indium oxide (ITO) have attracted researchers’ attention due to their unique properties for device applications such as gas sensors, photovoltaic devices and organic light-emitting diodes (OLED). Different forms of the nanostructure such as nanowires, nanobelts and nanoribbons can simply be fabricated by vapor deposition. These wide bandgap metal oxides in the nanostructure forms have the advantages of large surface to volume ratio that make them suitable for device application. For instance, ITO nanowires substrate is a good candidate as conducting electrode for improving the charge collection for photovoltaic devices while SnO2 nanostructures are of interest for gas sensors. In this study, nanowires of tin oxide, indium oxide and tin-doped indium oxide were fabricated by vapor deposition from a mixture of metal oxide nanoparticles and single-wall carbon nanotubes (SWCNT) placed in the heating zone at 1100 °C. Nanostructures of different morphologies were found on the Au coated single crystal Si substrates (100) placed at different temperatures downstream from the source. The morphology, growth direction and optical properties were characterized by field emission scanning electron microscopy, transmission electron microscopy and photoluminescence spectroscopy. The influence of source material composition and substrate temperature on morphology and photoluminescence was discussed.

8094-25, Poster Session

Optical and vibrational studies of surface modified ZnO nanostructures
T. Pandiyarajan, R. Nagalakshmi, B. Karthikeyan, National Institute of Technology, Tiruchirappalli (India)

Understanding the optical and electronic properties of semiconductor quantum dots is gaining much interest because of its greater versatility in application, improved performance and new functionalities of the future optoelectronic and bio-sensing devices. Among these semiconductors ZnO attracted much concentration due to its prospective performance in electronics, sensing and imaging related areas. In the present work, we report room temperature synthesis of ZnO nanoparticles. X-Ray diffraction studies confirm the prepared particles are in wurtzite structure. Scanning Electron Microscopy (SEM) studies depict the shape and morphology of the particles. Optical absorption measurements show the presence of exciton peak around ~375 nm. High-energy heavy ion irradiation is relatively a new curiosity in materials science and technology. The nature of modification depends on electrical, thermal and structural properties of target material, the mass of the projectile ion and irradiation parameters. The prepared particles were irradiated at room temperature with 150 MeV Ag+ ions at the fluences varying
from 1010 to 1012 ions/cm³ using 15 UD Pellettron accelerator. The pristine as well as irradiated ZnO nanostructures were characterized by X-Ray diffraction, Photoluminescence, FTIR and UV-Vis reflectance to study the radiation induced defects on the local structure of materials. Irradiation with the fluence changes the color of the sample from white to orange. Measured phonon modes show variation with fluence. Photoluminescence measurements are done at the excitation wavelength of 335 nm. Measured spectrum show the variation in peak intensity due to irradiation. These results will be discussed in detail in the complete paper.

8094-26, Poster Session

Gd and S sensitizer effect on the upconversion emission of ZrO2:Yb, Er nanocrystals prepared by precipitation method with a hydrothermal process

A. Urbina, E. De La Rosa Cruz, T. López, Ctr. de Investigaciones en Óptica, A.C. (Mexico); P. Salas, Univ. Nacional Autónoma de México (Mexico); C. Angeles, Instituto Mexicano del Petróleo (Mexico); A. Torres, Univ. Autónoma de Nuevo Leon (Mexico)

In this work, it is presented the synthesis of ZrO2:Yb3+, Er3+ nanocrystal by precipitation method with a hydrothermal process and annealing at 1000 oC. All the samples were prepared with 2% mol of Yb3+ and 1% mol of Er3+ and sensitized with different concentration of Gd3+ and S2-. The ceramic powders were characterized with different techniques to determine their chemical composition, crystalline structure, crystalline size, morphology and upconversion emission. All samples present the tetragonal crystalline phase with crystallite size lower than 70 nm with cubic shape. Experimental results suggest the presence of SO4 on the surface of nanocrystals reducing the OHs and then improving the signal emitted. The nanocrystals presented strong upconversion emission enhanced by the presence of both sensitizer, Gd3+ and S2-. A synergistic effect was observed with the combination of both sensitizers, improving the upconverted visible emission. The emission peak centered at 654nm dominates the red band and controlling the dopant composition and sensitizer it is possible to control the red/green intensity ratio.

8094-28, Poster Session

Temperature and frequency dependent admittance of InAs self-assembled quantum dots embedded in GaAs.

A. Sellai, Sultan Qaboos Univ. (Oman)

We have studied using frequency and temperature dependent admittance some electronic properties of InAs QDs embedded in a GaAs structure with emphasis on G-V data which is found to be more sensitive to some aspects of carriers exchange mechanisms. The presence of QDs in our structure is evidenced in the C-V characteristics at all temperatures and frequencies by a plateau-like structure in the bias range -3 V to -2 V that is related to charging and discharging of QDs. Concurrently, the G-V characteristics show a manifest peak in the same bias range at all considered frequencies but only for temperatures below 150K. The peak magnitudes in the concentration profiles, which are directly related to occupancy of charge states, increase as the temperature is decreased with a concomitant reduction of broadening of the profile. Below 40K a second peak, attributed to tunnelling, appears consistently at a slightly higher depletion width. The variations of conductance with both the temperature and frequencies show two regions of maximum G in the range -3V to -2V and for two temperature ranges 50K - 90K and below 40K. The T-dependence of the Gpeak, reveal two different behaviours depending on the T-range. These observations concur for the fact that one of two different mechanisms of carrier escape from the QDs prevails over each temperature range. Moreover, the measured G at any given temperature shows a very significant increase with increasing frequency suggesting that the emission rates are much higher than the frequency of the applied ac signal.

8094-17, Session 5

The photoluminescence of CuInS2 nanocrystals: Effect of surface modification

Y. Kim, Y. Cho, K. Chung, C. Choi, Korea Institute of Materials Science (Korea, Republic of)

We have synthesized highly luminescent Cu-In-S(CIS) nanocrystals (NCs) by heating the mixture of metal carboxylates and alkylthiol under inert atmosphere. We modified the surface of CIS NCs with zinc carboxylate and subsequent injection of alkylthiol. As a result of the surface modification, highly luminescent CIS@ZnS core/shell nanocrystals were synthesized. The luminescence quantum yield (QY) of best CIS@ZnS NCs was above 50%, which is 10 times higher than the initial QY of CIS NCs before surface modification (QY=3%). Detailed study on the luminescence mechanism implies that etching of the surface of NCs by dissociated carboxylate group (CH3COO-) and formation of epilithal shell by Zn with sulfur from alkylthiol efficiently removed the surface defects which are known to be major non-radiative recombination sites in semiconductor nanocrystals. In this study, we developed a novel surface modification route for monodispersed highly luminescent Cu-In-S NCs with less toxic and highly stable precursors. Investigation with the time- and the temperature-dependent photoluminescence showed that the trap related emission was minimized by surface modification and the donor-acceptor pair recombination was enhanced by controlling copper stoichiometry.

8094-18, Session 5

Nearly-total optical extinction in arrays of non-resonant nanorods

P. V. Ghenuche, Ctr. National de la Recherche Scientifique (France) and ONERA (France); G. Vincent, ONERA (France); M. Laroche, Institut d’Optique Graduate School (France); N. Bardou, Ctr. National de la Recherche Scientifique (France); R. Haidar, ONERA (France); J. Pelouard, S. S. Collin, Ctr. National de la Recherche Scientifique (France)

The interaction of light with non-resonant, dielectric nanostructures can be considerably enhanced by employing the diffraction effect resulting from the multiple scattering of a periodic arrangement of these particles. In this work we experimentally demonstrate nearly-total optical extinction in arrays of transparent material together with extremely sharp resonances. This phenomenon originates from multiple-scattering in a monolayer of periodical non-resonant scatterers. Freestanding Si/N4 membranes made of subwavelength square rods (width between λ/5 – λ/10) on large surface areas (2.6×2.6 mm2 ) were fabricated on a Si substrate and drilled by dry etching. Following this procedure, membranes with one-dimensional and two-dimensional patterns were fabricated, both having 500 nm square section bars and 3 μm pitch. High-resolution dispersion diagrams have been measured for the absolute transmission and reflection. Remarkably for a transparent material with a fill factor of only 15%, up to 96% extinction, independent of polarization, is found. The results are quantitatively described by a simple multiple-scattering model.

In addition, when the lossy material is used to fabricate the rods, a considerable absorption enhancement was observed, an indication of the interaction of light with non-resonant, dielectric nanostructures. The interaction of light with non-resonant, dielectric nanostructures can be considerably enhanced by employing the diffraction effect resulting from the multiple scattering of a periodic arrangement of these particles. In this work we experimentally demonstrate nearly-total optical extinction in arrays of transparent material together with extremely sharp resonances. This phenomenon originates from multiple-scattering in a monolayer of periodical non-resonant scatterers. Freestanding Si/N4 membranes made of subwavelength square rods (width between λ/5 – λ/10) on large surface areas (2.6×2.6 mm2 ) were fabricated on a Si substrate and drilled by dry etching. Following this procedure, membranes with one-dimensional and two-dimensional patterns were fabricated, both having 500 nm square section bars and 3 μm pitch. High-resolution dispersion diagrams have been measured for the absolute transmission and reflection. Remarkably for a transparent material with a fill factor of only 15%, up to 96% extinction, independent of polarization, is found. The results are quantitatively described by a simple multiple-scattering model.
resonances in dielectric systems may provide new opportunities for applications like stop-band filters, selective mirrors and for applications where fluorescence quenching must be avoided.

8094-19, Session 5
White light emissions from ZnO quantum dots under 350 nm excitation

J. Oliva, E. De La Rosa Cruz, Ctr. de Investigaciones en Óptica, A.C. (Mexico); A. Torres, Univ. Autonoma de Nuevo Leon (Mexico); O. Meza Espinoza, Ctr. de Investigaciones en Óptica, A.C. (Mexico)

There are many efforts around the world to design new lighting sources, above all for general illumination. Since Zinc Oxide (ZnO) is an innocuous, abundant and inexpensive material which has demonstrated its capability to produce visible emission by electroluminescence or ultraviolet excitation, it could be an excellent candidate to produce white light. In this work, we synthesized ZnO quantum dots with a wet chemical method. By changing the content of surfactant (Dodecylamine), we were able to control the ratio between the blue and yellow emission bands of ZnO. Luminescence measurements of ZnO nanoparticles dispersed in chloroform under 350 nm excitation and annealing treatments from 70°C to 800°C indicated that blue emission is produced by surface defects due to the interaction of ammines and OH groups with the surface of ZnO quantum dots and yellow emission is originated from oxygen vacancies. FTIR Spectra of as-prepared samples showed that the amount of OH groups, CO2 and bands associated with dodecylamine decreases if the content of this surfactant diminishes, that in turn promotes an increase in luminescence. Also, HRTEM images indicate that the size of spherical nanocrystals increases as the amount of surfactant increases, we obtained nanocrystal sizes ranging from 3 to 10 nm, as consequence, energy band gap values changed from 3.4 eV to 4.3 eV. CIE coordinates were (0.313,0.295), (0.332,0.321) and (0.401,0.406) for the samples which contained 0.17 ml., 0.34 ml., and 0.45 ml. of dodecylamine respectively. All these results point out that our nanoparticles can be used to tune white light emission from cool to warm white light as well as to use them like “seeds” to growth nanorods with hydrothermal procedures, which would be suitable to fabricate ZnO based LEDs.

8094-20, Session 5
How nanoscale structure determines photoluminescent quantum yield of CdSe/CdS core/shell nanorods

M. A. Pelton, C. She, A. Demortiere, E. Shevchenko, Argonne National Lab. (United States)

Heterostructure nanocrystals consisting of a nearly spherical CdSe core and a larger, rod-shaped CdS shell have attracted considerable attention for their novel optical and optoelectronic properties. They exhibit large absorption cross-sections, good photostability, and strong luminescence, making them attractive for devices such as optically pumped lasers and luminescent solar concentrators. Practical application of the nanocrystals will require optimization of their photoluminescent quantum yield, which in turn requires a fundamental understanding of the processes that limit the yield. We have investigated how optical properties depend on nanoscale structure by measuring quantum yield, time-resolved photoluminescence, and transient absorption on a series of CdSe/CdS core/shell nanorods with different core and shell sizes. We find that the radiative decay rate for all of the samples has a universal dependence on nanoparticle volume, consistent with the conduction-band electron being delocalized throughout the particle and the valence-band hole being confined within the CdSe core. Transient-absorption measurements provide further support for this quasi-type-II band alignment, and also show that trapping of hot carriers is not a significant factor determining luminescence quantum yield. Rather, quantum yields are limited by sample-dependent nonradiative recombination of band-edge carriers; ongoing work is dedicated to determining the microscopic mechanisms responsible for this nonradiative process.

8094-21, Session 5
Photoluminescence from silicon nitride alloys

J. O. Kistner, M. B. Schubert, J. H. Werner, Univ. Stuttgart (Germany)

Silicon nitride alloys emit photoluminescence (PL) all over the visible spectral range. Recent studies (e.g. Ref.[1]) ascribed this luminescence to quantum-size effects within silicon nanocrystals (Si-NC). These quantum dots were either shown or assumed to form inside the matrix of the silicon alloy. Possible luminescence of the alloy itself wasn’t taken into account. We fabricate silicon alloys using plasma enhanced chemical vapor deposition and carefully analyze their optical properties. Similar to the published data, our samples show visible PL, and the PL peak shifts all over the visible range if we tune the composition of the silicon nitride alloy. In contrast to the published data, however, HRTEM analyses prove that our samples don’t contain silicon nanocrystals. Therefore, the Si-NC luminescence model is inadequate to explain the observed luminescence. We found the Band Tail Luminescence model introduced by D.J. Dunstan to be in good agreement with our experimental results. This model suggests that the observed luminescence originates from the alloys matrix itself. While the Si-NC luminescence model merely links a predefined crystalline grain size to a luminescence center, the band tail luminescence model explains all aspects of the luminescence. Not only the PL peak position, but also spectral width and relative intensities of the luminescence are described by the band tail luminescence model. We conclude that silicon nitride is an inappropriate matrix for investigating photoluminescence from Si-NC.

References:

8095-01, Session 1

Lasing in photonic nanostructures
C. M. Soukoulis, Iowa State Univ. (United States)

A self-consistent computational scheme is presented for photonic systems with gain incorporated into the nanostructures. The gain is described by a generic four-level system. The loss compensation and the lasing behavior of the photonic nanostructures with gain are studied. A critical pumping rate exists in compensating the losses of the metamaterial. There exists a wide range of input signals where the composite system behaves linearly. When the pumping rate increases, there is a critical pumping rate at which the photonic crystals and metamaterial systems start lasing.

8095-02, Session 1

Advancing active nano-plasmonics
A. V. Kildishev, V. P. Drachev, S. Xiao, X. Ni, Purdue Univ. (United States); L. Prokopeva, Institute for Computational Technologies (Russian Federation) and Purdue Univ. (United States); J. Trieschmann, J. Fang, V. M. Shalaev, Purdue Univ. (United States)

Loss-free and active metamaterials and nanostructured plasmonic devices can enable new important applications ranging from advanced sensing and imaging devices to nanoscale lasers and optical waveguides. The interaction of light with optical gain materials is of great importance especially in metal-dielectric nanostructures, where the compensation of losses is essential for practical engineering.

In order to design active nano-plasmonic devices, accurate models of this light-matter interaction are required. A loss-free and active metamaterial in the visible has been recently experimentally demonstrated at the Birck Nanotechnology Center at Purdue; this experiment was supported by FEM-based simulations in frequency domain and the appropriate retrieval of the effective biaxial properties.

Our recent progress in this field will be reviewed followed by a brief discussion of the experiment-fitted parameters for (i) gain media - the 4-level system of auxiliary differential equations (ADE), and (ii) noble metals - the general dispersive material (GDM) model, which are imperative for accurate time-domain simulations of active nano-plasmonic devices.

8095-03, Session 1

Dynamics of amplification and gain in nano-plasmonic metamaterials
S. Wuestner, A. Pusch, K. L. Tsakmakidis, J. Hamm, O. Hess, Imperial College London (United Kingdom)

Negative-refractive-index metamaterials can enable a multitude of exciting and useful applications, such as subwavelength focusing, invisibility cloaking, and ‘trapped rainbow’ stopping of light. The realization of these materials has recently advanced from the microwave to the optical regime. However, at optical wavelengths, metamaterials suffer from high dissipative losses owing to the metallic nature of their constituent meta-molecules. It is therefore not surprising that overcoming loss restrictions is currently one of the most important topics in metamaterials’ research [1].

Here we study, based numerical on pump/probe experiments, the nonlinear dynamics of active, negative-refractive-index, double-fishnet metamaterials. We demonstrate that the use of an active medium (laser dyes) embedded into the structure of a double-fishnet NRI metamaterial can lead to complete compensation of optical losses, and even to light amplification [2,3]. Our analysis is based on a full-vectorial time-domain approach that manages to self-consistently couple the evolution of the occupation densities in the gain medium directly to Maxwell’s equations in three dimensions [2]. Nonlinearly, saturation of the gain medium and spatiotemporal variations of, both, absorption and emission are all inherent to our model [2,4], avoiding the need for external, pre-calculated inputs. We show that the highly nonlinear character of the pump process for times shorter than ~ 5 ps, as well as the non-instantaneous decay (on a timescale of approximately 100 fs) of, both, the upper absorption state and the lower emission state - both of which, cannot be captured by frequency-domain analyses. Further, we illustrate the importance of a judiciously chosen delay between the pump and the probe pulses in order to maximise the harnessed gain, and probe the system in its linear regime (where the standard effective-parameters retrieval methods apply). Finally we show that the pump-induced population inversion (gain) is found, when properly calculated, to be highly spatially-nonuniform. There are spatial regions where no population inversion occurs, with the probe-pulse being therein absorbed rather than amplified - therefore, particular care should be exercised to avoid using spatially-uniform population/gain distributions, as these could lead to unphysical or optimistic outputs.

References

8095-04, Session 2

Active infrared metamaterials
I. Brener, Sandia National Labs. (United States)

In this talk I will review the current status of electrically tunable metamaterials, both at Terahertz and shorter infrared frequencies. Scaling these active devices to mid and near infrared optical frequencies poses considerable challenges and requires new tuning mechanisms. Some examples include controlling coupling to other dipolar resonances such as phonons and engineered transitions in semiconductor heterostructures.

8095-05, Session 2

Infrared detectors with plasmonic cavities
S. Krishna, Ctr. for High Technology Materials (United States)

There is an increased emphasis on obtaining multicolor detectors as a part of the third generation detector development. We have been undertaking research on infrared detectors based on InAs/GaAs quantum dots in a well (DWell) and InAs/GaSb superlattices. We will discuss approaches to realize multicolor detectors using near field enhancement using surface plasmons coupled to infrared detectors. We will describe our recent work on the development of a plasmonic quantum dot focal plane array.

Acknowledgements: Acknowledgements: I wish to acknowledge my collaborators (Profs. Brueck/Hayat group at UNM, Dr. Cardimona’s group at AFRL, Prof. Perera’s group at Georgia State University, Prof. Painter’s group at Caltech, Profs. Ghosh and Grein at UIC, Dr. Tonii Taylor, Rohit Prasankumar, Aaron Gin at Center for Integrated Nanotechnology (CINT) and Dr. S.K. Noh and Dr. S.J. Lee from Korean Research Institute of Standards and Science (KRISS). This work would not have been possible with out the hard working members of the research group (Dr. L.R.
8095-06, Session 2

**Manipulating light with photonic metamaterials**

B. Ou, J. Zhang, T. S. Kao, K. F. Macdonald, E. Plum, N. I. Zheludev, Univ. of Southampton (United Kingdom)

[invited] We report on a number of new approaches to control the interaction of light with nanostructured photonic metamaterials and new types of metamaterials. This includes nano-mechanical reconfigurable metamaterials for the visible and near-infrared parts of the spectrum; bas-relief and intaglio “full-metal” metamaterials and “loaded plasmon” metamaterials as new types of frequency selective surfaces, perfect absorbers and magnetic walls. We also show how tailoring profile of the excitation optical field can be used to control localization of light in a certain class of plasmonic nanostructures with strongly interacting meta-molecules which has a potential for applications in data storage and imaging.

8095-59, Session 2

**Miniaturized gas sensors based macroporous silicon**

R. B. Wehrspohn, B. Gesemann, D. Pergande, Martin-Luther Univ. Halle-Wittenberg (Germany); S. Schweizer, Martin-Luther-Univ. Halle-Wittenberg (Germany); A. Lambrecht, Fraunhofer-Institut für Physikalische Messtechnik (Germany)

In many fields such as technical, environmental, automotive, and medical applications, miniaturized and mobile gas sensors are indispensable. Moreover, the 9/11 events have led to an increase in the request for sensors and sensor systems that can detect rapidly, efficiently, and at moderate cost trace explosives and a whole range of toxic substances at diverse control points, e.g., at airports and inside air conditioning systems in aircraft and public buildings. Most of the current miniaturized sensing methods are applicable only to certain specific gases that influence the physical properties of the detector materials. We will present two concepts of miniaturized element-specific sensors, based on electrochemically-prepared macroporous silicon. Firstly, we will show a miniaturized optical sensor using low-group velocities in a 2D photonic crystals and selective thermal emitters for compact gas sensing in the ppm range [1]. Secondly, a micro-ionization-mobility-spectrometer using needle-like macroporous silicon surfaces is presented that has the potential to measure in the ppt range [2]. The technological limits as well as the physical limits will be discussed.

8095-08, Session 3

**Slotted nanobeam microcavities enabling hybrid photonic devices**

J. Schilling, C. Schrieber, C. Bohley, Martin-Luther-Univ. Halle-Wittenberg (Germany)

Silicon nanobeam cavities consisting of two lines of equally spaced pores (Bragg mirrors) which enclose a straight section in a silicon strip waveguide gained recently renewed interest when several designs where developed allowing high Q-factors and relatively low mode volumina. With these properties the nanobeam cavities are of special interest for the enhancement of nonlinear optical processes e.g. optical bistability and opto-optical switching. However for efficient nonlinear processes in the near infrared the strong two photon absorption of silicon is a serious obstacle.

We therefore suggest a hybrid approach where a slot is introduced into the silicon nanobeam cavities. This slot can be infiltrated with other nonlinear optical materials (e.g. polymers or chalcogenide glasses) which experience the strong field enhancement within the slot, thus combining the efficient light confinement due to the high refractive index of silicon with the tailored nonlinear optical properties of the infiltrated material. Here we present first a theoretical investigation of the mode profiles, mode volumina and Q-factors of such infiltrated slot nanobeam cavities. General desing principals are discussed and in particular the impact of a gradual adjustment of the pore distance and pore diameter of the pores closest to the cavity is investigated. Especially the tapering of the pore diameter leads to a smoother transition of the mode profiles from the cavity centre to the adjacent Bragg mirror region resulting in a considerable increase of the Q-factors. Furthermore the influence of the length of the taper is considered and surprisingly a maximum Q-factor of 100 000 can be obtained with a linear taper including only two pores.

Besides these theoretical studies first experimental results demonstrating the described hybrid nanobeam cavity resonances in the near IR will be presented.

8095-09, Session 3

**Nanoscale photonics: nonlinear materials and processes**

C. Sibilia, Univ. degli Studi di Roma La Sapienza (Italy)

An overview of different nonlinear optical phenomena occurring in nanopatterned materials is presented . In particular a discussion about second order nonlinear effects is reported, including also some nonclassical properties of the interaction with non homogeneous materials.

8095-10, Session 3

**Enhancement of nonlinear refraction and absorption using cascaded plasmon resonances**

S. Toroghi, P. G. Kik, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States)

Metal-dielectric composites exhibit strongly modified linear and nonlinear optical properties due to the existence of localized surface plasmon resonances. We have previously shown that silver nanoparticle arrays can be used to strongly enhance the nonlinear optical refractive and absorptive properties of a composite, and that the spatial arrangement of the particles has a significant effect on the figure of merit for nonlinear absorption. In this talk we discuss an additional enhancement of the nonlinear optical response of such nonlinear metamaterials by making use of cascaded plasmon resonances on coupled silver nanoparticle arrays. The arrays consist of chains of particles with alternating sizes,
i.e. with a binary size distribution. Through numerical simulation, we study plasmon-induced changes in the linear and nonlinear optical properties of these nanoparticle composites as a function of dissimilarity in nanoparticle size within the structure. In successive simulations, the relative size of the particles is varied systematically while maintaining a fixed metal fill fraction. The relative particle volumes were chosen to be 1, 2.3, 4.8, 11 and 30, at a fill fraction of 1%. We find that the introduction of even a small size difference leads to the appearance of new plasmon resonance modes of the coupled nanoparticle chains, which are identified to be an anti-symmetric plasmon resonance (opposite field on neighboring particles), as well as several multipolar modes. It is found that the internal field enhancement in the small particles is four times larger than that found in arrays consisting of particles with a single size, demonstrating the presence of a cascaded resonance effect. We demonstrate that this seemingly moderate additional cascaded enhancement leads to a dramatically enhanced nonlinear optical response of the composites at specific frequencies. Methods for fabrication similar structures using existing nanofabrication tools will be discussed, and the viability of experimentally observing the predicted effects will be addressed.

8095-11, Session 3
Amplification of the nonlinear optical response of metals in induced transmission filters
C. Fuentes-Hernandez, J. Huo, D. T. Owens, A. R. Ernst, J. M. Hales, J. W. Perry, B. Kippelen, Georgia Institute of Technology (United States)

Metallic nanostructures, such as metal-dielectric photonic bandgaps have been proposed as one class of materials where the large nonlinear optical (NLO) response of metals can be accessed in spectrally broadband passbands that show high transmission in the visible range. Here, we propose another structure which has been somewhat overlooked in the literature in the context of NLO filters, namely the induced-transmission filter (ITF). In an ITF, a single metal layer, several times thicker than its skin depth, is surrounded by admittance matching layers that allow the opening up of spectrally narrow passbands with high transmittance in the visible range. We present the design and fabrication of Ag-based ITFs having a peak linear transmittance of 63% and we discuss the experimental demonstration of an enhancement in its NLO response by a factor of 30 over an isolated Ag film. We also present a physical model that describes the NLO properties of thin Ag films in the context of ultrafast electron heating and show that its predictions also allow modeling of the NLO response of ITFs. We use this model, to describe how variations in structure impact the strength of the response and demonstrate the possibility of a further enhancement in the nonlinearity by a factor of 2. Finally, we show that a stronger NLO response than Ag can be obtained with the use of Ag/Au bi-metal layers and that these bi-metal layers can be used to fabricate ITFs with more than 80% peak transmittance.

8095-12, Session 3
Second harmonic nanoparticles in imaging applications

Recent developments in nano-science have provided us with a diverse group of nanoparticles capable of second harmonic generation. We review the applications of these particles in imaging. We will focus on how the shape and the size of the particles determine their imaging capabilities.

8095-13, Session 4
Ultrafast switching of semiconductor microcavities
G. Cistitis, W. L. Vos, E. Yüce, Univ. Twente (Netherlands); J. Claudon, J. Gérard, Commissariat à l’Énergie Atomique (France)

Switches are widely applied and necessary ingredients in modulation and computation. Recent progress on photonic integrated circuits promises to overtake boundaries set by conventional switching. Therefore, ultrafast switching of photonic cavities is crucial as it allows the capture or release on demand of tunable photons [2], which is relevant to on-chip communication and to high-speed miniature lasers. Ultrafast switching would also permit the cavity quantum electrodynamical manipulation [3] in real-time.

Switching photonic nanostructures is achieved by changing the refractive index of the constituent materials. To date, the switching speed has been limited by material properties (see [4]), but not by optical considerations. We explore the ultimate fast switching of the cavity resonance in GaAs-AlAs in the telecom range. We exploit the instantaneously fast electronic Kerr effect by the judicious tuning of the pump and probe frequencies relative to the semiconductor bandgap, resulting in a shift of the cavity resonance by nearly one linewidth. The speed of the switching - both on and off - is only limited by the dynamics of the light in our cavity [5].

We explore the not-adiabatic regime of tuning of light in a single-resonance cavity. We observe that the frequency of probe light is changed to a value different from the cavity resonance. The light accumulates a phase shift while it is trapped in the cavity due to a fast change in the refractive index, induced by an earlier pump pulse. Consequently, all light trapped in the cavity obtains a frequency different from the cavity resonance. To our knowledge, such photonic non-adiabatic tuning has not been observed before [6].

References:

8095-14, Session 4
Dynamic optical media: ultrafast bandgap photonics application
M. K. Rafailov, RCI Inc. (United States)

It is known that ultra-fast laser is able to change the physical state of solids: to melt, to evaporate, to ionize. It is less known that ultra-fast laser is able to change the optical state of some solids: to bleach it. The effect is most pronounced in semiconductors were the bandgap amplifies the effect in highly non-linear manner. Change in optical state is on the scale of recombination time such short time changes in semiconductor optical characteristics depend on the bandgap structure, therefore we are introducing the term - Ultrafast Bandgap Photonics. Phenomena of Ultrafast bandgap photonics are time-dependent and bandgap-dependent the optical effects are reversible: ultra-fast laser “bleaches” semiconductor reflectivity, abnormally changes spectral reflectivity, “injectivity”, and transmittance as well as polarization characteristics. Applications of Ultra-fast bandgap photonics are remote control of semiconductor characteristics and material properties. Ultrafast Bandgap Photonics
effects may temporally alter photodetector’s fundamental characteristics - responsibility and detectivity as well as its response time and spectral bandwidth - all of these may happen with or without changes in photodetector electrical response. While Ultrafast Bandgap Photonic applications are directly depend on pulse dwell time and pulse repetition rate; it is important to say that laser energy per pulse should be carefully managed. In this paper we discuss some foundations of ultra-fast bandgap photonics - specifically for low pulse energy.

8095-15, Session 4

**Optical response of a slab with time-periodic dielectric function \( \varepsilon(t) \): Towards a dynamic metamaterial**

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A dielectric medium with time-periodic permittivity \( \varepsilon(t) \) gives rise to a band structure that is periodic in the frequency \( \omega \) and exhibits wave vector gaps \( \Delta k \). Light reflected from and transmitted by such a dynamic slab contains harmonics \( \omega = n\Omega (n = 0, \pm 1, \ldots) \) where \( \Omega \) is the modulation frequency. Also, giant resonances are obtained in the response for \( \omega = n\Omega/2 \) with odd \( n \), provided that a certain condition is satisfied for the slab thickness. Further, we show that a dynamic medium can be realized by means of a low-pass transmission line with varactors whose capacitance is \( C(t) = d\mu(t) \) and inductance \( L = d\mu_0 \) being the period.

8095-16, Session 4

**Theoretical modeling of the ultrafast recovery times and low saturation intensities of the intersubband absorption in the InGaAs/AlAs/AlAsSb coupled double quantum wells**

P. Ma, Y. Fedoryshyn, H. Jäckel, ETH Zurich (Switzerland)

Nonlinear optical devices, which are capable of performing ultrafast all-optical switching at reasonably low power levels, are required to fulfill the demands of the coming generation of all-optical communication networks. The InGaAs/AlAsSb material system is very promising in this respect due to a number of its specific properties, such as the large optical nonlinearities of the intersubband transitions in quantum wells, the ultra-short relaxation times, and the large conduction band offset [1].

The all-optical switching mechanism is based on the saturable intersubband absorption in the four-level quantum well system. Our recent pump-probe and absorption saturation experiments revealed ultrafast absorption recovery time scales with low material absorption saturation intensities in the strained InGaAs/AlAs/AlAsSb symmetric coupled double quantum wells. This article addresses a systematic study of the dynamic nonlinear processes in our quantum well structures by performing theoretical simulations in order to interpret the pump-probe and absorption saturation experimental results. First, the quantum well system is modeled by solving self-consistently the Schrödinger-Poisson equations. Then, modified optical Bloch equations in combination with the density matrix method are employed to simulate the time evolution of the optical nonlinearities under the pulsed excitation. Impact factors related to the dynamic and saturation characteristics of the material, such as the dephasing time, the doping concentration, and the pump pulse duration, are discussed theoretically. Furthermore, a novel switching operation mechanism, where the pump and signal light are resonant to two different intersubband transitions in the four-level quantum well system, are investigated theoretically. Our further experimental and theoretical studies, which are in progress, will provide a deeper understanding of the nonlinear phenomena and the dynamic processes in the coupled double quantum wells embedded into a waveguiding structure for all-optical switches [2].

Reference

8095-17, Session 5

**Electromagnetic unidirectionality in the presence of absorption or gain**

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Magnetic photonic crystals are spatially periodic structures composed of transparent materials, some of which being magnetically polarized. Magnetization, either spontaneous or induced, is always associated with nonreciprocal circular birefringence (magnetic Faraday rotation). It can qualitatively change electrodynamics of the composite medium. In particular, magnetic photonic crystals of certain configuration can display strong spectral asymmetry, implying that electromagnetic waves propagate in one direction much faster or slower than in the opposite direction. This phenomenon is essentially nonreciprocal and unique to magnetic photonic crystals. It can only exist if both time reversal and space inversion symmetries of the composite structure are broken. The spectral asymmetry can result in electromagnetic unidirectionality [1, 2]. In a unidirectional medium, the electromagnetic wave of certain frequency propagating in the forward direction has zero group velocity and greatly enhanced amplitude. Such a wave is referred to as the frozen mode [2, 3]. The wave of the same frequency propagating in the backward direction can have group velocity comparable to speed of light in vacuum.

Consider now forward and backward transmittance of a plane-parallel unidirectional photonic slab. At first sight, the transmittance in the direction of zero group velocity (the forward transmission) should be suppressed, as compared to the backward transmittance, where the light group velocity is large. Our rigorous analysis, though, shows that in the absence of absorption, the forward transmittance averaged over incident light polarization is exactly equal to that of the backward transmittance. But, if we introduce even a modest absorption, the forward transmission reduces dramatically, while the backward transmittance remains almost unchanged. Such a behavior is reminiscent of a nonreciprocal linear isolator. Even more intriguing behavior is expected if a unidirectional photonic crystal includes a gain component. In the latter case, the forward propagating wave can experience a dramatic amplification, while the backward propagating wave is not enhanced at all, or even suppressed. Either effect can be very attractive for practical applications.


8095-18, Session 5

**PT-synthetic optical materials**

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Transport properties of synthetic optical media, with Parity (P) and Time (T) symmetries imposed by a balanced arrangement of gain and loss, are investigated. We find that the temporal behavior of the total power of a propagating beam in linear PT media is insensitive to microscopic details of the system and follows three distinct universal laws which depends only on the magnitude of the gain/loss parameter. We further show that PT-symmetric Bragg grating structures, at the spontaneous PT-symmetry breaking (exceptional) point, can act as unidirectional invisible media. In this regime the reflection from one end is diminished while it is enhanced from the other. At the same time the transmission coefficient and phase, are indistinguishable from those expected in the absence of a grating. The phenomenon is robust even in

Reference
the presence of Kerr non-linearities, and it can also effectively suppress optical bistabilities.

Away from the exceptional point, the interplay of optical non-linearities with PT-symmetries, allow for diode action. Such PT-synthetic unidirectional optical valves may find promising applications in integrated photonic systems.

8095-19, Session 5

Retooling electromagnetic scattering: one-way photonic chiral edge states and optical manipulation

Z. Wang, Massachusetts Institute of Technology (United States); P. T. Rakich, Sandia National Labs. (United States); J. D. Joannopoulos, M. Soljacic, Massachusetts Institute of Technology (United States)

In ordinary waveguides, photons travel both ways, allowing discontinuities to readily scatter light and induce losses. Photonic chiral edge states, on the other hand, permit electromagnetic waves to propagate only in a single direction. Obstacles and disorder can no longer reflect waves, which exhibit 100% transmission in numerical simulations even across seemingly-impossible perfectly-conducting barriers introduced into the waveguide. I will explain how such phenomena, analogous to quantum-Hall edge states, can arise from magneto-optical photonic crystals. Generalizing earlier predictions by Raghu and Haldane, I show that the key requirement is related to a topological invariant of the bulk bands known as Chern number. I also present our experimental results verifying the existence of these novel phenomena. I will discuss the implications of these novel photonic states in altering the basic physics of momentum transfer. I will also discuss prospects of applying these novel photonic states in optical lattices and optical manipulation.

8095-20, Session 5

Time-reversal and nonlocal effects in PT-symmetric nonlinear lattices with balanced gain and loss

A. A. Sukhorukov, The Australian National Univ. (Australia)

Photonic structures composed of coupled waveguides with loss and gain regions offer new possibilities for shaping optical beams and pulses compared to conservative structures. Such structures can be designed as optical analogues of complex parity-time (or PT) symmetric potentials, which can have a real spectrum corresponding to the conservation of power for optical eigenmodes, for the magnitude of gain/loss below a certain threshold.

PT-symmetric potentials appear in many physical contexts, and one feature actively investigated in the context of quantum theories is the property of nonlocality. We reveal that effective nonlocality of PT-symmetric structures with gain and loss elements can lead to pronounced differences for optical beam dynamics in arrays of coupled waveguides with the same characteristics but different topology. We also reveal a generic connection between the effect of time-reversals and nonlinear wave dynamics in systems with parity-time (PT) symmetry, considering a symmetric optical coupler with balanced gain and loss where these effects can be readily observed experimentally. We show that for intensities below a threshold level, the amplitudes oscillate between the waveguides, and the effects of gain and loss are exactly compensated after each period due to periodic time-reversals. For intensities above a threshold level, nonlinearity suppresses periodic time-reversals leading to the symmetry breaking and a sharp beam switching to the waveguide with gain. Another nontrivial consequence of linear PT-symmetry is that the threshold intensity remains the same when the input intensities at waveguides with loss and gain are exchanged.

8095-21, Session 6

Spatial coherence of random laser emission

B. Redding, Yale Univ. (United States); M. A. Choma, Yale School of Medicine (United States); H. Cao, Yale Univ. (United States)

Lasing action in disordered media has been studied extensively in recent years and many of its properties are well understood. However, few studies have considered the spatial coherence in these systems, despite initial observations indicating that random lasers exhibit much lower spatial coherence than conventional lasers. We performed a systematic investigation of the spatial coherence of random laser emission as a function of the scattering mean free path and the excitation volume. Our experiments were performed on a series of Rhodamine 640 doped diethylene glycol solutions with varying concentrations of 240 nm diameter polystyrene spheres. Lasing was achieved under optical excitation and spatial coherence was characterized by imaging the emission spot onto a Young’s double slit and collecting the interference fringes in the far field. The visibility of these fringes provided a measure of the coherence between two points in the lasing spot separated by the distance of the two slits. We observed dramatic differences in the spatial coherence within our parameter space. Specifically, we found that samples with a shorter mean free path relative to the excitation volume exhibited reduced spatial coherence. We also found that the spatial coherence is strongest across a plane perpendicular to the longest dimension of the excitation volume. A qualitative explanation of the experimental results will be presented. This work provides a means to realize intense, spatially incoherent laser emission for applications in which speckle or spatial cross talk limits performance.

8095-22, Session 6

Classification of light sources and their interaction with active and passive environments

R. El-Dardiry, S. Faez, A. Lagendijk, FOM Institute for Atomic and Molecular Physics (Netherlands)

Emission from a molecular light source depends on its optical and chemical environment. This dependence is different for various sources. We present a general classification in terms of Constant Amplitude and Constant Power Sources. Using this classification, we have described the response to both changes in the LDOS and stimulated emission. To find the correct wave function from a single source or collection of sources becomes much more involved than previously assumed since it requires knowledge of the Green function for both the propagation and the generation of light.

The unforeseen consequences of this classification are illustrated for photonic studies by random laser experiments and are in good agreement with our correspondingly developed theory. In contrast to conventional lasers, random lasers have a statistically isotropic mode selectivity. Their mode selection is solely determined by the spectral shape of the gain curve. In a random laser therefore, measuring the emitted energy into a large enough solid angle corresponds to measuring the total emitted intensity: diffusion mimics an integrating sphere. In our experiments, we utilize this much neglected property of random lasers to study the influence of light source typology on the generation of light in complex media. Our results require a revision of studies on sources in complex media.

8095-23, Session 6

Random lasing in disordered arrays of ZnO nanorods

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K. Busch, Karlsruher Institut für Technologie (Germany)

A random laser is in general a strongly disordered, laser-active optical medium. Despite substantial investigations, the physics of homogeneously disordered random lasers bears intriguing, open problems. The conditions for transport and localization and, in particular, the origin of confined spatial regions from which laser radiation is emitted (observed “lasing spots”) as well as the dependence of their size on for instance the pump rate, have remained poorly understood. Here, we consider spatially disordered ZnO nanorod arrays with uniform rod size, as also considered in experiments. These pillars have average diameter of 200 nm and a length of 4.7 μm, with an average rod-to-rod spacing of 500 nm. For such samples, we develop a semianalytical transport theory for random, laser-active systems, including light diffusion, localization, i.e. self-interference effects, and coupling to the semiclassical laser rate equations to account for (coherent) stimulated and (incoherent) spontaneous emission. We solve this laser transport theory with appropriate boundary conditions to obtain the average spatial distributions of the light intensity and of the occupation inversion. The full spatial intensity profile of the lasing spots is obtained numerically in dependence of the pump rate and other parameters such as the average number of nanorods per unit cell (filling fraction), system size and losses, caused by photons escaping out of the disordered array.

8095-24, Session 6
Ultrafast active control of optical eigenmodes in a multiple scattering nanowire layer
O. L. Muskens, M. Abb, Univ. of Southampton (United Kingdom); E. P. A. M. Bakkers, Technische Univ. Eindhoven (United Kingdom)

The appearance of an interference pattern after transport of coherent waves through a random medium is the result of coherent summation of thousands of multiple scattering paths with random phases. Although the lack of many-body interactions makes phase coherence generally more robust for optical waves than for electrons, several dephasing processes can influence the transport of light, such as magnetic fields and inelastic scattering from colloids.

Here, we demonstrate a new regime of dephasing in photonic random media on ultrafast time scales. The random medium under study is a layer of strongly scattering nanowires, one of the most strongly scattering materials available today [1]. The nonlinear response of individual pseudomodes is found to be governed by dephasing of multiple scattering light paths on a picosecond time scale. By comparing our results with numerical simulations, we identify absorption and strain deformation as possible mechanisms responsible for the dephasing effects. The new dephasing nonlinearity results in large intensity modulations of around 50%, holding promise for ultrafast control of eigenmodes in nanophotonic switches, random lasers, and cavity quantum electrodynamics [2].

Of considerable importance is also the possibility of achieving nonadiabatic switching, i.e. dephasing of multiple scattered paths during the diffusion time of the light. We will discuss the possibility of controlling phase coherence of correlated paths in mesoscopic transport and, ultimately, the time-reversed light paths involved in photon localization.


8095-25, Session 7
Photonic band gap materials: light trapping crystals
S. John, Univ. of Toronto (Canada)

Photonic band gap (PBG) materials [1,2] are artificial periodic dielectric microstructures capable of trapping light in 3D [3] on sub-wavelength scales. This offers new opportunities for efficient solar energy trapping and harvesting in suitably microstructured thin films [4]. It also enables virtually complete control of the flow of light on microscopic scales in a 3D optical chip [5-7] as well as very strong coupling of light to matter where desired. By further engineering the electromagnetic density of states [8-10] within the chip it is possible to realize unprecedented coherent optical control of the quantum state of resonant atoms or quantum dots [11, 12]. This defines a fundamentally new strong-coupling regime for quantum optics. It enables multiple-wavelength channel optical logic to be performed on a chip on picosecond time scales at micro-watt power levels.

I discuss further consequences of light trapping in classical and quantum electrodynamics. I also discuss the challenges and requirements for materials fabrication to realize these remarkable effects.

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8095-26, Session 7
Strong coupling of plasmons in non-linear waveguides
D. Felbacq, A. Castanie, B. Guizal, Univ. Montpellier 2 (France)

Wave propagation in a planar metal plasmon waveguide is studied. More specifically, the dispersion curve of a metal-insulator-metal waveguide is investigated. Such structures have been investigated in the past in the situation of a thin insulator film. In this work, the situation when the insulator layer supports guided modes is considered. It is shown that, in that case, it is possible to realize the strong coupling of photon modes with plasmons. By means of complex plane analysis, the influence of this coupling on the losses is studied and, for the hybrid plasmon/ waveguide photon mode, spatial Rabi oscillations are observed. Finally the introduction of gain is considered as well as some more complicated geometries in view of the practical realization of devices.

8095-27, Session 7
Quantum electrodynamics in photonic crystals
P. Lodahl, Technical Univ. of Denmark (Denmark)

2D photonic crystal membranes fabricated in GaAs containing InGaAs quantum dots have in recent years proven to be a very successful platform for all-solid-state quantum optics experiments [1-4]. In a photonic crystal, the light-matter interaction strength can be tailored, i.e. either enhanced or suppressed by controlling the lattice constant of the structure. We will present experimental results on how highly efficient single-photon sources can be constructed by coupling single quantum dots to a photonic crystal waveguide exploring slow light [3]. The role of disorder in the form of fabrication imperfections is explored and found to lead to Anderson localization of light enabling cavity quantum electrodynamics by exploiting disorder as a way to enhance light-matter interactions [4]. The fundamental limits of using Anderson localization to enhance light-matter interactions are discussed, and the results are compared to the performance of state-of-the-art engineered
nancavities.


8095-28, Session 7

Selective addressing of the resonant modes of a micropolar cavity with white light

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There is a tremendous interest in high-quality micropolar resonators because of their potential in cavity-QED experiments such as the demonstration of the Purcell effect [1] or vacuum Rabi splitting [2, 3]. Most experiments are performed with quantum dots as internal light sources. Reflectivity experiments are rare because of symmetry constraints [4]. Here, we present broadband white-light reflectivity experiments on micropolar resonators with diameters ranging between 1 µm and 20 µm. The micropolars consist of a GaAs λ/4-layer, sandwiched between two Bragg-stacks made of λ/4 GaAs/AlAs layers, and were fabricated by molecular-beam epitaxy. We are able to spectrally resolve distinct transverse modes in the reflectivity experiments and to selectively address single modes by scanning the probe beam along the top facet of the micropolar. The positioning of the focused laser beam turns out to be crucial for pillar diameters exceeding the beam diameter, since at every position the coupling efficiency to different modes changes [5]. By decreasing the pillar diameter, we are able to resolve single modes, since the spacing between the modes increases.

References:

8095-29, Session 7

Diamond photonics and quantum optics

M. Loncar, Harvard Univ. (United States)

Individual color centers in diamond have recently emerged as a promising solid-state platform for quantum communication and quantum information processing systems, as well as sensitive nanoscale magnetometry with optical read-out. Performance of these systems can be significantly improved by engineering optical properties of color centers using nanophotonic approaches. In this work we describe a high-flux, room temperature, source of single photons based on an individual nitrogen-vacancy (NV) center embedded in a top-down nanofabricated, single crystal diamond nanowires. Using the nanowire geometry, an order of magnitude brighter single photon source is realized, with an order of magnitude lower pump power, compared to an NV center in a bulk diamond. We also describe fabrication process that combines ion implantation of nitrogen with nanowires fabricated in high-purity diamond crystals. This approach significantly improves single-photon properties of our devices. By embedding nanowires in metals, it is possible to further increase photon production rate (via Purcell effect), as well as improve collection efficiency of emitted photons. Finally, we will describe optical cavities realized in diamond and materials transparent at visible wavelengths (Si3N4 and TiO2) that can enable strong coupling between photons and NV centers.

8095-30, Session 8

Photic crystal nanolasers with nanoslot structure for sensing applications

T. Baba, S. Kita, H. Abe, S. Hachuda, M. Narimatsu, S. Otsuka, K. Nozaki, Yokohama National Univ. (Japan)

Photic crystals have achieved ultimately small nanolasers. For example, H0-type devices in GaInAsP semiconductors operate under room temperature cw condition by photopumping with a modal volume of less than 0.2 times the cubic wavelength. The volume is further reduced beyond the diffraction limit by introducing a nanoslot in the cavity. A very narrow nanoslot of 30 nm width is formed by using inductively coupled plasma etching with H1 gas. In such a nanoslot, strong mode localization occurs due to large discontinuity of electric field at high-index contrast boundaries. It enhances light-matter interaction in cavity QED and sensitivity of laser wavelength against environmental medium. The nanoslot nanolaser is particularly attractive as a sensor, because the device and optical I/O are much simpler and its performance is, in most cases, much better than passive cavity sensors. As a sensor of liquid index, it exhibits a high sensitivity of 410 nm/RIU. In addition, it shows low temperature dependence in water, which is attributed to the negative TO effect of water compensating positive one in semiconductors. It suppresses the thermal chipping in laser spectrum to 10 pm order even with the small modal volume, ensuring high resolution sensing. Moreover, remarkable performance is observed when sensing protein; it detects an extremely low concentration of BSA protein in water, i.e. 17 pg/ml. This value implies 200 times higher sensitivity than that of surface plasmon resonance sensors.

8095-31, Session 8

Active semiconductor nanophotonics based on deterministic quantum wire and dot systems

E. Kapon, Ecole Polytechnique Fédérale de Lausanne (Switzerland)

Incorporating semiconductor quantum nanostructures such as quantum wires (QWRs) and quantum dots (QDs) into nano-photonic structures provides means for exploring both fundamental quantum photons phenomena and applications in new photonic devices and systems. Examples include solid-state cavity quantum electrodynamics and quantum information processing and communications [1]. Most work in this field has been done using self-assembled quantum nanostructures, which, however, do not offer the necessary control in terms of optical spectra and positioning of the QWRs/QDs on the photonic chip. Here, we review recent progress in quantum nano-photronics based on ordered QWR and QD structures grown on patterned substrates [2]. In particular, we discuss V-groove QWRs and pyramidal QDs formed due to growth rate anisotropy and nano-capillarity during metalorganic vapor phase epitaxy on nonplanar, patterned GaAs substrates [3]. This approach yields high quality, site-controlled (In)GaAs/AlGaAs QWR and QD systems, e.g., regular arrays of pyramidal QDs with ~1meV inhomogeneous broadening [4]. The confining potential of these wires/dots can be shaped by thickness and/or composition adjustment, producing structures of elaborated potential distributions, e.g., QD molecules and superlattices [5]. The intrinsically high symmetry of the pyramidal QDs yields unique excitonic features such as vanishing fine structure splitting, permitting efficient generation of polarization-entangled photons [6]. Based on these ordered QWR/QD systems, several nano-photonic
devices have been conceived and studied. These include coupled photonic crystal (PhC) cavities showing coupled-mode loss splitting [7], optically pumped, ~1μm long PhC-QWR lasers with sub-μW threshold and coupled-cavity PhC-QWR lasers [8], and single-QDs integrated with PhC membrane cavities [9]. More recently, deterministic coupling of single pyramidal QDs in PhC membrane cavities has allowed the identification of phonon-mediated coupling of the QD exciton and the cavity mode, which persists only for limited (few meV) cavity detuning [10]. This paves the way to the deterministic coupling of several QD-excitons via cavity photons, interesting for exploring many-body quantum photonics phenomena [11]. Implications on the feasibility of realizing “true” QD lasers will also be discussed.

References:
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8095-32, Session 8

Optical antenna electrodes for modification of QW electroluminescence

K. C. Y. Huang, Stanford Univ. (United States); M. Seo, KAIST (Korea, Republic of); M. L. Brongersma, Stanford Univ. (United States)

We simulated, fabricated and characterized the electroluminescence from InGaAs/ GaAs QW with metal electrodes which function as plasmonic resonator antennas. By patterning the antenna electrodes in the vicinity of a single QW layer with deeply subwavelength lateral width, charge carriers are confined near the antenna and subsequently recombine with enhanced radiative decay rate depending on the electrode/ QW separation and electrode shape. We show that the emission can be efficiently coupled to the antenna resonance which is engineered to reradiate with a specific polarization and unidirectional far-field pattern. The simultaneous control of carriers and photons can be used to improve light extraction and detection from the semiconductor while enabling fast direct modulation of the spontaneous emission.

8095-33, Session 8

Quantum dot and high-Q 3D photonic crystal nanocavity coupled system for manipulating exciton-photon interaction

Y. Arakawa, A. Tandaechanurat, S. Iwamoto, The Univ. of Tokyo (Japan)

No abstract available

8095-34, Session 9

High aspect ratio nanoscale metallic structures: a platform for photonic devices

P. Kuang, J. Park, W. Y. Leung, K. P. Constant, S. Chaudhary, K. Ho, Iowa State Univ. (United States)

We will report our progress in using high aspect ratio nanoscale metallic patterned structures in a number of optical devices such as light-emitting diodes or solar cells. They have high visible light transmission comparable to indium-tin-oxide electrodes and superior electrical conductivities. They can also provide a platform for switchable optical devices.

8095-35, Session 9

Exceeding the classical light-trapping limit in solar cells

J. N. Munday, D. M. Callahan, H. A. Atwater, California Institute of Technology (United States)

We describe a methodology for designing solar cells that have intensity and absorption enhancements that exceed the ergodic light-trapping limit. From thermodynamic arguments, Yablonovitch determined the maximum absorption enhancement in the ray optics limit for a bulk material to be 4n^2, where n is the index of refraction of the absorbing layer. We extend this treatment by considering the local density of optical states (LDOS), which shows that absorption enhancements can exceed 4n^2 under specific design criteria. Using a combination of analytical and numerical methods, we show how structures can be designed to beat the ergodic limit over an arbitrarily large wavelength range using frequency sum rules. For thin film solar cells, incorporating a plasmonic back reflector can result in spatially averaged LDOS enhancements of 1 to 3, and a metal-insulator-metal (MIM) structure can result in enhancements of over 200 near the bandedge of Si. We also find that placing the active material within a localized metallic resonator can lead to a nearly spatially uniform LDOS with enhancements above 1000. Purely dielectric structures can also lead to intensity enhancements exceeding the ergodic limit. For a low index active layer (n=1.5) clad by a high index layer (n=3), the LDOS enhancement is greater than 10. Finally, we show that for thin film solar cells with dispersive dielectric structures such as photonic crystals the ergodic light-trapping limit can be exceeded with LDOS enhancements of 2 to 5 by placing a planar solar cell in close proximity to a photonic crystal.

8095-36, Session 9

Multiexciton effects in semiconductor nanocrystals from the perspective of lasing and solar energy conversion

V. I. Klimov, Los Alamos National Lab. (United States)

Using semiconductor nanocrystals one can produce extremely strong spatial confinement of electronic wave functions not accessible with other types of nanostructures. One consequence of this effect is a significant enhancement in carrier-carrier interactions that lead to a number of novel physical phenomena including ultrafast mutlicexciton decay due to Auger recombination and efficient generation of multiple electron-hole pairs by single photons via carrier multiplication. In this talk, I will discuss the implications of ultrafast Auger decay for lasing applications of nanocrystals and several recent approaches developed in our group for resolving this problem by engineering carrier-carrier interactions in various types of heterostructured nanocrystals. I will also review the current status of carrier-multiplication research including experimental challenges in studies of this phenomenon, the role of extraneous effects, the competing energy relaxation channels such as hot-electron transfer, and implications of carrier multiplication in solar photovoltaics.
8095-37, Session 10

Explorations of photonic nanostructures for thermal and quantum applications
S. Fan, Stanford Univ. (United States)
I will review some of our recent progresses in understanding photonic nanostructures. Examples including modified photon-photon interactions in one-dimensional nanophotonic systems, and new understandings of near-field thermal transfer.

8095-38, Session 10

Near-unity collection efficiency of single photons using a planar dielectric antenna
K. Lee, X. Chen, Max-Planck-Institut für die Physik des Lichts (Germany); H. Eghidi, A. Renn, ETH Zurich (Switzerland); S. J. Goetzinger, V. Sandoghdar, Max-Planck-Institut für die Physik des Lichts (Germany)
Single-photon sources have been discussed as the building blocks of quantum cryptography, optical quantum computation, spectroscopy, and metrology. However, the feasibility of these proposals depends on the availability of single photons with a high fidelity. For sources based on single emitters, this implies near-unity collection efficiency into well-defined modes. Some of the current state-of-the-art efforts aimed at achieving these criteria have been demonstrated, but despite an impressive progress the results still fall short. Here we report on a broad-band room-temperature scheme, which uses a layered dielectric structure for tailoring the angular emission of a single oriented molecule such that more than 96% of the emitted photons are collected with a commercially available microscope objective, leading to recorded photon count rates of about 50 MHz. Furthermore by adjusting the antenna parameters we could make an output mode to be very close to the radially polarized doughnut mode which can be converted into other modes such as the fundamental mode of an optical fibre with high fidelity. Our approach is wavelength insensitive and also compatible with cryogenic experiments. We will discuss various details of the design, fabrication and characterization of our dielectric planar antenna and its various applications to other types of single emitters - semiconductor quantum dots, diamond color centers, or solid-state ions.

8095-39, Session 10

Integrated quantum photonics
Quantum information science aims to harness uniquely quantum mechanical properties to enhance measurement and information technologies, and to explore fundamental aspects of quantum physics. Of the various approaches to quantum computing [1], photons are particularly appealing for their low-noise properties and ease of manipulation at the single qubit level [2]. Encoding quantum information in photons is also an appealing approach to quantum communication, metrology (eg. [3]), measurement (eg. [4]) and other quantum technologies [5]. However, the implementation of optical quantum circuits with bulk optics has reached practical limits. We have developed an integrated waveguide approach to photonic quantum circuits for high performance, miniaturisation and scalability [6]. Here we report high-fidelity silica-on-silicon integrated optical realisations of key quantum photonic circuits, including two-photon quantum interference and a controlled-NOT logic gate [7]. We have demonstrated controlled manipulation of up to four photons on-chip, including high-fidelity single qubit operations, using a lithographically patterned resistive phase shifter [8]. We have used this architecture to implement a small-scale compiled version of Shor's quantum factoring algorithm [9] and demonstrated heralded generation of tunable four photon entangled states from a six photon input [10]. We have combined waveguide photonic circuits with superconducting single photon detectors [11]. We describe complex quantum interference behaviour in multi-mode interference devices with up to eight inputs and outputs [12], and quantum walks of correlated particles in arrays of coupled waveguides [13]. Finally, we give an overview of our recent work on fundamental aspects of quantum measurement [14,15] and single photon sources [16,17].

8095-40, Session 10

Nonlinear optics near the single photon level with quantum dots coupled to photonic crystals
E. Waks, D. Sridharan, R. Bose, H. Kim, T. Shen, Univ. of Maryland, College Park (United States); G. S. Solomon, National Institute of Standards and Technology (United States)
Quantum dots (QDs) are stable, bright, semiconductor based light emitters that exhibit a quantized energy spectrum. For these reasons
they are excellent candidates for development of lasers, nonlinear optoelectronic components, and basic building blocks for future quantum information technology. Such applications critically depend on the ability to create strong interactions between QDs and photon fields. One method to engineer these strong interactions is to use photonic crystal structures. Photonic crystals are materials with a periodic index of refraction that can guide and confine light on the size scale of an optical wavelength, resulting in extremely strong atom-photon interactions. In this talk we will discuss our work to engineer strong nonlinear optical effects near the single photon level using a single quantum dot coupled to a photonic crystal cavity. We show that these interactions can be used to create all-optical switching with 8 GHz switching speeds using as few as two photons for the switching pulse. This device is approaching the fundamental limit where a single control photon can nonlinerly interact with a single target photon via cavity reflectivity modification. We then describe our effort to extend the device to a planar geometry that enables large scale integration on a chip. In addition, we show that by exploiting QD spin under high magnetic field we can attain improved switching performance, and also engineer entanglement between a photon and a single quantum dot, providing the potential for compact quantum devices that can be integrated on a semiconductor chip for future quantum information applications.

8095-52, Poster Session

The importance of nonlinear reflectance and transmittance measurements on the characterization of the nonlinear optical properties of metallic nanomaterials

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Z-scan is one of the most commonly used techniques to characterize the nonlinear optical (NLO) properties of many optical materials, including metallic nanomaterials such as ultrathin metal layers, metal nanoparticle doped glasses, and many others. To date, Z-scan data has been analyzed using the original formalism proposed by Sheik-Bahae M., et al. (IEEE Journal of Quantum Electronics, 26, 760, 1990). In this formalism, the NLO changes in the sample's reflectance, \( \Delta R(\ell) \), are neglected. This implies that the NLO changes in transmittance, \( \Delta T(\ell) \), measured in open-aperture Z-scan experiments can be directly correlated with the NLO changes in absorbance, \( \Delta A(\ell) \), such that \( \Delta A = -\Delta T - \Delta R \). Here, we discuss the implications of having strong changes in the reflectance by characterizing the NLO properties of a 20 nm Au film using a combination of T and R pump-probe and Z-scan experiments implemented with 500 fs pulses at 560 nm. We use spectroscopic ellipsometry to measure the linear refractive index of Au and use a physical model of the metal's permittivity to describe the linear and NLO properties measured by pump-probe experiments. Furthermore, we show that Z-scan traces can be recovered from these experiments and how neglecting \( \Delta R \) in the analysis of transmittance Z-scan data leads to misleading estimations of the magnitude, and even the sign, of the NLO changes observed.

8095-53, Poster Session

thermal tuning of a silicon photonic crystal cavity infilled with an elastomer


Thermal tuning of the transmission of a cavity in silicon photonic crystal (PhC) slab globally infilled with an elastomer was investigated. In contrast to liquids used for inflation, elastomers are more stable and durable. In addition, elastomers have a high coefficient of thermal expansion and as a result exhibit a relatively strong decrease of the refractive index upon heating. This appreciable thermo-optic property \((-3.5 \times 10^{-4}/K)\) can counteract the positive thermo-optic coefficient of the host material silicon \((1.85 \times 10^{-4}/K)\), and thus enables a measurable blue shift of the cavity transmission. Here, we use the elastomer Kraton SEBS G 1657 using global infilling and global heating of the PhC. The triangular hole-type PhCs are fabricated in silicon-on-insulator (SOI) material, using electron-beam lithography and cryogenic inductively coupled plasma etching in an SF6-based plasma. Membrane PhC devices are obtained by underetching the silicon layer in buffered HF. The infilling is done by applying a drop of the elastomer dissolved in cyclohexane \((2\% \text{ by weight})\) to the PhC membrane. The cavity we use is a hole-type cavity with modified surrounding holes. Transmission measurements are performed with the end-fire technique, using a white light source and an optical spectrum analyzer. The infill effect on the band gap and on the cavity resonance is clearly observed, the shift in either case being about 135 nm. Temperature-dependent measurements of the cavity resonance at eight temperatures in the range 293-333 K show a linear blue shift of 2.64 nm, large enough for tuning the transmission of modest Q cavities.

8095-54, Poster Session

Mode of propagation of optical radiation with self-similar pulse shape in layered medium with nonlinear absorption

V. A. Trofimov, O. V. Matusevich, D. A. Smotrov, Lomonosov Moscow State Univ. (Russian Federation)

We investigate the possibility of propagation of laser pulse which has self-similar shape at its propagation in a medium with two-photon absorption. The consideration is based on the solution of problem as nonlinear eigenfunction problem for the Schrödinger equation with periodic nonlinear coefficients which describe the nonlinear absorption and dielectric permittivity. Under certain conditions this eigenfunction gives us the pulse shape with requiring properties. We investigate the realization of mode of the laser pulse propagation with self-similar its shape in layered medium with two-photon absorption. In the case of homogeneous absorption medium the shape of pulse is similar to the soliton shape taking place for a propagation of laser radiation in a medium with Kerr nonlinearity.

8095-55, Poster Session

Photopolymer films doped with zeolite nanocrystals

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The effect of zeolites nanocrystals (pure silicate, aluminosilicates and aluminophosphate) incorporated in acrylamide based photopolymer layers for holographic applications is investigated. The presence of the zeolite nanocrystals improved the refractive index modulation and also resulted in substantial suppression of polymerization shrinkage. The
higher refractive index modulation achieved is beneficial for applications such as holographic data storage as it provides higher storage capacities. Besides, the high refractive index modulation is advantageous for the fabrication of spectroscopic devices and holographic optical elements. The holograms recorded in the acrylamide photopolymer films doped with the zeolite nanoparticles are identified for further sensor application.

8095-56, Poster Session

Coherent optical imaging through opaque photonic media

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Scattering of light is usually seen as a nuisance in microscopy. Scattering limits the penetration depth and strongly deteriorates the achievable resolution. However, by gaining active spatial control over the optical wave front it is possible to manipulate the propagation of scattered light even far in the multiple scattering regime [1]. It was recently shown that in this way scattered light can even be exploited for perfect optical focusing [2]. These wave front shaping techniques pave the way for new microscopy methods based on strong light scattering [3-6].

We use fluorescent beads to demonstrate concentration of scattered light into a focus much smaller than the wavelength. Exploiting such a small focus, we demonstrate imaging of gold nanostructures through an opaque scattering layer. We obtained a very high resolution proving that scattering can significantly improve the image quality in microscopy.

References:

8095-57, Poster Session

The effects similar to quantum teleportation and superluminality at propagating of laser pulse in medium with combined nonlinear response

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The effect of laser pulse propagation with group velocity, which is faster than light velocity at given conditions, is widely investigated at present, in particular for photonic crystals. We have found out the similar effect under the interaction of two laser pulse in medium with combined nonlinear response for 2D or 3D cases and for propagation of femtosecond pulse in nonlinear medium under the condition of temporal dispersion of nonlinear response.

The physical reason of such laser pulse propagation concludes in self-induced optical grating due to nonlinear interaction of laser radiation with matter. The grating acts on laser pulse in similar way as photonic crystal acts on velocity of laser light passed through the one.

We predict and investigate the increasing of group velocity of some sub-pulses, which appear under the dual-waves interaction in nonlinear medium.

We shown the distortion, introduced in one of pulses, acts on the other pulse immediately despite on time interval between the pulses. In this case we can say about the effect that is like to teleportation effect in quantum mechanics.

8095-58, Poster Session

Tunable subradiant lattice plasmons by out-of-plane dipolar interactions

W. Zhou, T. W. Odom, Northwestern Univ. (United States)

Plasmonic nanostructures can concentrate optical fields into nanoscale volumes, which is useful for plasmonic nanolasers, surface enhanced Raman spectroscopy, and white-light generation. However, the short lifetimes of the emissive plasmons correspond to a rapid depletion of the plasmon energy, preventing further enhancement of local optical fields. Dark (subradiant) plasmons have longer lifetimes, but their resonant wavelengths cannot be tuned over a broad wavelength range without changing the overall geometry of the nanostructures. Also, fabrication cannot be readily scaled because their complex shapes have subwavelength dimensions. Here we report a new type of subradiant plasmon with a narrow (~5 nm) resonant wavelength that can be easily tuned by changing either the height of large (>100 nm) gold nanoparticles arranged in a two-dimensional array or the incident excitation angle. At resonance, strong coupling between out-of-plane nanoparticle dipolar moments suppresses radiative decay, trapping light in the plane of the array and strongly localizing the optical field onto each nanoparticle. This new mechanism can lead to new applications for subradiant plasmons because height-controlled nanoparticle arrays can be manufactured over wafer-scale areas on a variety of substrates.

8095-41, Session 11

High-performance Ge quantum well modulators for optical interconnects


Electrical interconnects are rapidly nearing fundamental limitations related to their density-scaling a wire down in size does not allow it to carry more information-and the environmentally-significant amount of power they consume. Optical interconnects provide a promising solution, but require CMOS-compatible, low-energy optical components in order to be a feasible alternative. Ge/SiGe quantum wells (QWs) exhibit the quantum-confined Stark effect, a strong electroabsorption mechanism that enables compact optical modulators for use in future optical interconnect systems.

To design and optimize high-performance modulators, we have experimentally investigated the ultrafast carrier dynamics and transport properties of Ge/SiGe QWs. We have also developed a simple model for the electroabsorption spectrum of this material, which allows us to account for both absorption from our QW design and the less-desirable background absorption that limits device performance.

We have demonstrated Ge/SiGe QW modulators in both a surface-normal, asymmetric Fabry-Perot geometry and a waveguide geometry. The asymmetric Fabry-Perot design allows for high contrast ratios with small changes in absolute absorption. We have recently achieved contrast ratios of 4.8 dB over a 1 V swing. Better understanding of the background absorption in the QWs and resonator cavity will enable future contrast ratios of more than 10 dB with a greatly reduced insertion loss. The waveguide modulators are enabled by selective-area epitaxial growth of the QWs and provide easy integration with other interconnect components. We have demonstrated a waveguide modulator with an active area of 5μm2, an extinction ratio of 3.2 dB and a speed of 3.5 Gb/s.
Engineering aperiodic order for optical devices with photonic-plasmonic nanostructures

L. Dal Negro, Boston Univ. (United States)

Deterministic Aperiodic Structures (DAS) are generated by the mathematical rules of L-systems and number theory, manifest unique light localization and transport properties associated with a great structural complexity, and can be fabricated on-chips using conventional nano-lithographic techniques. When combined with metal-dielectric nanostructures, they give rise to large energy gaps like periodic media (i.e. photonic-plasmonic crystals) and highly localized, enhanced field states like disordered random media, including the formation of Anderson-localized modes, forbidden in periodic scattering media. Contrary to random media, DAS possess controllable transport properties from ballistic to anomalous diffusion (slower diffusion than classical random walks) and strongly localized field states with large fluctuations of the photonic mode density - essential attributes to achieve spatio-temporal energy localization and enhanced light-matter coupling, i.e. radiative rates of fluorescent molecules, absorption cross-sections, non-linear optical processes on the nanoscale. In particular, DAS fabricated using metal-dielectric nanoparticles are suitable to engineer efficient nanophotonic structures for Surface Enhanced Raman (SERS) sensing, optical detectors, and enhanced light-emitting and nonlinear components.

In this talk, by combining dark-field scattering characterization, micro-photoluminescence and Raman measurements with accurate electrodynamics calculations based on semi-analytical multiple-scattering theories, I will discuss electromagnetic coupling1,2, resonant scattering3, colorimetric biosensing4, light emission5 and surface enhanced Raman sensing6,7 in two-dimensional metal-dielectric photonic-plasmonic arrays based on deterministic aperiodic sequences. In particular, I will survey the optical properties, and assess the device performances, of different aperiodic systems ranging from quasi-periodic crystals to pseudo-random nanoparticle arrays8 fabricated by Electron-Beam Lithography (EBL) on transparent quartz substrates. Finally, I will present novel aperiodic optical nano-antennas structures that can provide strong field localization at multiple frequencies over a broad spectral range9.

References:

8095-45, Session 12

Integrated metephotonics
A. D. Boardman, P. Egan, R. R. C. Mitchell-Thomas, Univ. of Salford (United Kingdom)

Building up a range of integrated metamaterial waveguide devices is not only attractive from a fundamental point of view, but it is going to be possible to create a number of beautiful down-stream applications. It is in this sense that the presentation is developed under the general integrated metaphotonics heading. In the first instance, the propagation of waveguide modes in double negative material and materials characterised by other combinations of relative dielectric permittivity and relative permeability, together with some degree of geometrical complexity will be considered. The general properties of linear metamaterial guides will be exposed, and the extent to which nonlinearity and magnetooptic influence can be used as control agents will be investigated. The degree of control obtained by manipulating planar waveguide interfaces is shown to be another fascinating outcome from the use of special metamaterials and this will be highlighted for certain frequency windows. Certain systems lead to the possibility of not only slowing light down, but to the concept of actually stopping light, heralding new types of all-optical computer chips. Tapered, and discontinuous guides will be investigated, with this in mind, leading to new ideas about switches and X-junctions and the famous trapped rainbows. All of these will be shown to emerge from the use of modern metamaterials, and that there are certain novel features that always emerge from them. In addition to this and soliton propagation, transformation optics will be invoked by reaching out for a dramatic use of the spacetime cloak, or the history editor.

8095-46, Session 12

Active plasmonic devices enhanced by waveguide dispersion engineering
C. Min, G. Veronis, Louisiana State Univ. (United States)

Plasmonic devices, based on surface plasmons propagating at metal-dielectric interfaces, have shown the potential to manipulate light at deep subwavelength scales. One of the main challenges in plasmonics is achieving active control of optical signals. In this paper, we introduce active plasmonic devices enhanced by waveguide dispersion engineering. We consider plasmonic waveguide systems consisting of a metal-dielectric-metal waveguide (MDM) side-coupled to arrays of MDM stub resonators. The MDM waveguide and stubs are filled with an active material whose absorption coefficient can be modified with an external control beam. Such plasmonic waveguide systems can be engineered to support slow-light modes. We find that, as the slowdown factor increases, the sensitivity of the effective index of the mode to variations of the refractive index of the active material increases. Such slow-light enhancements of the sensitivity to refractive index variations lead to enhanced performance of active plasmonic devices such as switches. To demonstrate this, we consider absorption switches based on Fabry-Perot cavity structures, consisting of slow-light plasmonic waveguide systems sandwiched between two conventional MDM waveguides. We find that increased slowdown factor leads to increased induced change of the propagation length of the slow-light mode for a given refractive index variation, and therefore to increased modulation depth. Compared to conventional MDM absorption switches, slow-light enhanced switches achieve significantly higher modulation depth with moderate insertion loss. We use a scattering matrix theory to account for the behavior of the devices which is in excellent agreement with numerical results obtained with the finite-difference frequency-domain method.

8095-47, Session 12

Slow light using negative metamaterials
S. Srivastar, W. Lu, Y. Huang, D. Casse, S. Savo, Northeastern Univ. (United States)

Controlling the speed of light is a fundamental challenge that can lead to new physical phenomena and applications. We show that a nonresonant planar waveguide consisting of conventional dielectric cladded with single-negative materials supports degenerate propagating modes for which the group velocity and total energy flow can be zero if the media are lossless. We have carried out the first experimental observation of slow light utilizing the mechanism of the degeneracy of forward and backward waves, in the GHz microwave regime in a planar waveguide consisting of a dielectric core cladded by single-negative metamaterial. The metamaterial cladding consisted of periodic arrays of metallic split-ring resonators (SSRs), exhibiting negative permeability. Group delay dispersions obtained from pulsed measurements are in complete agreement with that obtained from a theory of slow light. Absorptive losses severely limit the velocity reduction, and will even destroy the zero-group velocity condition for real frequency/complex wave vector modes. We show that by incorporating gain G into the core dielectric, there exists a critical gain value Gc at which we can recover the condition of zero group velocity, so that light pulses can be stopped and stored. This structure is simpler to achieve than double-negative metamaterials, has small footprint, and can be incorporated into ultracompact on-chip optoelectronics. These nanoscale metamaterial waveguides offer the prospect of on-chip slow light devices where light speeds are reduced by orders of magnitude, enabling ultra-compact optical delay lines and buffers.

8095-48, Session 13

Electrically active 3D photonic and plasmonic crystals
P. V. Braun, Univ. of Illinois at Urbana-Champaign (United States)

Photonic and plasmonic crystals provide unprecedented control over light emission, absorption and propagation, which has led to the proposal of a large variety of optoelectronic devices. Three-dimensional devices with electronic functionality have however remained elusive, as fabrication of three-dimensional, electrically active nanostructured materials remains complex. Numerous techniques have been demonstrated to fabricate 3D photonic and plasmonic crystals, including colloidal crystallization, phase mask and multibeam interference lithography, direct laser writing, photolithography, and wafer bonding, but, most of these techniques result in amorphous or polycrystalline metamaterial which does not possess the required electronic properties for application in optoelectronics. There are a number of elegant techniques which make use of single crystal semiconductor substrates, however they tend to require elaborate, slow processing, are limited in what photonic crystal structures may be created, and have not demonstrated electrical functionality. In this work we demonstrate a method of forming 3D photonic and plasmonic crystals from single crystal III-V semiconductors by metal-organic vapor phase epitaxy (MOVPE). We employ a template-based fabrication method and grow semiconductor material to fill the structure using a form of selective area epitaxy.
The epitaxial growth process (originating at the substrate, in contrast to conformal growth) is much the same as the growth of planar III-V devices in that light emitting layers (e.g. quantum wells), cladding layers, electrically doped layers, etc may all be grown in a single process. Thus the layers of an optoelectronic device may be defined by the MOVPE growth parameters while the photonic crystal structure is simultaneously imparted to the material using the 3D template. To demonstrate the potential of this technique we have fabricated vertically emitting LED’s with embedded InGaAs QW’s. The fundamental behaviors of this growth technique will be discussed, including prevention of polycrystalline nucleation, doping and fabrication of light-emitting heterostructures.

8095-49, Session 13

‘Giant’ nanocrystal quantum dots: a new class of active emitters for photonics applications

J. Hollingsworth, Y. Ghosh, A. M. Dennis, J. Kundu, B. N. Pal, Y. Park, S. Brovelli, Los Alamos National Lab. (United States); A. V. Malko, The Univ. of Texas at Dallas (United States); V. I. Klimov, H. Hton, Los Alamos National Lab. (United States)

Nanocrystal quantum dots (NQDs) are nearly ideal candidates for light-emission applications due to high quantum efficiencies, and narrow-band and particle-size-tunable photoluminescence. However, they suffer from important deficiencies, including intermittency in fluorescence intensity, or “blinking”; at the single-NQD level and chemical-environment-dependent photo-instability at the ensemble level. We recently reported the first demonstration of an inorganic shell approach to address these outstanding issues; namely, the suppression of blinking and ensemble-level instabilities.[1,2] Here, I will review these results, as well as key findings establishing the new “giant” NQDs (g-NQDs) as a functionally new class of colloidal quantum dot: significant suppression of nonradiative Auger recombination,[3] highly emissive multieexcitons [4] and near-unity bivccton emission, and a shell-thickness-dependent transition from NQDs characterized by a continuous distribution of nonradiative Auger recombination,[3] highly emissive multieexcitons [4] and near-unity bivccton emission, and a shell-thickness-dependent transition from NQDs characterized by a continuous distribution of emission states (thin-shell systems) to NQDs characterized by a single emission state (thick-shell systems). Beyond a summary of these fundamental studies, I will focus on the fabrication of new g-NQD compositional systems and the ability to tune g-NQD emission wavelength by control of the core/shell electronic structure. Lastly, I will describe the integration of g-NQDs into light emitting devices, as (1) robust, “passive” phosphors and (2) active layers in electrically pumped light emitting diodes, where the thick-shell NQDs provide significant advantages compared to their thin-shell counterparts in terms of device efficiencies, self-reabsorption, and/or stabilities.


8095-50, Session 13

Tunable mesoporous Bragg reflectors based on block-copolymer self-assembly

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Mesoporous distributed Bragg reflectors (MBDRs) are an emerging class of photonic materials with unique properties due to their porosity on the sub-optical length scale.[1] MBDs have great potential as sensing materials, as adsorption and desorption of gas phase molecules lead to reversible changes in the refractive index of the stack. MBDR based “photonic noses” have been proposed that mimic the olfactory system.[2] In optoelectronic applications, MBDRs can be used to manipulate the flow of light. Examples include light harvesting elements in dye sensitised solar cells and resonance cavities for hybrid lasers.

We present a new route for the fabrication of MBDRs which relies on the self-assembling properties of the block copolymer PI-b-PEO in combination with sol-gel chemistry. This allows unprecedented control to finely tune porosity and pore size in the outcome inorganic material, which is exploited to manipulate the refractive index of the building blocks. Stacking-up multiple layers of alternating refractive index results in a fast and reliable assembly of a continuous network with well-defined interfaces. The outcome are MBDRs of high quality optical properties even when made of the same type of material. The effects of these unique characteristics on the photonic functioning will be discussed in detail.

References


8095-51, Session 13

Fabrication of three-dimensional gyroid photonic microstructures

M. Gu, M. Turner, Swinburne Univ. of Technology (Australia)

Three-dimensional (3D) photonic microstructures are an important platform for 3D photonic bandgap materials. If their feature size becomes smaller than the operating wavelength, they physically behave as metamaterials providing new properties that do not exit in nature. More importantly, the 3D photonic microstructures are necessary platforms to produce chiral geometries. It has been shown that chiral microstructures have important nanophotonic functionalities including their ability to enhance and control the chirality of light, which leads to applications such as negative index metamaterials, compact broadband circular polarisation filters, ultrasensitive biosensing and nanoscale plasmonic motors. However, the lack of symmetry and uniaxial chirality within typical chiral microstructures is not suitable for certain applications. In this talk, we will present our recent progress on fabrication, characterisation and metallisation of 3D microstructures based on the chiral, cubic networks found within the gyroid minimal surface inspired by a recent finding in butterfly wings.
Conference 8096: Plasmonics: Metallic Nanostructures and Their Optical Properties IX
Sunday-Thursday 21-25 August 2011 • Part of Proceedings of SPIE Vol. 8096
Plasmonics: Metallic Nanostructures and Their Optical Properties IX

8096-01, Session 1

Recent progress in plasmonics (Keynote Presentation)
X. Zhang, Univ. of California, Berkeley (United States)

Plasmonics takes advantage of the properties of surface plasmon polaritons in which photons are coupled to the quasi-free electron oscillations on metal surface. Recent advances of plasmonic applications include nano photonics, sub-diffraction-limit imaging, and plasmonic nano-laser etc.

Motivated by transformation optics - an approach to controlling the propagation of light by spatially varying material optical properties - various plasmonic lens designs will be demonstrated that can focus or bend surface plasmon polaritons with significantly reduced scattering loss in comparison to previously reported plasmonic elements. A technique that uses Brownian motion of single molecules for two-dimensional imaging of the enhancement profile of single hot spots on the surfaces of metallic thin films and nanoparticle clusters will also be introduced. Additionally I will show a nanoscale plasmonic motor directly driven by light and its rotation velocity and direction are controlled by tuning the wavelength of the incident wave to excite different plasmonic modes. I will also present the experimental demonstration of nanometer-scale plasmonic lasers, generating optical modes a hundred times smaller than the diffraction limit. Direct measurements of the emission lifetime reveal a broad-band enhancement of exciton spontaneous emission rate and the signature of apparently threshold-less lasing.

The abilities of advanced plasmonic techniques to transform surface plasmon polaritons, to image nanometer-sized hotspots, to generate significant optical torques at the nanoscale, and to create coherent light source at truly nano scale will benefit applications such as energy conversion, in vivo biological detection and manipulation, mechanical transducers and actuators, and active photonic circuits.

8096-02, Session 1

Plasmonics with gain (Keynote Presentation)
A. V. Zayats, King’s College London (United Kingdom)

We will consider strategies for amplification of surface plasmon polariton waves propagating on the interface of metal and gain dielectric. Various amplifying configurations including hybrid plasmonic crystals will be considered. The applications of gain-effects in all-optical nanophotonics will be dis-cussed.

Resonant interaction of surface plasmon polaritons (SPP) with molecules, ions and semiconductor quantum dots near a metal interface attracts considerable attention since its understanding may lead to new nanophotonic technologies for sensing, optical data processing and quantum information. One of the most significant applications may be the amplification of the SPP waves or lasing into SPP modes. In this talk we will discuss various experimental realisations of SPP amplification in dielectric-loaded plasmonic waveguides as well as plasmonic crystals hybridised with gain medium. We will report on the observation of amplified spontaneous emission of surface plasmon polaritons excited at the inter-face with a resonant amplifying medium. Generally, amplified spontaneous emission occurs during light propagation in the gain medium with inverse population and is sometimes called, travelling wave lasing or superfluorescence. Significant spectral narrowing of the SPP emission line is observed with the very low ASE threshold. We will also report on SPP Bloch mode amplification in plasmonic crystals were this effect leads to the increase in the enhanced transmission.

The amplification of SPPs and associated Ohmic loss compensation during their propagation on a metal-dielectric interface have profound implications in design of plasmonic interconnects and all-optical signal processing devices based on plasmonic components.

8096-03, Session 2

Superconducting plasmonics
A. Tsiatmas, R. Buckingham, V. A. Fedotov, N. I. Zheludev, Univ. of Southampton (United Kingdom)

[Invited] Superconductors due to their vanishing ohmic resistance and dominant kinetic inductance have the ability to support propagating plasmonic excitations from low frequencies up to the THz regime. These modes can be confined on the scale of few tens of nanometres and propagate up to hundreds of times their wavelength. This reveals a significant potential for applications of superconducting plasmonic structures that originates from the easy incorporation of active control in these devices.

8096-04, Session 2

Near-field imaging of terahertz plasmon waves with a subwavelength aperture probe
O. Mitrofanov, R. Mueckstein, Univ. College London (United Kingdom)

Visualization of Terahertz (THz) plasmons with THz local near-field probes allows studying ultra-fast plasmonic phenomena in the time domain, with access to the electric field of plasmonic waves rather than the intensity. We demonstrate that the integrated sub-wavelength aperture near-field probe can be used to map THz surface plasmon waves in space and time with high resolution. The precise knowledge of the probe structure, which incorporates a photoconductive detector in the near-field zone of the sub-wavelength aperture, allows to identify the coupling mechanism and to explain the nature of the observed phenomena. Using this probe, we mapped (in space and time) THz plasmon waves formed on a metallic surface by tightly focused 0.2THz pulses (Ref. 1) and the formation of standing plasmon waves in THz antennas. Using several experimental near-field observations we show that this probe detects the spatial derivative of the electric field of surface plasmons rather than the field itself. The coupling mechanism results in an apparent spatial phase shift of the detected surface plasmon wave.

The understanding of the coupling mechanism provides a framework for analysis and interpretation of THz near-field images, where surface plasmon effects may be present. We will discuss how this microscopy method can be applied to track surface plasmon propagation and formation of plasmonic resonances. The method can provide a vital insight into the role of THz surface plasmons in basic physical phenomena and in THz devices.

Reference 1: Optics Express, 19, 3212 (2011)

8096-05, Session 2

From vacuum Rabi splitting towards stimulated emission with surface plasmon polaritons.
R. J. Moerland, A. Väkeväinen, A. Eskelinen, G. Sharma, P. Törnä, Aalto Univ. School of Science and Technology (Finland)

Coherent phenomena in Surface Plasmon Polariton (SPP)/emitter systems, where strong coupling dominates, are an intensely studied
subject for lasing and coherent energy transfer applications. Also a coherent phenomenon is vacuum Rabi splitting; we have reported on strong coupling between SPP and Rhodamine 6G (R6G) molecules, showing double vacuum Rabi splitting energies up to 230 and 110 meV [1]. The system in Ref. 1 consisted of a 50 nm layer of silver on top of a SiO2 substrate. A layer of R6G molecules, embedded in PMMA, is deposited on top by spincoating. The same system is also interesting for studying enhancements in spontaneous emission, and for obtaining stimulated emission. The R6G molecules in the system are pumped by a 532 nm laser, while the emission spectrum of the hybrid SPP/emitter system is recorded. As the laser pump intensity is increased, the recorded spectrum reflects the change from spontaneous emission towards stimulated emission. We will show our latest results in this area of research.


8096-06, Session 2

Transformation plasmonics and gradient index plasmonics

Y. Liu, T. Zentgraf, M. H. Mikkelsen, Univ. of California, Berkeley (United States); J. G. Valentine, Vanderbilt Univ. (United States); X. Zhang, Univ. of California, Berkeley (United States)

Taking advantage of transformation optics, we demonstrate that the confinement as well as propagation of surface plasmon polaritons (SPPs) can be managed in a prescribed manner by carefully controlling the dielectric material properties adjacent to a metal. Since the metal properties are completely unchanged and the transformed dielectric materials can be isotropic and non-magnetic, it provides a straightforward way for practical realizations. We show that our approach can assist to tightly bound SPPs over a broad wavelength range at uneven and curved surfaces, where SPPs would normally suffer from significant scattering losses. In addition, a 180-degree plasmonic bend with almost perfect transmission is designed.

We further propose to slowly change the thickness of an isotropic dielectric cladding layer and hence the local effective index of SPPs, instead of directly modifying the permittivity of the dielectric medium. As the local effective index of SPPs is varied gradually in a truly continuous manner we term our approach gradient index (GRI) plasmonics, in analogy to the well-known GRIN optics. Applying this method, we design and demonstrate two different devices: a plasmonic Luneburg lens to focus SPPs and a plasmonic Eaton lens to bend SPPs. In comparison with previously reported plasmonic elements, the scattering loss of SPPs in our designs can be significantly reduced since the optical properties are adiabatically changed. Fluorescence imaging and leakage radiation microscopy are applied to characterize the performance of the fabricated GRIN plasmonic devices based on gray scale lithography, showing a good agreement with the numerical simulation.

8096-07, Session 2

Controlling the motion of metallic nanoparticles with fast electron beams

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We analyze the total momentum transfer from fast electron beams, like those employed in scanning transmission electron microscopy (STEM), to plasmonic nanoparticles. The calculation of the momentum transfer is obtained by integrating the electromagnetic forces acting on the particles over time. Numerical results for single and dimer metallic nanoparticles are presented, for nanoparticle sizes ranging between 2 and 10 nm. Our calculations show that depending on the specific values of impact parameter and separation distance, the total momentum transfer yields a force that can be either attractive or repulsive. We corroborate these findings with experimental results that confirm the theoretical predictions. The time-average forces calculated for electron beams commonly employed in STEM are on the order of piconewtons, comparable in magnitude to optical forces and are thus capable of producing movement in the nanoparticles. This effect can be exploited in mechanical control of nanoparticle induced motion, as demonstrated experimentally.

8096-08, Session 3

Quantum plasmonics and plexcitonics

P. J. Nordlander, Rice Univ. (United States)

A recently developed fully quantum mechanical approach for the description of plasmonic and excitonic nanoparticles is discussed. [1] It is shown that quantum effects can have a pronounced influence on the electric field enhancements near the nanoparticle surfaces and on the optical properties strongly coupled nanoparticles. For closely spaced metallic nanoparticles, electron transfer and nonlocal screening can drastically reduce the electric field enhancements across the gap and result in a Charge Transfer Plasmon (CTP) where an oscillatory electric current is induced between the different particles. [2] The energy of the CTP is found to depend strongly on the electronic structure of the junction and the presence of molecules inside the gap. [3] For the coupled plasmonic-excitonic system where bonding and antibonding hybrid plexciton states are formed, [4] quantum effects can lead to a drastic enhancement of the excitation cross section of the excitons.


8096-09, Session 3

Theoretical modeling of relaxation dynamics in gold nanorod-dye assemblies for fluorescence enhancement

J. Vella, Jr., Air Force Research Lab. (United States) and General Dynamics Information Technology (United States); A. Urbas, Air Force Research Lab. (United States)

Using metal nanostructures to concentrate optical-frequency electric fields has garnered significant interest in the literature. For example, by combining an organic dye with a nanorod whose plasmon resonance frequency is similar to the absorption maximum of the dye, a significant enhancement in the fluorescence quantum yield can be observed. The prevalent theory for describing such an enhancement is kinetic and ascribed to an increase in the intrinsic rate of fluorescence, while the rate of non-radiative decay remains constant. Analysis of the literature will reveal that systems exhibiting fluorescence enhancement also show an alternation of the Stokes shift. The traditional kinetic description of plasmon-enhanced fluorescence cannot explain the origin of this shift. Using well-known theories developed by Onsager and Debye, it will be shown that it is possible to model plasmon-enhanced fluorescence not as an increase in the intrinsic rate of fluorescence, but by a perturbation of the equilibrium, photoexcited dipole moment of an emitter situated between two gold nanorods. This theory not only offers an explanation.
of the altered Stokes shift in plasmon-enhanced fluorescence systems, but also offers the possibility of the direct and absolute calculation of the electric field that is concentrated between two gold nanorods.

8096-10, Session 3
Quantum plasmonics
V. Zwiller, R. Heeres, S. Dorenbos, Technische Univ. Delft (Netherlands)

Our work centers on the demonstration of quantum plasmonics, where single plasmons are created, propagated and detected. A crucial part is played by Superconducting Single-Photon Detectors, which have some very useful properties such as short dead-time, low dark counts, wide operating wavelength range (UV - IR) and straightforward operation. The sensitivity in the >1μm range is especially interesting to ensure low losses for plasmons and for telecom applications. We have recently demonstrated that these detectors are also suitable for integrated quantum optics experiments by showing on-chip detection of single plasmons. In this experiment, a single quantum dot was used as a single photon source and the stream of single photons was coupled through free-space to a plasmonic waveguide made of a narrow gold stripe making its way to the superconducting detector. This on-chip detection of single plasmons enables the development of complex optics circuits at a small length scales. In the future, a single emitter could also be integrated in the near-field, resulting in more efficient excitation of plasmons and a potential enhanced emission rate due to the Purcell effect.

We are currently building more advanced systems where plasmonic beam splitters and pairs of detectors are combined to form an interferometer. An experiment that is now within reach is the observation of Hong-Ou-Mandel interference with plasmons.

8096-11, Session 3
Room temperature semiconductor plasmon laser
R. Ma, R. F. Oulton, V. J. Sorger, G. Bartal, Ctr. for Scalable and Integrated Nanomanufacturing (SINAM) (United States); X. Zhang, Ctr. for Scalable and Integrated Nanomanufacturing (SINAM) (United States) and Lawrence Berkeley National Lab. (United States)

Plasmon lasers are a new class of coherent optical amplifiers that generate and sustain light well below its diffraction limit. Their intense, coherent and confined optical fields can enhance significantly light-matter interactions and bring fundamentally new capabilities to biosensing, data storage, photolithography and optical communications. However, metallic plasmon laser cavities generally exhibit both high metal and radiation losses, limiting the operation of plasmon lasers to cryogenic temperatures, where sufficient gain can be attained. Here, we present room temperature semiconductor sub-diffraction limited laser by adopting total internal reflection of surface plasmons to mitigate the radiation loss, while utilizing hybrid semiconductor-insulator-metal nano-squares for strong confinement with low metal loss. High cavity quality factors, approaching 100, along with strong lambda/20 mode confinement lead to enhancements of spontaneous emission rate by up to 18 times. By controlling the structural geometry we reduce the number of cavity modes to achieve single mode lasing.

8096-12, Session 4
Using chiral metamaterials for the ultrasensitive characterisation of biomacromolecular structure
M. Kadodwala, Univ. of Glasgow (United Kingdom)

Spectroscopic techniques based on circular dichroism, the differential interaction of circularly polarised electromagnetic (EM) radiation with matter, are powerful tools for studying bio-materials, liquid crystals, polymers, and magnetic materials. The inherent weakness of the underlying dichroic phenomena require relatively large amounts of material for spectroscopic measurements, typically for biomaterials ≥ microgram are necessary. We have created a new type of light, which is generated in the vicinity of plasmonic chiral metamaterials, that has a greater level of chirality than circularly polarised light, this new property is referred to as superchirality. Our discovery transforms circular dichroic measurements, because the superchiral light magnifies the asymmetries displayed in dichroic measurements by at least six orders of magnitudes. This new form of spectroscopy, could presage new powerful biosensing array technologies, which would allow for the first time both the ultrasensitive detection and structural characterisation of a biomaterial.

8096-13, Session 4
Importance of magnetic polarization in the absorption of metallic nanoparticles
A. Asenjo-Garcia, A. Manjavacas, V. Miroshnychenko, J. García de Abajo, Consejo Superior de Investigaciones Científicas (Spain)

We study the dipolar magnetic polarizability of common metallic nanoparticles. Remarkably, particles of size and morphology commonly encountered in colloidal synthesis can exhibit a strong imaginary part in the magnetic polarizability, which is comparable in magnitude to or even larger than the electric polarizability. This means that the absorption of a particle can be dominated by its magnetic response. However, this contribution is routinely overlooked. Our results demonstrate that this is not correct in many situations. We study the magnetic polarization of common metallic nanoparticles of different materials, sizes, shapes, and show that the magnetic contribution will dominate the absorption in many cases. Various particle shapes, such as spheres, rods, ellipsoids, or disks, are numerically analyzed and compared to analytical solutions when available. In the case of spheres, analytical solutions are provided based upon the Mie formalism [1]. For non-spherical particles, we produce numerical calculations using the boundary element method [2]. It is found that this behavior is highly dependent on the particle geometry. For instance, the contribution of magnetic polarization to light absorption is largely enhanced in disk-shaped particles of large aspect ratio. The opposite behavior is found for metallic rods.

Our work provides a clear demonstration of the unexpected large effect of magnetic polarization in the absorption properties of commonly encountered metal nanoparticles extensively used in plasmonics.


8096-14, Session 4
Dipole limit and resonance-domain effects in second-harmonic generation from arrays of metal nanoparticles
M. Kaaranen, G. Genty, R. Czaplicki, H. Pietarin, H. Husu, M. Zdanowicz, K. O. Koskinen, R. Silikanen, Tampere Univ. of
The optical properties of metal nanoparticles are dominated by their plasmon resonances, which depend on the particle size and shape. The resonances give rise to strong local fields near the particles, which can enhance nonlinear interactions. However, localized surface defects can also support their own plasmonic modes and thereby lead to highly local nonlinear responses.

We have earlier shown that localized nonlinear sources that are retarded with respect to each other can lead to effective quadrupole effects in second-harmonic generation (SHG) from arrays of metal nanoparticles. Such effects significantly complicate the analysis of the nonlinear response. In this paper, we show that such effects are suppressed essentially completely by the improved sample quality made possible by state-of-the-art lithographic techniques. This opens the possibility of designing nonlinear metamaterials with truly engineered properties.

To demonstrate tunable nonlinear responses, we order anisotropic, L-shaped nanoparticles in a lattice with sub-wavelength period for their resonant wavelengths. By varying the mutual orientation of the particles, we modify the symmetry and dichroic properties of the structures. More importantly, the SHG responses of two samples that have similar orientational particle distribution are found to vary by more than an order of magnitude depending on the detailed particle ordering. The results are explained by long-range coupling between the particles, which becomes possible because the changes in particle ordering double the structural period and thus open diffraction orders. Such resonance-domain effects provide new approaches for optimizing the optical responses of metamaterials.

Directional light scattering of Au nanoshells and nanocups at a dielectric interface

N. S. King, Y. Li, Y. Zhang, P. J. Nordlander, N. J. Halas, Rice Univ. (United States)

The fields of plasmonic solar cell enhancement and remote sensing require a strong understanding of the effects of an inhomogeneous medium on the plasmonic response and resulting scattering profile. In this presentation, we show how the refractive index of a supporting substrate modifies the far-field radiation pattern of symmetric and asymmetric nanoparticles. Asymmetric nanoparticles, such as nanocups, are of particular interest because the reduction in symmetry produces two orthogonal dipole modes that align with the structure of the nanoparticle and are independent of the direction of the incident illumination. Controlling the orientation of these particles requires a supporting substrate or encapsulating medium, but offers the ability to selectively excite a specific plasmonic mode, determining the scattering properties of the system. Angular radiometric measurements confirm the predicted cos²θ dipole scattering of nanoshells and the unique scattering properties of oriented nanocups on simple glass substrates. High refractive index substrates, such as silicon, lift the degeneracy of the dipole plasmon modes and allow for hybridization with higher order modes. The resulting scattering profile for both nanoshells and nanocups differ greatly in both intensity and localization of the scattered light.

Multi-band scattering and enhancement in a reduced symmetry cross nanoantenna

R. Adato, A. A. Yanik, H. Altug, Boston Univ. (United States)

Metal nanoparticles function as optical frequency antennas, providing a means with which to impedance match nanoscale emitters, absorbers or scattering objects to far-field radiation. This antenna functionality, however, results from the particles’ structural resonances, and is typically narrowband. Single element antenna geometries that extend the bandwidth, or offer tunable resonances at multiple frequencies would open new opportunities in surface enhanced spectroscopies, ultra fast / small detector elements and nonlinear process enhancement. To this end we propose a cross shaped nanoparticle antenna which provides multiple resonances that are independently tunable over a wide range of frequencies. By adjusting the polarization of the incident light, the dimensions and symmetry of the structure we experimentally demonstrate the ability to tune several addressable resonant modes over a spectral range of greater than 4-5 μm in the mid-infrared. Numerical simulations indicate strong near-field enhancements similar to those of the dipolar resonances of rod shaped antennas. Finally, we show that the behavior of the nanoparticle can be predicted via classical antenna / circuit theory. The particle design can therefore be systematically engineered in an intuitive manner and easily fabricated in a repeatable manner that is suitable to high-throughput methods. This is essential for practical implementation and in contrast to geometries that rely on near-field coupling effects and therefore the presence of nanoscale, difficult to control gaps.

Nonlinear photothermal and photoacoustic plasmons beyond the spectral limits

V. P. Zharov, Univ. of Arkansas for Medical Sciences (United States)

Advanced plasmonic nanostructures with enhanced absorption, fluorescence, and scattering properties enable progress in microscopy, spectroscopy, diagnostics, and cancer therapy. However, because of their relatively broad plasmonic bands of 100 to 200 nm, multicolor capacity of these structures is limited.

To resolve this fundamental problem of conventional spectral microscopy we introduce a platform which comprises three interrelated steps1-2: 1) the development of nanostructures with relatively narrow conventional plasmonic bands (e.g., multilayer nanotubes); 2) laser-induced nonlinear signal amplification accompanied by spectral narrowing phenomena due to synergy of nonlinear effects (e.g., optical, thermal, acoustic, or nanobubbles); and 3) spectral reading of narrow plasmon resonances without broadening effects. Using nonlinear photothermal and photoacoustic spectroscopy with advanced tunable pulse lasers, we demonstrated ultrasharp resonances up to a few nanometers wide in relatively broad plasmonic spectra of various nanostructures, including golden carbon nanotubes and multilayer gold nanorods.

The described approaches can use various detection schematics (e.g., thermal-lens, photoacoustic, radiometry, phase-contrast, and heterodyne methods) for study of laser-nanoparticle interactions with resolution beyond the spectral limits, measurements of tiny red and blue plasmon resonance shifts in plasmonic microspectroscopy, and multispectral imaging and multicolor cytometry.

References:
We present a plasmonic hydrogen sensor which consists of a single Pd dot and a plasmonic gold nanoantenna. The Pd dot is brought into the nanofocus of the gold nanoantenna, which is resonantly excited by light. Upon exposure to hydrogen, the Pd dot changes its dielectric properties. Hence, the resonance of the gold nanoantenna is shifted and can be easily detected.

We record several series of experiments, using different amounts of hydrogen as well as different shapes of nanoantennas and different separations between the Pd dot and the antenna. It turns out that the triangular nanoantenna with a distance of 10 to 20 nm yield the best results, giving a spectral shift of around 5 nm for a hydrogen concentration of 1% in nitrogen.

Our work will open a pathway for extremely sensitive detection of molecules and atoms down to the single particle level.

Engineering light scattering and field concentration in nano-plasmonic necklaces for multi-parametric sensing

A. J. Pasquale, B. M. Reinhard, L. Dal Negro, Boston Univ. (United States)

Particle clusters with different degrees of rotational symmetry consisting of circular loops of gold nanoparticles, dubbed “Nano-Plasmonic Necklaces,” are proposed as a novel, reproducible platform for elastic and inelastic (SERS) optical sensors with polarization insensitive behavior. The engineering of nano-plasmonic necklaces allows for full control of the plasmonic hot-spot locations and optimization of near-field strength by photonic cavity coupling with gap plasmons, making them a promising candidate for inelastic surface-enhanced molecular Raman sensing. The polarization insensitivity of plasmonic necklaces guarantees that the plasmonic hot-spots remain excited within the necklaces irrespective of the incident polarization of the excitation field, which is a significant advantage compared to hot-spots in the usual plasmonic dimer configurations. Moreover, the necklace configuration enables photonic-plasmonic coupling effects where the incident radiation gets resonantly trapped into circular resonator modes which strongly enhance the hot-spot intensity. Plasmonic necklaces of different rotational axes were fabricated using electron-beam lithography and electron-beam deposition of gold films. Engineering design rules are determined for hot-spot formation, polarization insensitivity, and intensity distribution in nano-plasmonic necklaces and the results are confirmed by experimental Surface Enhanced Raman Scattering (SERS) data obtained using a molecular monolayer of p-mercaptoaniline as the analyte.

Electrochemically controlled nonlinear generation of light with plasmonics

W. Cai, A. Vasudev, M. L. Brongersma, Stanford Univ. (United States)

Plasmonics enables a unique opportunity to develop ultra-compact optical devices at a subwavelength scale by utilizing two of its most important strengths: extreme concentration light intensity to far below the diffraction limit and an ability to support simultaneous electrical and optical functions. These features also make plasmonics an ideal candidate for electrically manipulating nonlinear optical interactions at the nanoscale, an area that has remained largely unexplored. Here we experimentally demonstrate electrochemically controlled harmonic generation of light from a plasmonic nanocavity filled with a nonlinear medium. The metals that define the nano-resonator also serve as electrodes that can facilitate high electric fields across the nonlinear material. We tune the frequency-doubling of a 1.56 µm fundamental wave by applying a control voltage to the electrodes, yielding a nonlinear modulation of ~7% per volt and ~140% at a bias of 20 volts.

Interacting with light at the nanoscale

L. K. Kuipers, FOM Institute for Atomic and Molecular Physics (United States)

As we perfect our ability to engineer the optical properties of nanostructures, we obtain a handle on light-matter interactions. We can enhance them and even induce new ones, such as the effective light-matter interaction mediated by the magnetic component of light rather than the electric component. Here, we present our latest results on local investigations of light-matter interactions. We use the fact that our near-field nanoprobes are actually metallo-dielectric nanostructure to gain access to light-matter interactions on a sub-wavelength scale. The symmetry of the probe allows, on the one hand, different vector components of the light to be distinguished and, on the other hand, diamagnetic light-matter interactions to be induced.

Close interactions in gap nanoantennas

J. Aizpurua, R. Esteban Llorente, P. Albea, Centro de Fisica de Materiales (Spain); N. Large, Centro de Fisica de Materiales (Spain) and Ctr. d’Elaboration de Matériaux et d’Etudes Structurales (France); A. Garcia Etxarri, Centro de Fisica de Materiales (Spain) and Stanford Univ. (United States); M. Schnell, P. Alonso-Gonzalez, CIC nanoGUNE Consolider (Spain); R. Hillenbrand, CIC nanoGUNE Consolider (Spain) and Ikerbasque, Basque Foundation for Science, Bilbao (Spain)

Many concepts from the electromagnetic response in radiowave technology can be transferred to the optical and infrared range of the spectrum. In particular, metallic gap antennas offer the possibility to tune the spectral response by simple modification of the material properties within the gap. Particularly interesting is a situation where the gap surfaces forming the gap are in close proximity. Under these conditions, aspects such as non-locality of the response or the dimension of the gap modify drastically the near-field properties of the antenna. Furthermore, the presence of free-carriers within the gap can modify the optical response of the antenna within a very short time, showing the potential to act as an ultrafast optical switcher. We study theoretically the spectral response of these antennas and identify the surface modes that interfere to produce distinct spectral features. These modes are experimentally identified with use of scanning-near-field optical microscopy both in amplitude and phase. The characterization and understanding of the amplitude and phase of the local fields in gap antennas is of utmost importance in sensing and for design of optical nanodevices.

Seeing magnetic light-matter interactions: quantifying and enhancing magnetic dipole emission

R. Zia, Brown Univ. (United States)

Although it is often assumed that light-matter interactions are dominated by electric dipole transitions, strong optical frequency magnetic dipoles do exist. In fact, we see magnetic dipole emission everyday from the Lanthanide ions that help to illuminate everything from fluorescent lighting to solid-state lasers. Nevertheless, most applications have...
overlooked the device implications of these magnetic dipole transitions throughout the visible and near-infrared regime. Moreover, the magnetic dipole contributions of many important transitions (such as the 1550nm line of Erbium) have not been fully characterized. In this talk, we will illustrate how the naturally occurring magnetic dipole transitions of Lanthanide ions provide a new degree of design freedom for photonic and plasmonic devices. Specifically, we will demonstrate how the different symmetries of electric and magnetic dipoles can be exploited to identify, enhance, and control light emission.

8096-24, Session 6

Coupling mechanisms for nano-U-dimers

N. Gneiding, E. Krutkova, Erlangen Graduate School in Advanced Optical Technologies (Germany); E. Tatartschuk, Erlangen Graduate School in Advanced Optical Technologies (Germany) and Clemson Univ. (United States); E. Shamonina, Imperial College London (United Kingdom) and Erlangen Graduate School in Advanced Optical Technologies (Germany)

Properties of split-ring metamaterials are governed by inter-element interactions. These interactions lead to slow eigenmodes of coupling, which, due to their short wavelengths, are ideal candidates for the design of near-field manipulating devices. In this paper we explore the electric and magnetic coupling mechanisms in nano-U dimers comprising two identical nano-U elements per unit cell arranged axially and twisted relative to each other by an arbitrary angle. We study theoretically coupling in a periodic chain of nano-dimers in the frequency range 100-300 THz. In our analytical model, the electric and magnetic coupling can be expressed through the self and mutual terms for magnetic and electric field energy, considering the continuity equation between the current and charge distributions within each U-element. In addition, we incorporate the effect of kinetic inductance due to the inertia of the electrons (noticeable as element dimensions become as small as 100 nm). The resulting dependence of the electric, magnetic and the total coupling constant on the twist angle within the dimer obtained analytically is shown to agree with numerical simulations (CST Microwave Studio). Our approach should enable an effective design of metamaterial structures with desired properties and would be a useful tool in developing THz range manipulating devices based on propagation of slow waves propagating by virtue of coupling.

8096-25, Session 6

Plasmonic enhancement of ultrafast all-optical magnetization reversal

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Ultrafast all optical magnetization switching in GdFeCo layers on the basis of Inverse Faraday Effect (IFE) was demonstrated recently and suggested as a possible path toward next generation magnetic data storage medium with much faster writing time. However, to date, the demonstrations of ultrafast all-optical magnetization switching require powerful femtosecond lasers and are not yet compatible with the size, cost, and power consumption requirements of data storage and data processing applications. In this contribution we show that utilization of IFE enhancement in plasmonic nanostructures may provide the way to achieve fast all-optical magnetization switching with smaller/ cheaper laser sources with longer pulse durations. Our modeling results predict that significant enhancement of IFE around all major types of plasmonic nanostructures for a circularly polarized incident light. Unlike the IFE in uniform bulk materials, nonzero value of IFE is predicted in plasmonic nanostructures even with a linearly polarized excitation, which is the highest for the intrinsically chiral (non-rotationally symmetric) plasmonic nanostructures. The DC magnetic fields around plasmonic nanostructures in most cases are highly nonuniform even on the nanoscale. However, we will show the plasmonic geometries at which the uniform on the nanoscale ExE product is predicted to exceed ~10^4. IFE enhancement. Experimentally, all-optical remagnetization at 20 times lower laser fluence and roughly 100 times lower value of laser fluence/pulse duration ratio was achieved in plasmon-enhanced samples to verify the model predictions. The path to achieve higher levels of enhancement experimentally will be discussed.

8096-26, Session 7

Strongly driven electron emission from nanoparticles in few-cycle laser fields (Keynote Presentation)

S. Zherebtsov, F. Süßmann, Max-Planck-Institut für Quantenoptik (Germany); J. Plenge, Freie Univ. Berlin (Germany); J. Passig, Univ. Rostock (Germany); C. Graf, V. Mondes, Freie Univ. Berlin (Germany); M. I. Stockman, Georgia State Univ. (United States); E. Rühl, Freie Univ. Berlin (Germany); T. Fennel, Univ. Rostock (Germany); M. F. Kling, Max-Planck-Institut für Quantenoptik (Germany)

The acceleration of electrons in local near-fields of nanoparticles driven by few-cycle laser pulses is studied and provides insight into the electron dynamics and surface charging of the particle. Liberated electrons are accelerated / decelerated in the local field at the surface and affected in their attosecond dynamics by the build-up of a surface trapping potential and electron-electron interactions. By using isolated nanoparticles we can explore the regime near, at and beyond the material damage threshold. The extremely short pulse duration of only a few cycles in our studies ensures that the electron dynamics responsible for the observed phenomena occurs before any nuclear dynamics. At high intensities, a higher effective dielectric constant is predicted for dielectric nanoparticles. Experiments to observe such non-linearities are currently underway. They may allow insight into non-linear effects in bulk materials, which cannot be easily studied at these intensities. The approach holds promise that the regime of non-linear plasmonics may be reached and examined for the first time. Experimental results and calculations on the strongly driven electron emission from isolated nanoparticles in few-cycle laser fields will be presented.

8096-27, Session 7

Plasmonic field enhancement for generating ultrafast extreme-ultraviolet light pulses

I. Park, S. Kim, J. Choi, S. Kim, KAIST (Korea, Republic of)

Ultrafast extreme-ultraviolet (EUV) light pulses are a key tool for time-resolved spectroscopy to investigate atomic motion in molecules and electronic motion inside and between atoms. High-harmonic generation by focusing near-infrared (NIR) pulses on noble gases is a well-known method of generating such ultrashort EUV pulses. In this report, we show a 3-dimensional metallic waveguide that enables plasmonic generation of ultrashort EUV pulses through field enhancement by means of surface-plasmon polaritons. Compared with bow-ties previously used for field enhancement by stationary resonance of localized surface plasmons, the net volume of more than 20 dB intensity enhancement turns out to be three orders of magnitude larger. The intensity of incident NIR pulses is enhanced by a factor of ~350, being strong enough to produce EUV harmonics up to the 43rd order in interaction with Xe gas directly from a modest input of ~1011 Wcm-2. This plasmonic method maintains pulse repetition rate as high as 75 MHz in our experiment without use of extra cavities. No phase-matching is needed since EUV pulses are generated within a sub-wavelength spot near an exit aperture of 100 nm diameter whereby driving NIR pulses are mostly blocked. Furthermore, ultrafast DUV pulses with a center wavelength of 286 nm can also be produced by means of surface third-harmonic generation with deposition of a SiO2.
layer at the exit aperture. The plasmonic waveguide is fabricated on a cantilever nanostructure, with immunity to thermal damage and optical breakdown, to be suited for near-field spectroscopy with atomic-scale lateral selectivity.

8096-28, Session 7

Adiabatic and nonadiabatic metallization of dielectric nanofilms by strong optical fields

M. I. Stockman, M. Durach, A. Rusina, Georgia State Univ. (United States); M. F. Kling, Max-Planck-Institut für Quantenoptik (Germany)

We consider a 1-10 nm-thin nanofilm of an insulator subjected to a strong oscillating electric field normal to it. The frequency of this field may be in the range from microwave to optical, depending on the film thickness (in the near-infrared visible range for a 1-2 nm thickness). The strength of this field is considered to be in the range ~1-10 V/nm. When this field is slow, adiabatic, it induces a reversible phase transition in the film to a state reminding metal. The electron population can be transferred from one surface of this nanofilm to another. For fast, nonadiabatic fields, using quantum-mechanical treatment we demonstrate that a femtosecond pulse causes nonlinear polarization and ultrafast formation of plasmonic band in the high-frequency response of a nanostucture. This ultrashort pulse creates a non-equilibrium excitation of the nanostructure, which can be controlled using adiabatic phase accumulation effect. The demonstrated possibility of ultrafast switching between insulator and plasmonic metal phases can be employed for creation of active plasmonic elements for ultrafast nanocircuits.

8096-29, Session 7

Attosecond control of electrons emitted from a nanometric metal tip

P. Hommelhoff, Max-Planck-Institut für Quantenoptik (Germany)

It is well known that plasmonic effects can lead to greatly enhanced field strengths near surfaces. In this contribution we discuss the interaction of few-cycle femtosecond laser pulses with a sharp tungsten tip. We measure the emission current and record electron energy spectra. We observe above-threshold photoemission (ATP), i.e., electrons promoted in energy to states higher than needed to leave the metal. When we increase the laser intensity, the electronic spectral peaks start to shift, indicating the onset of strong-field effects [1]. Further, we show measurements with carrier-envelope-phase (CEP) stable pulses. We observe strong CEP effects (spectral interference). We show that electrons are detected originating from either one or two sub-cycle emission points in time. We observe that plateau electrons re-collide with the tip elastically and coherently, well known from high harmonic generation and above-threshold ionization in the gas phase. Because of field-enhancement, a simple laser oscillator suffices to reach the required peak field strengths. With different tip materials, we believe that this work will enable probing of plasmonic near-fields on the (sub-)nanometer-attosecond scale.


8096-30, Session 8

Plasmonic nanoantennas: new properties and functions (Keynote Presentation)

N. J. Halas, Rice Univ. (United States)

Nanostructures designed to harvest light can have many functions: energy and/or charge transfer and storage, light scattering or refraction, for example. We will describe two families of nanoantennas with unique properties: nanoscale hemispheres, and nanoantenna-diodes. Nanoscale hemispheres possess both electric and magnetic plasmon modes, each with their own unique light-refractive properties. Nanoscale hemispheres can also give rise to strong nonlinear optical effects, dependent upon their orientation with respect to incident excitation. These properties will be discussed. The integration of nanoantennas into electronics, where an optical structure can simultaneously provide an electrical response, is a new functionality better known in electrochemical than in electronic device contexts. We will describe how an optical antenna can also function as a photodetector, with a device response that is a hybrid combination of these two distinct types of devices.

8096-31, Session 8

Resonant properties of transmitting and receiving plasmonic resonator antennas

E. S. Barnard, Geballe Lab. for Advanced Materials (GLAM) (United States); M. L. Brongersma, Stanford Univ. (United States)

A combined theoretical and experimental study of wavelength-scale plasmonic resonator antennas is presented. Using full-field electromagnetic simulations and analytical optical antenna models, we are able to derive simple and intuitive design rules to achieve antennas with a desired set of optical properties (field enhancement, scattering cross section, absorption cross section, and resonant frequency) based on their geometric properties. As part of these design rules we are able to quantify reflection phase and understand this quantity in terms of the end-face near-field. With these design rules, we have constructed resonance maps that allow a designer to choose an antenna structure that provides desired resonant properties for a specific application. We then apply these design rules to create antennas that resonantly enhance absorption on thin silicon detectors as well as enhance emission of cathodoluminescence (CL). Through spatial and spectral mapping of both photocurrent and CL we clearly show the fundamental and higher-order resonant modes of these antennas. With CL we are also able to map the spatial distribution of these resonant modes with 10 nm resolution. In addition to these specific demonstrated applications, the results of this study enable optical engineers to more easily design a myriad of plasmonic devices that employ optical antenna structures, including nanoscale photodetectors, light sources, sensors, and modulators. Additionally the understanding of phase may be critical to designing resonant elements for metamaterials.

8096-32, Session 8

High resolution structural and optical characterization of top-down and bottom-up engineered plasmonic nanostructures

D. T. Schoen, M. L. Brongersma, Stanford Univ. (United States)

The use of electron energy loss spectroscopy (EELS) in the scanning transmission electron microscope (STEM) has been recently demonstrated to be a powerful tool for the high resolution mapping of plasmonic mode density in small metallic structures. To date, the majority of these studies have focused on small particles or the inverse structure, holes in a thin metallic film, either singly or in small clusters. One area largely unexplored so far by these techniques is the influence of material processing and quality on more complicated engineered nanostructures like would be used in integrated nanoplasmonic circuitry. Results of STEM EELs plasmon mode mapping of a variety of engineered metallic nanostructures will be presented. A comparison will be made between structures fabricated with top-down techniques, including electron beam lithography and focused ion beam milling, with structures fabricated by bottom up techniques, including chemically synthesized silver nanowires. Results of structural characterization by atomic force microscopy and high resolution TEM will also be presented and correlated with the optical property measurements.
8096-33, Session 8

High resolution fluorescence microscopy using plasmonic nanoantennas

K. Kim, Y. Oh, W. Lee, D. Kim, Yonsei Univ. (Korea, Republic of)

High resolution imaging below the diffraction limit has been widely investigated since precise molecular tracking and nanoscaled scanning are needed to understand various phenomena in sub-cellular environments. STED microscopy, field optical superlens imaging, and photo-activated light microscopy have been notably come into the spotlight as new approaches for sub-diffraction imaging. In this paper, we introduce a concept for high resolution imaging based on the excitation of surface plasmons. It is commonly known that electromagnetic fields are localized to small spots, which is called hot spots, by plasmonic nanoantenna structures. Hot spots that are smaller than the diffraction limit can in principle excite molecular fluorescence. If a hot spot is formed in an extremely small size on a molecular scale by an optimum design of plasmonic nanoantenna, fluorescence excitation can be post-processed to produce highly localized images. The concept was experimentally confirmed by imaging nanosized fluorescent beads, tracking dynamics of rhodamine tagged microtubule, and visualizing endocytotic internalization of GFP-tagged adenoviruses in live cells. Various plasmonic nanoantennas were fabricated by electron beam lithography and chemical annealing method. The imaging results confirm the enhancement of resolution after appropriate post processing methods.

8096-34, Session 9

Metamaterials from plasmonic nanoantenna arrays

M. Orenstein, Technion-Israel Institute of Technology (Israel)

Nano antennas are an exciting new addition to the field of photonics. The nanoantenna element exhibits two desirable characteristics - first it collects light from much larger effective area than its actual size and if the second - it can concentrate the collected energy in an effective light capacitor (stopped light) with dimensions in the nano regime - much smaller than the actual antenna size. Using these unique features we constructed arrays of such nanoantennas to generate metamaterials - the latter was employed for the enhancement of light-matter interactions. In the process of construction of these metamaterials we would discuss parameters such as the inter-antenna spacing to avoid cells interactions (especially because such nanoantenna may have effective cross-section dimension of 1 wavelength - which contradicts the subwavelength requirements of metamaterials), and the separate optimization of the antenna efficiency and light field enhancement. We’ll discuss robust ways to fabricate the antenna with predetermined resonance(s) and discuss in details nanoantenna configurations yielding either spectral broad-band or multi-harmonic responses.

In the second part of the talk, several applications of nanoantenna based metamaterials - that we experimentally realized, will be discussed, including high efficiency organic solar cells, enhanced emission rate communications wavelength LEDs - breaking the bottle neck for faster data modulation of such devices, and finally manipulating nonlinearly the vacuum field.

8096-35, Session 9

Diode-coupled Ag nanoantennas for nanorectenna energy conversion


Arrays of “nanorectennas” consist of diode-coupled nanoantennas with plasmonic resonances in the visible/near infrared (vis/nir) regime, and are expected to convert vis/ninfrared radiation power into useful direct current [1,2]. We study plasmonic resonances in large format (~1 mm^2 area) arrays, consisting of electron beam-patterned horizontal (e.g., parallel to the substrate) Ag lines patterned on, and Ag nanoparticles dispensed atop, ultrathin (<20 nm) tunneling barriers (NiO, Al2O3, and other oxides) [3]. These tunneling barriers, located on a metallic ground plane, rectify the alternating current generated in the nanoantenna at resonance. We measure the plasmonic resonances in these Ag nanoantennas, and find good agreement with modeling, which also predicts that the electric field driving the electrons into the ground plane (and therefore the rectification efficiency) is considerably enhanced at resonance. Various metal-insulator-metal tunneling diodes, incorporating the aforementioned barrier layers and different metals for the ground plane, are experimentally characterized and compared to our conduction model. We present experimental data on and analysis of nanorectenna power generation vs. wavelength and power of incident vis/nir radiation. Our e-beam fabrication technique is scalable to large dimensions [4], and allows us to easily probe different antenna dimensions.


8096-36, Session 9

Addressing quantum emitters with optical antennas

A. G. Curto, G. Volpe, T. H. Taminiau, M. P. Kreuzer, R. Quidant, N. F. van Hulst, ICFO - Instituto de Ciencias Fotonicas (Spain)

Optical antennas offer the promise of complete electromagnetic control over single photon emission and absorption at the nanoscale. They can efficiently address quantum emitters by modifying their interaction with light in polarization, angular radiation pattern and transition rates. Here, we report unidirectional and multipolar emission of quantum dots by near-field coupling to nano-antennas. The emitters are locally deposited at the end of metal nanowires. Yagi-Uda antennas are shown to direct and polarize quantum dot luminescence. Nanowire linear antennas supporting resonances of increasing order convert an otherwise purely dipolar emission into multipolar radiation. Finally, we quantify emitter-antenna coupling.

8096-37, Session 10

Toward low-loss plasmonics without metals

M. A. Noginov, L. Gu, J. E. Liveneere, G. Zhu, A. K. Pradhan, R. Munde, M. J. Bahoura, Norfolk State Univ. (United States); A. Urbas, J. Vella, Jr., Air Force Research Lab. (United States); V. A. Podolskiy, Univ. of Massachusetts Lowell (United States); E. Narimanov, Purdue Univ. (United States)

In this presentation, we will review our recent efforts aimed at the development of low-loss plasmonics that does not use metallic components. In particular, we will focus on two types of systems (i) highly concentrated dyes, in which the negative value of electric permittivity is sought in the vicinity of a very strong absorption line, and (ii) transparent conductive oxides - heavily doped degenerate semiconductors - in which plasma frequency corresponds to a near infrared range.
8096-38, Session 10  

**Nanoplasmonics in direct band-gap semiconductors**  
N. Dietz, M. I. Stockman, Georgia State Univ. (United States)  
We explore nanoplasmonics concepts on selected group of III-Nitride compound semiconductor nanostructures, e.g., indium-rich InGaN alloys, that can be tuned over a large transmission range and fabricated with almost metal-like free-carrier concentrations of up to $-10^9$ cm$^{-2}$ 3. We have experimentally shown that for the highly doped InN the permittivity is negative (metal-like) and plasmonic quality factor is $Q$=5-6 for its frequency 0.4-0.7 ev, or wavelength 1.5-3 micron, which is in the same range as for gold in the visible region. Thus, the heavily doped InN is a very promising plasmonic material in the near-infrared. Theoretically, we have shown that an adiabatic cone compressor built on InN is able to enhance the optical intensity by a factor of ~500 with a high throughput. We also develop theory of a spaser built on a highly-doped InN plasmonic core surrounded by moderately-doped GaN gain medium.

8096-39, Session 10  

**All-optical control of single plasmonic nanoantenna-ITO hybrids**  
O. L. Muskens, Univ. of Southampton (United Kingdom); M. Abb, Univ. of Southampton (United States); N. Large, J. Aizpurua, Centro de Física de Materiales (Spain) and Donostia International Physics Ctr. (Spain)  
Nanoscale plasmonic components are of enormous interest for their capabilities of locally enhancing electromagnetic fields and controlling emission. Active control of such components will enable a new generation of tunable devices. We present theoretical and experimental work exploring different routes toward achieving all-solid state modulation of nanoantenna resonances.  
A new approach to antenna switching has been introduced recently where we make use of a photoconductive bridge between the two arms of a dimer antenna [1]. In order to experimentally achieve nonlinear control of nanoantennas on ultrafast time scale in a solid-state configuration, we are exploring hybrid nonlinear antenna systems. As a first important candidate, we have investigated Indium Tin Oxide (ITO) as a nonlinear optical material for plasmonic applications. We have investigated the nonlinear response of nanoantenna-ITO hybrids under picosecond pulsed laser excitation using a combination of linear and ultrashort single-antenna spectroscopy [2]. We find that the modulation of the nanoantenna-ITO hybrid is distinct from that of a pure gold nanoantenna in absence of ITO, and from ITO in absence of the antenna. We will discuss possible mechanisms of enhanced antenna-ITO nonlinearity. Our results hold promise for new types of nonlinear antenna devices which could enable active control of local optical fields for use in nanophotonic modulators, nonlinear optics, sensing, and emission control.


8096-40, Session 10  

**Coupling of plasmon with semiconductor nanoresonators: from modeling to device design**  
P. Fan, J. Liu, R. Pala, L. Cao, M. L. Brongersma, Geballe Lab. for Advanced Materials (GLAM) (United States)  
As both metallic and semiconductor nanostructures have the unique abilities to control the flow of light within a deep subwavelength volume, they are promising candidates as building blocks for compact photonic and optoelectronic devices and circuitry. Hereby, we theoretically and experimentally studied the light coupling of a propagating surface plasmon wave supported by a metal surface to the optical resonances of a semiconductor nanowire. We examined the structure as a side-coupled-cavity system and demonstrated efficient excitation of optical resonances in the nanowire by a propagating surface plasmon. Strong light coupling leads to a sharp suppression of plasmon transmission as well as efficient absorption in nanowire. These optical properties provide guidelines for incorporating multiple optical components and engineering complex optoelectronic functionalities within compact device systems, such as nanowire plasmonic photodetection and surface plasmon modulation.

8096-41, Session 10  

**Plasmonically enhanced emission from an inverted III-nitride light emitting diode**  
M. A. Mastro, U.S. Naval Research Lab. (United States)  
Silver thin film and nanoparticles deposited on the surface of InGaN quantum well structures have been shown by several groups to plasmonically enhance the optically pumped emission. The necessity of placing the active region of the device within approximately 30 nm of the plasmonic metal is a subtle dilemma for GaN-based LEDs. Hence, nearly all reports of exciton to surface plasmon coupling have been based on quantum well structures that are not designed for electroluminescence. The final grown layer in a traditional GaN-based LED structure is a $p$-type GaN:Mg contact layer. The magnesium dopant has a high activation energy in GaN, which limits the conductivity of the $p$-type contact layer. This necessitates a thick (100 to 300 nm) current-spreading $p$-type layer in commercial LEDs, which places the active region beyond the plasmon fringing field thickness, making exterior plasmonic enhancements impractical. A new inverted LED approach was developed with the key layer for enabling plasmonic enhancement being a thin $n$++ ($Al$)GaN top contact, which brings the quantum well into the fringing field of the silver nanoparticles. This proximity allowed the excitons induced within the quantum well to couple to the surface plasmons, thereby increasing the emission by approximately a factor of four in a functional LED. Furthermore, the inverted LED allows flexibility in the alloy composition of the top contact layer, which alters the dielectric environment and plasmonic response of the metal.

8096-42, Session 10  

**Silicon plasmonics**  
U. Levy, B. Desiatov, I. Goykhman, The Hebrew Univ. of Jerusalem (Israel)  
In the past two decades we are witnessing a rapid progress in towards the realization of CMOS compatible, silicon nanophotonic devices for monolithic on-chip integration of optical devices and systems. In parallel, the field of plasmonic is blooming, offering substantial advantages in the confinement of electromagnetic energy at the nanoscale. Thus, the combination of silicon nanophotonics with plasmonics seems to be a natural choice. In this work we review our work in the field of silicon plasmonics. Specifically, we demonstrate nanoscale confinement of light by the use of silicon plasmonic nanotapers on a chip. In addition, we report on our silicon plasmonic hybrid waveguide showing sub 100 nm confinement together with a propagation length of ~ 100 microns. Finally, we demonstrate a silicon plasmonic Schottky detector that allows the detection of signals at telecom wavelengths. The device is based on a self aligned process and combined LOCOS waveguide interfaced with a metal strip.
Surpassing conventional light-trapping and efficiency limits for solar energy conversion with plasmonic structures (Keynote Presentation)

H. A. Atwater, California Institute of Technology (United States)

Light-trapping and enhanced absorption is an important avenue for improved photovoltaic efficiency and cost reduction. We describe plasmonic thin film photovoltaic designs for light absorption and conversion efficiency that exceed what is achievable in conventional solar cell designs, and we report on experiments illustrating enhanced light absorption and conversion efficiency in thin film Si and GaAs and polymeric photovoltaic structures[1].

Thermodynamic arguments predict the maximum absorption enhancement in the ray optics limit for bulk dielectric materials to be 4n^2, where n is the index of refraction of the absorbing layer [2] and a similar analysis for thin waveguide structures found a maximum absorption enhancement of <4n^2 [3]. Using a combination of analytical and numerical methods, we describe why these structures do not surpass the conventional light trapping limit, and show how to design structures that can. The conventional limit can be exceeded in waveguide-like structures with elevated local density of optical states (LDOS) compared to that of the bulk, homogeneous material. To achieve this, modes of the structure must also be populated via an appropriate incoupling mechanism. We find using full wave simulations that ultrathin solar cells incorporating a plasmonic back reflector can achieve spatially averaged LDOS enhancements of 1 to 3, and a metal-insulator-metal (MIM) structure can achieve enhancements over 50 at a wavelength of 1100 nm, the band edge of Si. We also report in detail on plasmon-enhanced light trapping in thin film amorphous silicon solar cells that achieve near-record photovoltaic conversion efficiency.

Nonlinear optical responses of aperiodic plasmonic arrays for on chip applications

G. F. Walsh, Boston Univ. (United States) and U.S. Army Natick Soldier Research, Development and Engineering Ctr. (United States); S. Minissale, Boston Univ. (United States); B. R. Kimball, U.S. Army Natick Soldier Research, Development and Engineering Ctr. (United States); L. Dal Negro, Boston Univ. (United States)

Symmetry breaking in deterministic aperiodic plasmonic nanostructures produces significant spatial field localization distributed over broad frequency spectra. These characteristics are ideally suited to enhance second and third order nonlinear processes for on-chip nano-plasmonic device applications. In this paper, we experimentally investigate the nonlinear optical properties of non-centrosymmetric aperiodic arrays of gold nanoparticles, with a controlled degree of disorder, fabricated by electron beam lithography. Two nonlinear optical phenomena, second harmonic generation (SHG) and the optical Kerr effect are investigated. Arrays are pumped with femto-second optical pulses at near infrared wavelengths and surface SHG is measured by angularly resolved scattering measurements. Experimental results are also reported for additional arrays coated with thin polymer films exhibiting strong optical Kerr effects. Localized enhancements of the nonlinear index are characterized by z-scan measurements and by a novel Fourier space measurement technique that we have developed to investigate optical nonlinearities in aperiodic structures ranging from quasi-crystals to pseudo-random media. These studies are important to the engineering of the next generation of plasmonic switches with controlled nonlinear index and frequency generation on a single chip.

Applications of plasmonic oligomers, metamaterials, and nanoantennas (Keynote Presentation)

H. W. Giessen, Univ. Stuttgart (Germany)

We present an overview of 2D and 3D plasmonic oligomers [1], metamaterials, and nanoantennas which are utilized for different purposes. Stacked 3D metamaterials can be used as perfect absorbers, which give angle and polarization independent absorption beyond 90% in the visible and near-infrared region [2]. Utilizing transition metals as well as plasmonic induced transparency schemes [3], the application of sensors for liquids and gases becomes feasible [4]. Cavity enhancement allows for tailoring the spectral resonances of plasmonic systems and results in very high figures of merit for the sensor schemes [5,6]. Arranging plasmonic substructures in 3D geometries, chirality can result as optical property. Using this method allows for the construction of novel broadband circular polarizers with large angle acceptance angles. Nanoantennas can aid the sensing and nonlinear properties of plasmonic nanostructures as well. We are going to discuss applications in this area as well.

References


Nonlinear plasmonics with nanocavity gratings

F. Capasso, Harvard Univ. (United States); P. Genevet, Univ. de Nice Sophia Antipolis (France)

Here we report on a novel approach based on plasmonic nanocavity gratings to enhance surface nonlinear processes.1 We have designed plasmonic nanocavities, made of nanogrooves in a gold film and arranged them periodically. A single narrow groove (tens of nanometers wide) defined on a metal surface can be viewed as a portion of a metal-insulator-metal waveguide terminated by a metallic mirror on one side and a dielectric mirror (air) on the other. It therefore forms a cavity that sustains Fabry-Perot modes. Because the cavity mode is confined in a sub-wavelength volume, large fields are established both in the metal and in the dielectric under resonant excitation. In addition to these localized surface plasmons a grating of nanogrooves enables the coupling of free space light to surface waves propagating on the corrugated surface.

We apply this concept of coupled resonances to four-wave-mixing in gold and demonstrate an enhancement of the generated signal of up to 2000 compared with an un-patterned surface, two orders of magnitude higher than previously reported.1 This result shows that
plasmonic nanocavity gratings are a promising route to enhancing optical nonlinearities in the metal and also in any material filling the cavities, with potential applications to nanoscale frequency conversion and highly sensitive vibrational spectroscopy and microscopy.


8096-48, Session 12

Attosecond measurement of petahertz plasmonic near-fields

F. Süßmann, S. Zherebtsov, Max-Planck-Institut für Quantenoptik (Germany); T. Fennel, Univ. Rostock (Germany); E. Rühl, Freie Univ. Berlin (Germany); M. F. Kling, Max-Planck-Institut für Quantenoptik (Germany)

As compared to conventional electronics, plasmonic systems can operate at highwave (petahertz) frequencies and have enormous potential to push the frontiers in electronics in both size and speed. The development of lightwave electronics would mark a major breakthrough and enable among other applications up to 6 orders of magnitude faster computation and communication technology. Attosecond metrology enables access to petahertz optical phenomena. We aim to control and measure nanoplasmonic fields on attosecond timescales and extend the attosecond streaking spectroscopy technique to measurements of enhanced plasmonic near-fields of isolated metal spheres. Temporal resolution is achieved by limiting the emission of high energetic, direct photoelectrons to a sub-cycle time window using attosecond XUV pulses that are phase-locked to the driving NIR field. These direct photoelectrons integrate the force exerted by the optical fields on their way to the detector, leading to a change in their kinetic energy. TOF spectra recorded for different time delays between the NIR and XUV pulses will give insight into the evolution of the local electric field and surface charge dynamics. Unlike in traditional streaking experiments, both the temporal and the spatial decay of the near-field cause the energetic shift of the electrons. This has to be considered during the reconstruction of the local field.

First experimental results and simulations will be presented, showing the feasibility of such an approach and the influence of laser intensity, particle size and composition on the obtained waveforms.

8096-49, Session 12

Optical response and ultrafast spectroscopy of metal-based hybrid nanoobjects

F. Vallee, D. Mongin, A. Lombardi, P. Maioli, A. Crut, N. Del Fatti, Univ. Claude Bernard Lyon 1 (France)

The size, shape and structure dependencies of the properties of nanoobjects, and the concomitant possibilities opened to control them, lead to considerable activities in the academic and industrial domains. Confinement effects in nanooobjects formed by a single material, e.g., a metal or a semiconductor, have now been extensively studied. Less interest has been devoted to complex systems, combining multiple material components in the same nanoparticle, e.g., bimetallic or hybrid metal-semiconductor particles. However, combining the plasmonic response of their components offer wide ranges of possibilities for developing novel plasmonic systems, and also raise fundamental questions on plasmon-plasmon or plasmon-exciton coupling and on energy and charge transfer mechanisms between the forming materials.

We report on investigation of the linear optical response (extinction) of hybrid hammer-like shape nanoparticles formed by a metal (Au sphere) and a semiconductor (CdS or ZnO rod). The results on ensemble and a single particle are interpreted in terms of dielectric coupling of the two-materials, yielding a good reproduction of the experiments in the non-resonant exciton-plasmon regime. The ultrafast nonlinear response of these nanohybrids has also been investigated using a two-color wavelength-tunable femtosecond pump-probe technique. When carriers are injected in the semiconductor part, a spectral shift of the gold surface plasmon resonance is observed yielding evidence for ultrafast electron transfer between the two-materials. Measurements performed in CdS-Au hybrids probing the carrier population in the semiconductor part with 50 fs pulses suggest an upper limit for the electron transfer time of about 10 fs.

8096-50, Session 12

Light-field control of electronic motion at nanoscaled condensed matter interfaces

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The advent of intense few-cycle near infrared (NIR) laser pulses with stable and tunable carrier envelope phase (CEP) has enabled the control of electromagnetic fields with attosecond time precision [1]. Here we aim at exploiting these few-cycle NIR optical fields with well-defined CEP to generate and control the motion of charge carriers within heterogeneous nanoscaled solid state interfaces. We demonstrate the generation of directly measurable photocurrents in unbiased gold-coated SiO2 nanogaps, whose magnitude and directionality can be tuned with the laser CEP. This effect vanishes with the increase of the laser pulse duration. We claim that such phenomenon is the signature of optically induced electron tunneling at the metal-dielectric interface with subsequent acceleration of the charge carrier in the ultrashort laser field. This ultrafast current injection at a nanoscaled condensed matter system represents a first step towards femtosecond lightwave electronics.


8096-51, Session 13

Resonance energy transfer near metal nanostructures mediated by surface plasmons

T. V. Shahbazyan, Jackson State Univ. (United States); V. Pustovit, Ctr. de Recherche Paul-Pascal (France)

A theory of resonance energy transfer (RET) between donor and acceptor molecules (or quantum dots) situated near a plasmonic nanostructure is presented that incorporates nonradiative and radiative transfer channels while maintaining energy balance between transfer, dissipation and radiation. It is shown that plasmon-enhanced radiative transfer (PERT) is the dominant RET mechanism in a wide range of parameters. Numerical calculations performed for molecules near spherical Ag nanoparticle indicate that RET is determined by competition between plasmon enhancement and metal quenching and its magnitude is highly sensitive to molecules positions. There are regions in parameter space where plasmon-mediated RET can be either enhanced or reduced relative to Förster transfer, consistent with experiment. A comparison between our theory and previous models is performed.
Theory of energy transfer interactions near sphere and nanoshell based plasmonic nanostructures

M. S. Shishodia, Tel Aviv Univ. (Israel) and Holon Institute of Technology (Israel); B. D. Finager, Holon Institute of Technology (Israel) and Tel Aviv Univ. (Israel); A. Nitza, Tel Aviv Univ. (Israel); G. Li, Northwestern Univ. (United States)

Molecular exciton-metallic nanoparticle complexes are the subject of intensive study. Metallic nanostructure mediated electric-field enhancement, and the proximity of a metal interface can greatly alter dipole-dipole interactions in excitonic and energy transfer donor-acceptor systems. In addition, excitonic (energy transfer) interactions accompanied by plasmonic response of metallic contacts can have substantial effects on the electronic transport properties of molecular nanojunctions [1]. In this paper, we present a theoretical model for energy transfer near sphere and nanoshell particle/particle-pair based metal nanostructures. The model is based on multipole spectral expansion and uses the surface plasmon-dressed Coulomb interaction [2]. We study also the energy transfer in a molecular wire between two metallic contacts representing a nanoparticle dimer in the presence of plasmonic hybridization. It is worthy to note that nanoshell exhibits superior plasmonic properties by virtue of geometry controlled spectral tuning of resonances arising from the hybridization of cavity and sphere plasmons. Exploiting tunability feature of nanoshells, wavelength specific designs for optimal energy transfer and the possible effects on molecular junctions will be presented.


Fluorescence lifetime measurements of single molecules in DNA templated gold nanoparticle dimers

M. Busson, L’Institut Langevin (France); B. Rolly, B. Stout, N. Bonod, Institut Fresnel (France); S. Bidault, L’Institut Langevin (France)

Gold nanoparticle groupings can act as optical antennas: they couple efficiently in the near field to photon emitters to enhance their interaction with the far field. A typical way to design nanoantennas is to couple the plasmonic modes of gold nanoparticles positioned a few nanometers apart. We demonstrate here how efficient optical antennas can be synthesized by the programmed assembly of DNA functionalized gold nanoparticles. This bottom up strategy allows us to tune particle sizes and spacings while fully controlling the chemical environment of the antenna.

In practice, a known number of thiolated DNA single strands are grafted on the surface of polyethylene glycol stabilized gold particles with diameters ranging from 5 to 40 nm. Hybridization of complementary DNA sequences drives the assembly of well defined nanoparticle groupings with spacings ranging between 6 and 30 nm. The optical properties of single groupings are studied by confocal scattering spectroscopy. Shortening the DNA linker induces a clear red shift of the plasmon resonance wavelength. Experimental data from scattering spectroscopy are correlated with electron microscopy images and theoretical calculations.

The interaction of the antenna with a single chromophore added to the DNA scaffold is studied using fluorescence lifetime measurements. Experiments are performed on single molecules using time-correlated single photon counting in a confocal geometry. The increased local density of optical states in the antenna enhances the de-excitation rate of the fluorescent molecule. The influence of the dimer interparticle spacing on single molecule fluorescence lifetime is being investigated.

Hybrid semiconductor/plasmonic devices for nanophotonics (Keynote Presentation)

M. L. Brongersma, Stanford Univ. (United States)

Metamaterials and nanophotonic devices are most commonly constructed from metallic (i.e. plasmonic) nanostructures. However, recent research has begun to also exploit the optical resonances of high-permittivity semiconductor and dielectric nanostructures to realize similar optical functionalities. In this talk, I will illustrate the use of plasmonic, semiconductor, and dielectric nanostructures in a variety of applications (nanoscale sources, high-speed modulators, and detectors) and discuss their relative strengths and weaknesses. I will also discuss several exciting new hybrid semiconductor/plasmonic devices that capitalize the relative strengths of each of the constituent materials to obtain new functionalities.

Controlling electroluminescence from QW using plasmonic resonator antenna electrodes

K. C. Y. Huang, Stanford Univ. (United States); M. Seo, KAIST (Korea, Republic of); M. L. Brongersma, Stanford Univ. (United States)

We simulated, fabricated and characterized the electroluminescence from InGaAs/ GaAs QW with metal electrodes which function as plasmonic resonator antennas. By patterning the antenna electrodes in the vicinity of a single QW layer with deeply subwavelength lateral width, charge carriers are confined near the antenna and subsequently recombine with enhanced radiative decay rate depending on the electrode/ QW separation and electrode shape. We show that the emission can be efficiently coupled to the antenna resonance which is engineered to reradiate in a specific polarization and unidirectional far-field pattern. The simultaneous control of carriers and photons can be used to improve light extraction and detection from the semiconductor while enabling fast direct modulation of the spontaneous emission.

Enhancing photonic-plasmonic interactions on active devices using circular scattering in aperiodic spirals

J. Trevisio, S. Yerci, L. Dal Negro, Boston Univ. (United States)

Deterministic arrays of Au nanoparticles arranged in aperiodic spiral geometries (Vogel's spirals) have been engineered and fabricated onto planar optical devices in order to enhance photonic-plasmonic coupling and increase light-matter interactions over broad frequency spectra. Vogel's spirals lack both translational and orientational symmetry in real space, while displaying continuous circular symmetry (i.e., rotational symmetry of infinite order) in reciprocal Fourier space. We investigate the novel regime of “circular multiple light scattering” in finite-size deterministic structures and we experimentally and theoretically show that circular symmetry in diffrused reciprocal space gives rise to polarization-insensitive planar diffraction over a large and controllable range of wavelengths. The multi-band/broadband polarization-insensitive planar diffraction observed in aperiodic spirals is a highly desirable property for the engineering of a variety of device applications that require enhancing photonic-plasmonic coupling over planar optical...
Coupling of nanoparticle plasmons with molecular linkers

N. Zabala, Univ. del País Vasco (Spain) and Centro de Física de Materiales (Spain) and Donostia International Physics Ctr. (Spain); O. Pérez-González, Univ. del País Vasco (Spain) and Donostia International Physics Ctr. (Spain); P. J. Nordlander, Rice Univ. (United States); J. Aizpurua, Centro de Física de Materiales (Spain) and Donostia International Physics Ctr. (Spain)

Following the emerging interest in connecting molecular electronics and plasmonics, we study the spectral signatures of molecular linkers in plasmonic cavities of gold nanoparticle dimers. Different dielectric models and sizes for the linker are considered to envisage the relation between the spectral changes observed in the extinction spectra and the electronic transport through the molecules.

For thin junctions a BDP (Bonding Dimer Plasmon) mode, arising from the coupling of dipolar modes of the individual particles, is excited and blue-shifted as the radius is increased. When wider junctions are involved another mode, which corresponds to a real charge transfer between the nanoparticles and is known as CTP (Charge Transfer Plasmon), emerges at longer wavelengths. The characteristics of these modes are observed with a simple pure conductor, but when an excitonic bridge is considered, more features appear in the extinction spectra as a consequence of the plasmon-exciton coupling, as revealed from the dispersion curves obtained for different sizes and characteristic resonant frequencies of the molecules.

The electromagnetic field is obtained by solving Maxwell’s equations numerically with the Boundary Element Method (BEM).

We believe that the understanding of the spectral changes in plasmonic cavities with molecular linkers may help to control the switch of different plasmon modes.

Tayloring the optical properties of LEDs by using surface plasmon polariton gratings

J. Moosburger, OSRAM Opto Semiconductors GmbH (Germany)

The enhancement of light extraction and tailoring the emission characteristics are two of the major challenges for state-of-the-art LED chips. Beside conventional approaches like surface roughening, metal gratings and metal nano particles can be used as an alternative approach.

Looking at the extraction efficiency of LED chips, SPP gratings on one side can be used to avoid the limitations of total internal reflection (TIR) at planar surfaces, where light should be coupled out. At a flat surface, light beyond the critical angle is reflected back and hence the probability of absorption within the chip increases. With SPP gratings, light beyond TIR can couple into extraction modes via SPP states.

On the other side, SPP gratings can be used to make unavoidable absorbers ‘translucent’. The main focus here are metal contacts at the emitting surface that normally contribute to internal losses.

In addition, the emission characteristic of a LED chip can be shaped by defining SPP gratings on top. Due to the periodicity of the grating, the SPP’s can couple to discrete extraction modes. Hence by changing periodicity, filling factor and over all pattern of the grating, the extraction profile can be altered.

The presentation will summarize theoretical calculations, experimental results and fabrication issues of plasmonic structures on inorganic LEDs. Furthermore a benchmark with state of the art LEDs and an outlook for future potentials of SPP gratings for LEDs will be given. This work was done within the EU funded project PLEAS.

Thermo-induced electromagnetic coupling in gold/polymer hybrid plasmonic structures probed by surface enhanced Raman scattering

N. Felidj, L. Dos Santos, H. Gehen, G. Charon, J. Grand, J. Aubard, C. Mangeney, Univ. Paris 7-Denis Diderot (France)

Since its discovery four decades ago, surface enhanced Raman scattering (SERS) has been considered as one of the most sensitive tools for the chemical analysis of very few amount of molecules adsorbed onto metallic nano-particles (NPs), especially gold and silver.

One challenging aspect in SERS concentrates on the demonstration that a single molecule or very few molecules could be detected under specific conditions. It requires very huge electric field enhancements occurring within the gap between two NPs or between NPs and a gold film. Of particular interest is the possibility to control this latter interaction in order to optimize the Raman enhancement factor. In this work, we propose to address this issue by designing a stimulable device made of gold colloidal nanoparticles connected to a gold flat film through an active thermosensitive polymer brush layer, capable to externally modulate the distance between the NPs and the substrate. As a linker, we used Poly (N-isopropylacrylamide) that undergoes a reversible, inverse phase transition at a lower critical solution temperature (LCST) of about 32°C in pure water. Below the LCST, the polymer chains are in an extended conformational state. Above the LCST, it is in a hydrophobically collapsed conformational state. These conformational changes of the linker between the gold nanoparticle assemblies and the surface induce dramatic modifications of the optical properties of the substrate. In particular, above the LCST, the proximity of the colloidal particles to the gold film leads to a strong interaction regime with higher SERS spectra than below the LCST.


Origin of localized surface plasmon resonances in thin silver film over nanosphere patterns

S. K. Cushong, L. A. Hornak, J. Lankford, Y. Liu, N. Wu, West Virginia Univ. (United States)

Film over nanosphere (FON) patterns are formed by depositing a silver film on top of a close-packed polystyrene (PS) sphere template. Multiple localized surface plasmon resonance (LSPR) peaks are experimentally measured by transmission UV-Vis spectroscopy in the three dimensional FON pattern for thin silver films. Increasing the sphere size in the close-packed template or increasing the deposited silver film thickness redshifts the LSRR peaks to varying degrees. A finite difference time domain (FDTD) analysis reveals that the main LSRR peaks originate from a quadrupole and a dipole coupling mode near the triangle gap.
surrounded by three adjacent PS spheres. The physical location and the electromagnetic enhancement of the two resonant modes are determined for different thickness of deposited silver films. It is found that the resonance modes do not change with varying film thickness.

8096-75, Poster Session

**Semi analytical numerical analysis of plasmonic structures in layered geometries**

A. Alparslan, C. Hafner, ETH Zurich (Switzerland)

Following the advancements in the fabrication process of photonic structures, various nano devices became quite popular, including photonic crystals, chemical and bio sensors, optical antennas and waveguides. Usually, these devices are fabricated in a multilayered structure. In the numerical analysis of such structures, the multilayered geometry is often ignored for sake of simplicity, which can cause inaccuracies in the results. Especially for structures that support Surface Plasmon Polariton (SPP) or guided wave modes, the errors become so high that the computations become useless. In order to analyze such structures, it is crucial to use a numerical tool that deals with layered geometries in an efficient and robust way.

The Multiple Multipole Program (MMP) is one of the most accurate simulation tools for the analysis of plasmonic structures. It uses a superposition of analytical solutions of Maxwell’s equations (point sources, plane waves, Bessel functions, etc., so called expansions), to fulfill the boundary conditions on the boundaries or interfaces of structures. In the case of structures involving layered geometries, the boundary matching procedure becomes expensive, if not impossible, since the number expansions and matching points increases dramatically. In order to tackle this problem, layered media Green’s functions (LMGF), which are the analytical responses of the layered geometry in presence of a point source, are introduced as a new expansion set for MMP. By using the advantages of MMP and LMGF, a robust, efficient and user-friendly simulation tool is obtained. In this talk, the derivation of the method together with some results from OpenMaX, the open-source program that includes the latest MMP version, will be presented.

8096-76, Poster Session

**Site selective surface enhanced Raman scattering on nanostructured cavity arrays**

F. Lordan, J. H. Rice, Univ. College Dublin (Ireland); B. Jose, R. J. Forster, T. E. Keyes, Dublin City Univ. (Ireland)

Raman spectroscopy is an extremely powerful analytical tool. Surface enhanced Raman spectroscopy (SERS) enables sample sensitivity to extend down to the single molecule level. There is presently great interest in using uniform nanostructured surfaces to give reproducible and strong SERS signal. The nanocavities studied here have spherical cap architecture and are arranged uniformly in an Au array. These structures support both localised and delocalised plasmons. Localised surface plasmon polaritons exist inside the nanocavities (Mie plasmons) and delocalised or propagating surface plasmon polaritons exist on the flat surface of the sample (Bragg plasmons). The angle dependence property of surface enhanced Raman is used in the present work to enable comparison between SERS caused by localised plasmons and SERS caused by delocalised plasmons. The samples used here were modified to enable separate investigations of the two plasmon types. The externally modified array had dye placed only on the flat top surface of the array. The internally modified array had dye placed only on the internal walls of the cavities. Results show that the changes in Raman intensities with respect to the incident angle depend on the location of dye on the array.

8096-77, Poster Session

**Enhanced polarization anisotropy of metal nanoparticles and their spectral characteristics in the surface plasmon resonance band**

N. Ghosh, J. Soni, Indian Institute of Science Education and Research (India)

The spectral and angular polarization behavior of light scattered from metal nanoparticles were investigated using polar decomposition of the scattering matrices. The scattering matrices (S(θ, λ), lambdatheta) is the scattering angle, lambda the wavelength) for both preferentially and randomly oriented spheroidal (prolate and oblate) silver nanoparticles were generated in their surface plasmon resonance spectral region (380 - 600 nm) using the T-matrix approach. S(θ, λ) were generated for silver nanoparticles having varying sizes and aspect ratios and for dielectric particles having identical size and shape. These were analyzed using the polar matrix decomposition approach, to derive quantitative individual polarization properties, namely, retardance, diattenuation and depolarization. The decomposition-derived linear retardance (delta, phase difference between orthogonal linear polarizations) from preferentially oriented silver nanoparticles showed distinct spectral features, the values for delta peaking around the spectral overlap region (400 - 450 nm) of the longitudinal and the transverse plasmons. Further, the magnitude of delta and its spectral behavior was observed to undergo systematic changes with varying aspect ratio and the size of the nanoparticles. In contrary, for similar dielectric nanoparticles, the scattering-induced delta was considerably weaker and did not show any appreciable spectral variation. The decomposition-derived value for diattenuation (D), differential attenuation of two orthogonal polarization states) for the silver nanoparticles also showed interesting spectral characteristics, which were again absent for the dielectric particles. The enhanced linear retardance (and its distinct spectral characteristics) for the metal nanoparticles was attributed to the additional phase differences between the longitudinal and the transverse plasmon polarizabilities, which was confirmed further by studying the angular variation of delta (theta) for these nanoparticles. The analysis also revealed that when averaged over all possible orientation of the particles (for randomly oriented spheroids), addition of the retardance and diattenuation matrices having random orientation of axes manifests as stronger depolarization (D) of light in spheroidal metal nanoparticles as compared to their dielectric counterparts. The details of the studied dependence of delta, d and D on size parameter and aspect ratio of the nanoparticles will be presented. Initial results of complementary experimental studies and their implications for spectral, polarimetric biomedical imaging will also be discussed.

8096-78, Poster Session

**Manipulation of multi-dimensional plasmonic spectra for information storage**

K. Yang, W. T. Chen, P. C. Wu, C. J. Chen, National Taiwan Univ. (Taiwan); C. Weng, Instrument Technology Research Ctr. (Taiwan); C. Kuan, National Taiwan Univ. (Taiwan); M. Mansuripur, College of Optical Sciences, The Univ. of Arizona (United States); D. P. Tsai, National Taiwan Univ. (Taiwan) and Instrument Technology Research Ctr. (Taiwan) and Research Ctr. for Applied Sciences (Taiwan)

We demonstrate a concept of optical data storage through plasmonic resonances of metallic nano-structures. Metallic nano-structures exhibit strong variations in their reflectance and/or transmittance spectra due to surface plasmon polariton resonances. We study the variations of spectra through 50x50 arrays of repeated unit cells covering a total area of ~500x500µm². Each cell contains 10 different nano-features, such as an ellipse, a ring, a circle, a triangle, a square, etc. The size of each unit cell is 500x500µm², and the periodicity is 1.0µm. The variations of spectra is
obvious enough to be distinguished, so that it should be possible to store and then retrieve data from different spectra. This paper presents the results of a study aimed at proving the feasibility of the concept.

8096-80, Poster Session

Controlling the fluorescence dynamics of a single emitter by coupled metallic nanostructures

C. Vandenbem, Facultes Univ. Notre Dame de la Paix (Belgium); L. S. Froufe-Pérez, Instituto de Ciencia de Materiales de Madrid (Spain); R. Carminati, Ecole Supérieure de Physique et de Chimie Industrielles (France)

A key issue in photonics is the controlled modification of spontaneous emission. Changes of the spontaneous decay rate are induced by changes in the local density of electromagnetic modes, and are quantitatively described by the classical electrodynamic response of the surface. In consequence, the development of nano-optics techniques has stimulated the use of metallic nanostructures to act on the spontaneous decay rate but also on the fluorescence intensity, and on the radiation pattern of isolated emitters, leading to the concept of optical nanoantenna.

In addition, control of plasmon-resonance frequencies can be achieved either by playing with the shape of metallic nanostructures either by coupling different plasmonic modes of nanostructures. The latter case has the advantage that these hybrid plasmonic modes can lead to either radiative or non-radiative coupling depending on their coupling to free space.

In the present work, we study theoretically and numerically the possibility of controlling the fluorescence features with systems involving coupled plasmon modes. Depending if the emitter is coupled to the radiative mode or the non-radiative mode (dark mode), the apparent quantum yield and the fluorescence lifetime exhibit different behaviors. The concept is general and can be illustrated on several geometries such as the dimer of two nanoparticles, a thin metallic film or a hybrid system coupling a metallic film and a single metallic nanoparticle.

8096-81, Poster Session

Optical properties of silver nanoparticle dispersed in polymer matrix

A. Ziaemehr, Imam Khomeini International Univ. (Iran, Islamic Republic of); R. Poursalehi, Shaded Univ. (Iran, Islamic Republic of)

We studied the effects of nanofiller size on the refractive index and optical transparency of nanoparticle polymer nanocomposite. The size of nanofillers has been considered from 3 up to 30 nm. In a precise calculation of absorption and scattering of polymer matrix, the modified size dependent refractive index is used. In addition, this quantity obtained with considering size dependent surface effects.

The calculated results indicated the particles refractive index depends strongly on the diameter of particles, especially for smaller particles at long wavelengths. Also it was found that optical extinction intensity increases for larger nanoparticle and the wavelength of maximum of optical exhibited a red shift. Inconsistency between refractive index of nanofiller and polymer matrix increases the scattering, and in some application, light scattering and any other type of wastage are extremely important.

The results of this study can be applied for optimization of size and loading fraction of nanoparticle filler for preparation of modified nanocomposites with lower light scattering and lower refractive index mismatch.

8096-82, Poster Session

hp-FEM applied to scattering problems in plasmonics

M. Wang, C. Engström, ETH Zurich (Switzerland); K. Schmidt, Technische Univ. Berlin (Germany); H. Brandsmeier, C. Hafner, ETH Zurich (Switzerland)

The simulation of plasmonic structures is numerically difficult mainly because of the rapid field variation at the metallic surface. Standard low-order finite element and finite difference methods are inefficient for this class of problems. Therefore, it is highly desirable to develop efficient finite element methods able to simulate plasmonic structures.

In this paper, we use high-order curvilinear finite elements for scattering problems with both Absorbing Boundary Conditions (ABCs) and radial Perfectly Matched Layers (PMLs). For ABCs, we develop adaptive strategies, which are implemented in the hp- finite element code CONCEPTS. CONCEPTS uses blending technique for high-order boundary approximation, which is mandatory for curved boundaries.

We study the plasmonic behavior of two nearby nano particles with smooth interfaces and use solutions obtained with the Multiple Multipole Program (MMP) as reference solutions. The hp-FEM simulations with ABC and PML show a very good agreement with MMP. Of central importance is the use of quadrilateral curvilinear finite elements, which accurately describe the geometry of the problem. Together with high-order basis functions and an adaptive strategy, these elements significantly enhance the performance of FEM.

8096-84, Poster Session

near-field mapping by laser ablation of PMMA coatings

J. Pietowski, C. Maibohm, J. Kjelstrup-Hansen, H. Rubahn, Univ. of Southern Denmark (Denmark)

Near-Field optics has attracted much attention in various fields of science due to its prospect for spatially resolving optical fields at length scales far below the diffraction limit. Though several applications for local field enhancement have been successfully demonstrated, spatial mapping and direct measurement of the optical near-field surrounding nanostructures of noble metals is still important both for basic and applied studies of exploitation of localized surface plasmons (LSP). Spatial mapping and direct measurement of the optical near-field surrounding noble metal nanostructures are often done with optical scanning techniques such as scanning near-field optical microscopy (SNOM) or photon scanning tunneling microscopy (PSTM). Here we report sub-diffraction spatially resolved mapping of strong localized field intensity enhancement on gold nanostructures based on local laser ablation of an “imaging” polymer layer. We take advantage of the transparency and well known ablation threshold of poly (methyl methacrylate) PMMA thin films, spin coated onto regular arrays of elevated gold nanostructures on a gold substrate. Sub-ablation threshold illumination is obtained via Laser Scanning Microscope with a femtosecond laser system tuned to excited Localised Surface Plasmons (LSP) on the nanostructures. The accompanying field enhancement on the nanostructures together with sub-threshold excitation exceeds the PMMA ablation threshold creating arrays of local ablations and corresponding topographic modifications of the polymer film. Such modifications can be quantified straightforwardly via, e.g., scanning electron or atomic force microscopy.

8096-85, Poster Session

Study of the morphology and optical properties of nanoparticle-polymer conjugates

R. C. Wadams, L. Fabris, Rutgers, The State Univ. of New Jersey
Organic-based bulk heterojunction solar cells (BHJSCs) consist of phase-separated blends of conducting polymers and fullerene derivatives. The polymer active layer donates electrons to the n-type fullerene phase upon absorption of solar radiation. Ideally, electrons diffuse into the heterojunction before recombination, and are dissociated at the polymer-fullerene interface. BHJSC quantum efficiency is limited by the polymer and fullerene morphology, and by the polymer’s narrow absorption spectrum. It has been proposed that nanoparticle incorporation into the active layer can enhance light absorption. Noble metal nanoparticles exhibit localized surface plasmon resonances (LSPRs) upon absorption of electromagnetic radiation. The absorption spectrum is size, shape, and material dependent. Spherical nanoparticles exhibit one LSPR. Once symmetry is broken, such as with rods, multiple absorption bands are possible. Additionally, pairing nanoparticles in dimers creates intense electromagnetic field enhancements within the intermetallic junction due to plasmonic coupling. The introduction of nanoparticles in BHJSCs can potentially increase the absorption spectrum of the active polymer layer. Recently, nanoparticles have been covalently bonded to polymeric chains allowing investigation of polymer-nanoparticle interactions, and 1-dimensional nanoparticle assemblies. Our expectation is that binding nanoparticle dimers onto polymer backbones will affect the morphology and optical properties of the conjugate. It is anticipated that ordering of the polymer-based active layer can be induced by the presence of anisotropic nanoparticles with elongated shape, such as nanorods. Herein we describe our approach for the synthesis of covalent nanoparticle dimer-polymer conjugates. Gold and silver nanoparticles, of various morphology (e.g. spheres, rods, bones), and their dimers are synthesized, and conjugated to polymer chains. The effects on the morphology and optical properties induced by the coexistence of the nanoparticle dimers and polymers are analyzed, and the potential benefit brought about by these hybrid nanostructures is evaluated.


8096-87, Poster Session
Surface-plasmon-enhanced visible light emission of ZnO/Ag grating structures
M. Gwon, E. Lee, Ewha Womans Univ. (Korea, Republic of); K. Yee, Chungnam National Univ. (Korea, Republic of); D. Kim, Ewha Womans Univ. (Korea, Republic of)
Surface plasmon polaritons (SPP) are resonant interactions between the surface charge oscillations and the electromagnetic waves at the metal/dielectric interface. Periodic nanostructures can bridge the SPP-photon momentum gap and modify the optical properties of the dielectric layers. ZnO/Ag thin films can be used as back reflectors in silicon thin film solar cells. It is interesting to investigate how the grating structures can influence SPP-photon coupling and resulting optical properties of ZnO/Ag layers. ZnO/Ag thin films were deposited on one-dimensional periodic structures, with the periodicity of 1000 and 1400 nm, fabricated by nanoimprint lithography. The ZnO/Ag grating structures exhibited multiple peak features in visible-range photoluminescence (PL). Whereas a ZnO/Ag planar thin film showed two major PL peaks in UV and visible region. Moreover the PL intensity of the periodic structures was 100 times larger than that of the planar counterpart. These results could be understood as a result of SPP-exciton interaction. The grating structures also exhibited quite distinctive features in reflectance from the planar samples. There were several reflectance dips, which were caused by photon-induced SPP excitation via the grating coupling. Thus, the PL peaks, well matched with the reflectance dips, represent the excited SPP energies, determined by the grating periodicity. Finite-difference time-domain simulations supported all the experimental results.

8096-88, Poster Session
Two dimensional standing wave surface plasmon fluorescence imaging by subwavelength slit arrays
W. Qian, Nanyang Technological Univ. (Singapore); J. Bu, Nankai Univ. (China); P. S. Tan, Sr., Nanyang Technological Univ. (Singapore); X. C. Yuan, Sr., Nankai Univ. (China)
Four counter-perpendicular sub-wavelength slit arrays embedded on the silver film are proposed to convert free-space light to surface plasmon (SP) waves. The excited counter-propagating SP waves interfere each other to form two dimensional standing wave patterns in the region of the structure center area. Since the SP wavelength is shorter than free space propagating electromagnetic waves, this constructive interference pattern contains an attenuation of the high spatial frequency kSP=4π/λSP This standing wave profile can served as the virtual probing mechanism to excite fluorescence near the metal surface. Then a linear inversion scheme is utilized to recover the fluorescence density from a serial of images obtained by conventional microscopy by using phase shifting method. The simulation results show that the resolution can reach to λSP/4 which is clearly beyond diffraction limit. The main advantages of these promising new paths are that they do not require any scanning of the sample and do not require one to mount an interference setup in the microscope. This designed sub-wavelength slit arrays structure is one of the potential methodologies to realize the real time, wide field, on-chip, and high-spatial resolution fluorescence imaging.

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(United States)

Surface-plasmon-enhanced visible light emission of ZnO/Ag grating structures
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8096-89, Poster Session

**Numerical study of optical and EELS response of coupled metallic nanoparticles**

S. Guillaume, L. Henrard, Facultes Univ. Notre Dame de la Paix (Belgium)

Localized surface plasmon resonances (LSPR) govern the optical properties of metallic nanoparticles at the nanoscale level and depend strongly on their shape, size and environment. Furthermore, for particles close to one another, coupling occurs and gives rise to new plasmon modes that can be described in terms of hybridization of the plasmon modes of the individual nanoparticles. For given geometries, such as a dolmen-like structure made of 3 gold nanorods, a transmission window appears in the optical spectrum due to Fano resonances. Because, dark modes are invisible in optics, one has to probe locally the response of the nanoparticles to get insight on the origin of these Fano resonances. This is why we investigate numerically the energy electron loss (EELS) response of coupled metallic nanoparticles, together with their optical properties. To achieve this, calculations are performed in the frame of the discrete dipole approximation both for optical and EELS excitations.

In the case of a gold dolmen-like structure, the bright mode of the monomer and the dark mode of the dimer are found to have a similar energy. Moreover, the dark mode is narrower compared to the broad dipolar mode of the monomer. These observations explain the origin of the transmission window and the Fano resonances of the spectrum. However, it also appears that the “optical Fano mode” is unexpectedly very active in EELS at a lower energy than in the optical spectra. Influence of the system configuration on EELS excitability is then questioned for other geometries.

8096-90, Poster Session

**Design and analysis of subwavelength plasmonic waveguide array**

V. Dillu, S. Singh, R. K. Sinha, Delhi Technological Univ. (India)

We examine the propagation of plasmonic TM (Transverse Modes) modes generated in the designed periodic array of silicon (Si) and silver (Ag) on Si substrate. The properties of surface plasmons are tailored by altering the size of Ag nano rods and its periodicity. Conventional waveguides cannot guide electromagnetic energy below the diffraction limit of light, which can be overcome by texturing the metal or dielectric surface. In this design we have textured by placing metallic, Ag nanorods on Si substrate. This provides the missing momentum needed, since SPP modes always lay beyond the light line. Ag nanorods are structured at nano dimensions to control and manipulate Surface Plasmon Polariton (SPP) propagation and thus open new possibilities in light matter interaction.

Here, we report the design and analysis of subwavelength plasmonic photonic crystal structure for the purpose of generation and propagation of SPP. TM polarized SPP propagating through the linear defect created in the periodic array of Ag (Silver) and Si (Silicon) nano rods on Si substrate have been theoretically analyzed using Finite Difference Time Domain (FDTD) computational calculations. The band gap and transmission spectra for the full structure are studied and further the structure with linear defect is designed for propagating plasmonic radiations. The structure shows high confinement below the diffraction limit and helps in scaling down the size of the proposed device. These investigations validate the use of nano structures for SPP propagation and hence miniaturize the optical and electronic devices for specific applications.

8096-91, Poster Session

**Plasmonic cavity made of defect in an array of asymmetric T-shaped structures**

Y. Chang, M. N. Abbas, M. Shih, Academia Sinica (Taiwan)

Plasmonic cavities that strongly confine light are finding applications in many areas of physics and engineering, including coherent electron-photon interactions. Here, we introduce a defect in a 1D array of asymmetric T-shaped structures to form an optical cavity to confine the light in small area, and we obtained a relatively high quality factor (~200) with very small effective mode area [0.0375(λ/λ0)2] which is far below the diffraction limit. Furthermore, we showed that abrupt change at defect edge will increase the radiation losses and will suppress the quality factor to 64.

8096-92, Poster Session

**Properties of nano-ridge surface plasmon mode**

J. Guo, The Univ. of Alabama in Huntsville (United States); R. A. Soref, W. R. Buchwald, Air Force Research Lab. (United States); G. Sun, Univ. of Massachusetts Boston (United States)

We investigate the surface plasmon-polariton mode guided by nanometer scale metal ridges embedded in dielectric materials. We calculate the mode confinement, attenuation, and figure-of-merit for a variety of metal ridge structures in the 1.5 to 4.5 um infra-red wavelength range. We compare the properties of the surface plasmon nano-ridge mode and the nano-strip surface plasmon mode. Although the trade-off between the confinement and the propagation length always holds, we find the properties of the nano-ridge surface plasmon mode are quite different from the nano-strip mode. The nano-ridge surface plasmon waveguide can provide a more strongly confined mode within the surrounding dielectric. This mode property enables potentially a variety of integrated sensor applications in the infra-red wavelength regime.

8096-93, Poster Session

**Mapping localized plasmon modes in metal nanoparticles via electron energy loss spectroscopy and cathodoluminescence**

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Localized surface plasmon (SP) modes can be tailored by controlling the size and morphology of metal nanoparticles. This finds exciting applications in photonic devices and optical sensing. The development of these applications requires knowledge of the spatial variation of the near fields associated to SPs.

In this work, the rich structure of SP modes localized in individual noble-metal nanoparticles prepared via lithography or colloidal chemistry is explored by optical spectroscopy [1], spatially resolved electron energy-loss spectroscopy (EELS) performed in a scanning transmission electron microscope (STEM) [2,3], and by electron beam-induced radiation emission performed in a scanning electron microscope (SEM) [4]. Spectral features and spatially-resolved maps of SP modes collected for individual nanoparticles of different morphologies (rods, decahedra, prisms, and split-ring resonators) are shown to be in good agreement.
with theoretical STEM-EELS and optical excitation calculations obtained using the boundary element method based upon rigorous solution of Maxwell’s equations [5]. Our results show the unmatched capability of electron beams for spectrally and spatially probing SP modes in nanoparticles with a wide variety of morphologies.


8096-94, Poster Session

Role of silver nanoparticles in the laser-induced reversible colour-marking and controlled crystallization of mesoporous titania films

N. Crespo-Monteiro, Univ. Claude Bernard Lyon 1 (France) and Lab. Hubert Curien (France); N. Destouches-Castagna, Univ. Claude Bernard Lyon 1 (France) and Lab. Hubert Curien (France) and Univ. Jean Monnet (France); L. Bois, F. Chassagneux, Univ. Claude Bernard Lyon 1 (France); E. Gamet, Lab. Hubert Curien (France)

Due to their surface plasmon resonance silver nanoparticles are known to absorb visible light and give glasses various colors. Grown in mesoporous titania films, they give the material a photochromic behaviour that can be used to produce rewritable data carriers. 1 On the one hand, UV light forms silver nanoparticles thanks to the photo-induced generation of electrons by titania matrix. On the other hand, visible light oxidizes the silver nanoparticles via the photoexcitation of electrons on Ag and their stabilization by oxygen molecules. The well controlled porosity of the mesoporous films allows to tune the nanoparticles size and to obtain, under UV illumination, homogenous distributions of small nanoparticles embedded within the titania matrix, which color the films. As all nanoparticles absorb light similarly, the film can then be completely bleached under exposure to a visible laser beam whose wavelength falls in the SPR band of the particles. Therefore, CW UV and visible focused-laser radiations, respectively, can repeatedly print and completely erase colored micropatterns within TiO2/Ag films. The paper shows patterns printed under different conditions, deals with the reproducibility of the process and the inscription stability, and explains the nanoscale mechanisms, including silver migration during exposures, leading to the reversible color changes on the basis of TEM, SEM, absorption spectroscopy and Raman micro-spectroscopy characterizations. The paper also evidences that CW laser illuminations at higher intensity locally crystallize the titania matrix and investigates the influence of the absorption-induced heating around nanoparticles.


8096-95, Poster Session

Three-dimensionally arranged metal-nanoparticles based on phase separation of block-copolymer

H. Yabu, T. Higuchi, M. Shimomura, Tohoku Univ. (Japan)

Metal-dielectric hybrid nanostructures are received great interests due to their potentials for novel photonic materials including left-handed metamaterials. Recently, we found a simple method for preparing block-copolymer and polymer blend particles by evaporation of good solvent from their solution containing poor solvent (Self-ORGanized Precipitation (SOPR) method). Moreover, lamellae and other phase-separation structures are formed in block-copolymer nanoparticles. In this paper, we show the preparation of nano-structured metal-polymer hybrid particles by combination of the SOPR method and electroless plating. Their optical properties will be discussed.

Metal-dielectric hybrid nanostructures are received great interests due to their potentials for novel photonic materials including left-handed metamaterials. However, few effort has been done for developing nanoparticles having well-controlled metal-dielectric hybrid nanostructures. Recently, we found a simple method for preparing block-copolymer and polymer blend particles by evaporation of good solvent from their solution containing poor solvent (Self-ORGanized Precipitation (SOPR) method). Moreover, lamellae and other phase-separation structures are formed in block-copolymer nanoparticles. In this paper, nanoparticles of metals stabilized with block-copolymer micelles are also embedded in the phase-separated block-copolymer nanoparticles. Au nanoparticles were prepared in the block-copolymer micelles of poly(styrene-block-2-vinylpyridine) (PS-b-P2VP), PS-b-P2VP micelles were formed in toluene, and then, Au ions are complexed with pyridine moieties of PS-b-P2VP. After reduction of Au ion to Au, Au nanoparticles embedded in PS-b-P2VP micelles (AuNP@PS-b-P2VP) were prepared. The tetrahydrofran (THF) solution of AuNP@PS-b-P2VP was mixed with THF solution of poly(styrene-block-isoprene) (PS-b-PI), water was added into the mixed solution. After evaporation of the THF, the polymer-metal composite particles were prepared. Their internal structures were observed by using a transmission electron microscope (TEM), the particles with phase separation structures were formed. Furthermore, Au nanoparticles were included into the phase-separated particles. Their optical properties will be discussed.

8096-96, Poster Session

Experimental demonstration of long range surface plasmon devices based on metallic subwavelength gratings

Z. Wu, Q. Zhan, Univ. of Dayton (United States)

The electron density oscillations along metallic surfaces, or on metallic films can cause electromagnetic surface waves propagation, which is known as surface plasmon polaritons (SPPs). When the incident light couples into SPPs, a sharp decrease in reflectivity of the incident light will occur. This sharp decrease in reflectivity is known as surface plasmon resonance (SPR). Devices such as electro-optic (EO) modulators, spectral notch filters, and refractive index and biochemical sensors have been designed using attenuated total reflection type arrangement based on SPR. The performance of the SPR in these applications is largely determined by the width as well as the depth of the dip in the reflectance curve. Recently, long range surface plasmon (LRSP) device design that replaces the metallic thin film with a metallic subwavelength grating to support the propagation of LRSP and offer much narrower SPR has been proposed and studied. In this paper, we experimentally demonstrate the SPR of LRSP propagating along metallic gratings is indeed narrower than that propagating along metallic films. An ultra-high resolution rotational stage with a resolution of 5.5x10^-5 rad is used to resolve the ultra-narrow SPR curves.

The experiment measurement of the SPR curves of LRSP devices with a gold film and a gold grating are shown, which clearly demonstrates that the device with a gold grating yields a much narrower SPR curve. The experiment result confirms our numerical prediction that LRSP devices with metal gratings give better device performance than those with metal films.

8096-97, Poster Session

A plasmonic phase plate using nanoslits

E. H. Khoo, A*STAR Institute of High Performance Computing (Singapore); K. Crozier, Harvard Univ. (United States)

Today’s demand for sensing and imaging application are greatly satisfied by nano-plasmonics devices. One interesting property of plasmonics is their polarization sensitivity in nanoslits. Lightwave with polarization
perpendicular to the nanoslit is transmitted with amplitude greater than unity. This is termed as “extraordinary optical transmission” [1]. When the polarization is parallel to the nanoslit, no light is transmitted. The phase of lightwave transmitting through the nanoslit can be altered. It is done by altering the geometrical dimension and/or filling the nanoslit with high index materials.

We propose a phase plate using nanoslits. The nanoslits are placed in perpendicular on a gold film with thickness 200 nm. Incident lightwave with linear polarization 45 degree from x and y axis are transmitted through the corresponding nanoslots Ny and Nx. The nanoslit, Nx is altered to have phase delay for electric field polarization in y direction (Ey).

Nanoslit Nx is filled up with SiO2 so as to create a 0.5 pi phase delay. It is observed that the transmitted amplitude of Ey through Nx is twice of Ex through Ny. Hence to equalize the amplitude, two Ny nanoslits are required.

The field distribution amplitude is obtained by using FDTD with Lorentz-Drude model of gold film. Hence a linear polarization lightwaves at 45 degree from x and y axis is converted to a right-hand circular (RHC) polarization. If RHC polarized light is incidence onto the phase plate, then linear polarized light at 45 degree from x and y axis is obtained.

8096-98, Poster Session
Distance-dependent fluorescence intensity on PMMA structures on a metallic film
Y. Hung, National Sun Yat-sen Univ. (Taiwan); J. Tai, National Sun Yat-Sen Univ. (Taiwan) and Academia Sinica (Taiwan); C. Yuan, M. Shih, J. Tang, Academia Sinica (Taiwan)

Fluorescence intensity on PMMA gratings and plain PMMA mesa on Au film was investigated. The intact Au film thickness is 50nm on a cover glass and PMMA thickness on top of Au ranges from 50nm to 320nm. A layer of fluorophore material was spun on top of PMMA grating structures which are patterned by using E-beam lithography system. It is found that the fluorescence intensity changes rapidly by varying the PMMA thickness. The fluorescence intensity performs quite the opposite on PMMA grating area and plain PMMA mesa. Both are on Au film. Detailed surface plasmon mode calculations on the different PMMA thickness will be performed and analyzed. The lifetime of fluorophore material on the PMMA mesa and PMMA grating structures has been measured. This is to distinguish how the optical mode distribution of the pumping light effects the fluorescence intensity and how the different dielectric environment (optical mode density) affects the emission cycles which result in the emission intensity difference. Spatially-precise lifetime measurement and fluorescence intensity on grating valley and hill are performed by using a confocal microscope. The fluorescence emission shows different intensity performance on grating valley and hill when different PMMA thickness is coated. The measurement and observation is quite different from what people think about the quenching effect on a direct metal film. The optical field distribution will be analyzed by simulations.

8096-99, Poster Session
Localized surface plasmon lithography for Nanopatterning fabrication
X. Dong, Y. Zhang, Institute of Optics and Electronics (China); J. Du, Sichuan Univ. (China); L. Shi, C. Du, Institute of Optics and Electronics (China); F. Gao, Sichuan Univ. (China)

A method is reported for manufacturing nanostructures by employing localized surface plasmon (LSP) lithography. At the first, the mechanism for realizing LSP lithography by using different kind of masks for exciting LSPs and accumulating a large amount of localized energy from the incident light field are described, where the masks can be selected with formals of nano-tip array, nano-pattern with the fine tapers and a structure formed by a soft mould on a thin metal film; then, the masks as the important part for fulfilling the nanolithography are characterized in design and fabrication under the available lab environment; finally, the typical experiments by using the mask formed of a soft mould on a thin metal film are carried out for fabricating nanopatterns with the minimum feature size from 100 nm – 30 nm in both regular and arbitrary arrangement and the dependence of the resolution (pattern periodicity) and stability of lithography on the geometrical parameters of the soft mold, such as ridge width, mold periodicity, ridge depth and slope, have been systematically studied and analyzed by Finite-Difference Time-Domain. In conclusion, the optimal minimum feature size can reach 17 nm by the proposed method.

8096-100, Poster Session
Measurement of spontaneous emission enhancement in subwavelength metallo-dielectric lasers using phase-resolved spectroscopy
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Subwavelength scale laser devices are of great interest as potential components for integrated photonic circuits. We previously reported room temperature lasing operation of subwavelength scale metallo-dielectric cavity lasers with InGaAsP MQW in the 1.5 µm region [1]. In this paper, we investigate the Purcell effect, which describes the enhancement of spontaneous emission (SE) in a small volume and/or highly resonant cavity. Using phase-resolved spectroscopy, we measure carrier lifetimes of bulk InGaAsP MQW wafer as well as optically pumped metallo-dielectric lasers with cavity size ranging from 300nm to 1µm. After extracting the SE lifetime from carrier lifetime through numerical models, we are able to obtain the SE enhancement rate of various sizes of lasers with respect to their bulk counterpart. Through rate equation modeling and fitting to experimental light-light (LL) curves, we study the SE enhancement’s effect in lasing characteristics, especially in the sub-threshold region. In addition, by using cavity quantum electrodynamics (CQED) theory, we investigate SE enhancement’s dependence on various parameters including homogeneous broadening linewidth of emitters, density of emitter states, quality factor Q and effective mode volume Veff. With this knowledge, we can further optimize the design of our laser cavity structure. Due to shortened SE lifetime and potentially low lasing thresholds, these lasers can find applications in high-speed optical communications, information processing, and on-chip optical interconnects.


8096-101, Poster Session
Scattering readout at detuned surface plasmon resonance of gold nanorods for continuous-wave multi-dimensional optical storage
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Exciting progress has been made in the field of gold-nanorod based five-dimensional optical storage, utilizing surface Plasmon resonance (SPR) mediated photothermal melting and two-photon luminescence (TPL) from gold nanorods as the recording and read-out mechanisms [1]. However the requirement of femtosecond pulses limits the applicability to consumer electronics. To address this, we propose the use of a continuous wave (CW) readout mechanism. CW readout is however hampered by exponential signal extinction in multi-layer setting.
For multilayered gold nanorod films, readout is achieved by strong scattering under SPR condition. Due to the magnitude of this scattering decreasing away from the peak SPR wavelength, deluting the readout wavelength can reduce the level of signal extinction through the layers, yielding more efficient readout at deeper layers in the sample matrix. Detuning from SPR however results in reduced scattering from the nanorods. We show that balancing these two factors results in an optimal readout wavelength that is specific to each layer.

Continuous wave laser operation provides a viable alternative to TPL based readout, and should be studied rigorously for its successful device application. We have already demonstrated that the continuous wave recording is possible [1]. Here, we demonstrate the viability CW readout in a 16-layer gold nanorod sample matrix.


8096-102, Poster Session

Hybrid photonic-plasmonic crystal nanocavities

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Optical cavities with both high quality factor Q and small modal volume Vm are of great importance in the enhancement of light-matter interaction. Although conventional dielectric cavities can be designed to have ultrahigh Q factors, such as microspheres, microtoroids and photonic crystal cavities, the physical sizes of these cavities cannot be smaller than the wavelength scale in order to confine photon effectively. Therefore, the mode volumes for these dielectric cavities are diffraction limited. Surface plasmon polaritons (SPPs) provide a new way to confine electromagnetic waves beyond the diffraction limit. The unique dispersion relation of SPPs supports high wave vectors with ultrashort wavelengths, resulting in different kinds of plasmonic nanocavities with subwavelength mode volumes and metal-loss-limited Q factors. Here, we propose a novel hybrid photonic-plasmonic crystal nanocavity consisting of photonic crystal structures coupled to a metal surface with a nanoscale air gap in between. Based on the periodic variation in the effective index of hybrid mode, a unique hybrid photonic-plasmonic crystal with a transverse magnetic (TM) band gap is formed at the wavelength of 1,550 nm. One-dimensional hybrid crystal nanocavities having parabolic variation of lattice constant are then designed with high quality factor Qtot of 330 and deep subwavelength mode volume Vm of 0.0056 λ3. The calculated Purcell factor is as high as 4,560 with an extremely large QtoV/ Vm of 60,000 ~3. This new type of high-Q/Vm broadband nanocavity will be of great importance in the enhancement of light-matter interactions, such as cavity QED, nonlinear optics, low-threshold nanoscale lasers, and optomechanics.

8096-103, Poster Session

Optimizing of the surface plasmon induced strengthening of PV efficiency

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The experimentally observed significant increase of photo-voltaic efficiency due to surface plasmons mediating the energy transfer in solar cells with metallic nanoparticles deposited on a photo-active layer of semiconductor (i.e. Si or III-V type and also of conjugated organic polymer semiconductor) is explained as the result of strengthening of inter-band transition probability induced by electrons coupling to plasmons in the near-field regime. We identify and analyze two competitive mechanisms which contribute to the overall PV efficiency increase which can be optimized with respect to the dimension of metallic nano-components. The first effect resolves itself to strengthening of the dipole plasmon oscillation amplitude with the nanoparticle radius growth, which favors larger nanoparticles sizes in regard to PV efficiency increase. The second one, oppositely, favors lower radii of particles, as it is related to partial departure from the momentum conservation principle in a translation non-invariant nano-system with coupling in the near-field. The atomic scale limit of the latter effect gives pronounced enhancement of the interband transition probability due to allowing all indirect (with nonconserved momentum) transitions [1]. The effect is, however, strongly reduced with the growth of metallic nano-particle radius. Particularities of this dependence are analyzed, including various types of nanoparticles depositions on the photo-active layer. The other effect of plasmon radiation efficiency size dependence is analyzed also for larger metallic nanospheres (with radii beyond 50 nm for Au and Ag nanoparticles) when saturation of Lorentz friction is predicted and experimentally confirmed.


8096-104, Poster Session

Au/TiO2 and Ag/TiO2 nanocomposites with high concentrated “hot spots” under near IR femtosecond pulsed excitation

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Luminescence of gold and silver nanoparticles photodeposited on titanium dioxide mesoporous films was studied by multi-photon and near-field aperturerless microscopy. Luminescence was registered under the multi-photon excitation by femtosecond pulses of Ti:sapphire laser. It was observed that Me/TiO2 (Me=Au, Ag) nanocomposites have high concentration (~10^5) of bright luminescence spots (“hot spots”) which reveal stability to degradation under long illumination. Moreover the most intense “hot spots” have luminescence enhancement of order of 10^4. Application of Me/TiO2 mesoporous films for Raman scattering spectroscopy was demonstrated for Rhodamine B molecules. Me nanoparticles configuration of “hot spot” was established by polarized multi-photon experiments and FDTD analysis. “Hot spots” luminescence enhancement analyzed by FDTD in terms of Me nanoparticles near-field enhancement coefficient at wavelength of excitation. It was shown that the highest enhancement coefficients are in near IR wavelengths for Me/ TiO2 nanocomposites. Thus Me/TiO2 nanocomposites can be effectively used for near IR single molecule spectroscopy and biological objects visualization. Additionally various Me/substrate (Me=Au, Ag; substrate permittivity range: from 1 to 10) systems were analysed by FDTD to get the “best” substrate in terms of near-field enhancement coefficient for each wavelength of excitation.

8096-105, Poster Session

Silver core-pectin shell nanoparticles on metal enhanced singlet oxygen generation

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The photosensitized production of singlet oxygen can induce cell death, and therefore be explored in several areas, such as Photodynamic Therapy (PDT). PDT is a photochemical process that has been used on cancer treatment, photorejuvenation, wrinkles, discoloration, fungal and bacterial infections. Photosensitizer molecules, as Riboflavin, can activate singlet oxygen generation by a triplet interaction with ground-state molecular oxygen. We demonstrate the potential application of
new monodispersive core-shell (silver core-pectin shell) nanoparticles on PDT. Here, localized Plasmon Resonance was explored improving PDT photosensitizer excitation process. Metal-enhanced singlet oxygen generation in Riboflavin-Silver colloid was observed. The developed silver-Pectin nanoparticles consist of 13 nm silver nanospheres involved by a 11 nm thicker monolayer of Pectin. Pectin, a complex carbohydrate found in plants primary cell walls, isolates the Silver nanosphere increasing the biocompatibility of the colloid. The nanoparticle-photosensitizer distance is an important parameter for the enhancement of singlet oxygen production. Therefore, the Riboflavin interaction with silver nanospheres without Pectin shell was also analyzed. Both Riboflavin photosensitizer and silver localized Plasmon can be excited with a blue light. Blue LEDs were used to excite the colloid with Riboflavin. The singlet oxygen fluorescent sensor Green Reagent was used to monitor the singlet oxygen production in the colloid. We report a 1.8-fold increase in the Riboflavin emission and a 1.7-fold enhancement in singlet oxygen production.

8096-108, Poster Session

Complete three-dimensional optical characterization of single gold nanorods
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We will show a powerful technique to fully characterize individual gold nanorods by using confocal microscopy in combination with higher order laser modes. We obtain topological information far beyond the optical diffraction limit. This achievement extends and completes what was previously shown using a 2D system. We demonstrate that it is possible to determine the orientation of gold nanorods by looking at their elastic and inelastic scattering patterns. This extends the results achieved already in [1] with high precision (i.e. less than 1 degree for the in plane and about 5 degree for the out of plane angle) to a 3D system. On the other hand, we clearly show that this improved technique permits to detect local changes of the refractive index of the dielectric medium surrounding the particles. In order to extend the results already shown in [2] we applied this technique to a 3D system. More over the elastic scattering pattern is strongly dependent on the phase relation of the scattered and reflected light, while the inelastic scattering pattern does not depend on this phase relation. Thus, by measuring in-situ the elastic and inelastic scattering patterns, it is possible to gain additional information while measuring the 3D orientation. For example, when the distance of a particle to an interface changes, the phase relation changes and therefore the elastic scattering pattern is strongly influenced. This phase relationship can be also influenced by the aspect ratio of the particle. Thus by comparing elastic and inelastic scattering, one can determine the distance from the interface and the aspect ratio of a single gold nanorod.


8096-109, Poster Session

Controlling inter-nanoparticle coupling: Highly uniform SERS substrates of plasmonic colloids
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Metallic nanoparticles and especially gold, are in the focus of interest because of their highly depend electric and optical properties on the specific particle size, shape, and surrounding environment. Therefore, they are ideal candidates for their potential use in microelectronic, optical, and biomedical applications. Thus, a big effort has been put in developing new methods which allow a fine control over the particle shape and size. These achievements allow us to fine tune the materials properties in order to use them for a desired application. However, the lack of capability to form organized structures is still a very important challenge in order to use these materials in many applications. In this work we report a novel method to structure, in a macroscale range, arrays of organized gold colloids into 1 and 2D linear parallel arrays which are highly uniform substrates for Surface Enhanced Raman Scattering (SERS). These structures were fabricated through self-assembly of gold nanoparticles upon solution-drying in a periodic confining structure. The technique leads to uniform, parallel linear nanoparticle arrays with the precise arrangement defined through the dimensions of the particles and the grooves. Moreover, the good reproducibility of these structures among big areas, make them perfect candidates as ultrasensitive substrates for SERS due to the controlled formation of arrays of hot spots. Which provide high and uniform SERS enhancement over extended areas. Furthermore, this method, is completely lithography-free so, low cost processing and allows tuneability of the width and spacing of the channels and consequently of the particle patterns between fractions of a micron and many micrometers. Characterization was done by means of transmission electron microscopy (TEM), scanning electron microscopy (SEM), atomic force microscopy (AFM), UV-vis, dark field, and SERS spectroscopy.

8096-111, Poster Session

Selective plasmonic excitation of rotation-symmetric nanostructures

The plasmonic properties of nanostructures depend strongly on their size, shape and environment [1]. We investigated the plasmonic excitation of rotation-symmetric gold nano-post arrays fabricated on a Si wafer under different laser wavelengths and polarization conditions. Confocal optical microscopy and spectroscopy were performed by confocal optical microscopes using either parabolic mirror or an air-objective-lens for laser focusing and signal collection. Instead of using linearly polarized Gaussian beams, we used cylindrical vector beams to distinguish between different plasmonic modes. Our experiments demonstrated that radially polarized beam focusing by parabolic mirror excited the plasmonic modes along the z-direction of the nano-posts more effectively than by the objective-lens due to a dominant out-of-the-plane electric field. Axially polarized beam focusing by either parabolic mirror or objective lens was effective to excite the circular plasmonic modes of the rotation-symmetric nanostructures. Spectroscopic investigations revealed that the two-photon photoluminescence intensity was an excellent indicator of the resonance excitation of the nanostructures [2]. In addition, a short excitation wavelength such as 514 nm was found to selectively excite the plasmonic modes along the circular rim of the posts, whilst the 633 nm excitation was more effective to excite the plasmonic modes along the z-direction of the posts. The capability of selective excitation of different plasmonic modes is important for optical sensor design based on metallic nanostructures.


8096-113, Poster Session

Spectral dependence of the amplification factor in surface enhanced Raman scattering
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Surface Enhanced Raman Scattering (SERS) is characterized by a strong signal amplification (up to 10^8-10^10) when both the excitation and the Raman photons frequencies match the localized plasmon resonances (LSPR) of the nanoparticles (NPs). In order to understand if the effective LSPR profile refers to the bare NPs or to the resonance of NPs “dressed” with the probe molecules, we perform multilayer absorption (514nm, 633nm and 785nm) SERS experiments using evaporate gold NPs as SERS-active substrate on which we deposited Methylene Blue molecules (MB) that yields a resonance energy red-shift and a broadening of LSPR profile.

The SERS spectra at the investigated excitation wavelengths display a different intensity ratio of the characteristic MB band (peaks at 450 cm-1 and 1620 cm-1) with respect to the Raman counterpart. While at 515nm the 1620 cm-1 mode is more enhanced with respect to the peak at 450 cm-1, at 785 nm the opposite is observed. At 633 nm the two modes experience the same enhancement factor. This behavior is compatible with the hypothesis that the re-radiation enhancement factor is proportional to the LSPR of “dressed” NPs.

The results are, also, compared with experiments carried out on Mercaptopyridine and L-Tyrosine molecules that not affect the LSPR profile.

8096-114, Poster Session
Laser induced photothermal aggregation of gold nanorods for SERS detection of biomolecules in liquid environment
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Surface-Enhanced Raman Scattering (SERS) from isolated metal nanoparticles is usually much weaker compared to what is observed on aggregates due to the strong field enhancement occurring in the gap regions (hot spots) between adjacent nanoparticles [1]. The controlled creation of highly efficient hot spots in liquid (the natural habitat of biomolecules) is a challenge in which optical forces can play an important role by promoting the aggregation of metal nanoparticles in the focus of a laser beam (optical trapping) or their accumulation on a surface (by radiation pressure). Here we show that laser induced aggregation of gold nanorods in a buffered solution of Bovine Serum Albumin (BSA) leads to the formation of SERS-active agglomerates. Indeed, due to the blue shifted excitation (632.8 nm line of a He-Ne laser) with respect to their localized surface plasmon resonance (LSPR = 687 nm [2]) the gold nanorods are pushed by the radiation forces. Approaching the laser focus towards the bottom of the glass cell containing the solution, the optical forces and the involved thermal effects, make to aggregate such rods into highly efficient “hot spots” regions. This occurrence enables us to observe a strong SERS signal of BSA molecules staying in their proximity, with an enhancement factor of 10^5 allowing the detection of protein at concentrations as low as 10-7 M in its natural habitat.

References

8096-115, Poster Session
Optical properties of metal coated nanoscrew Si
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Optical properties of random nanoscale features provide applications such as light scattering in photovoltaics or surface enhanced Raman scattering (SERS) substrates for biosensing. Randomized nanostructures reduces the specular reflectance and in turn increases diffusive reflectance. Nanowire growth, chemical etching or RIE based random etch has been demonstrated to form such surfaces. Previously demonstrated work have produced nanoscale features that resemble nanowhiskers, porous surface, cones or straight pillars.

In this paper, a unique nanoscrew Si structure is presented. The nanoscrew surface is made by anodized aluminum oxide (AAO) mask formation followed by extended deep reactive ionic etching (DRIE). Dense random zig-zag pillar structures that represent screw shapes are formed, with 1 um in height and the bottom base width ranging from 100 nm to 250 nm. The tip of the nanoscrews have radius of curvature even lower than 10 nm. The apparent naked-eye view of the nanoscrew surface, which only consists of nanopatterned N-type single crystalline Si is diffusively green. The optical properties of nanoscrew Si with and without metal deposition is presented as discussion in applications for SERS.

8096-117, Poster Session
Reshaping the fluorescence spectrum with random metal dielectric films
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The effects of metallic nanostructures on the emission of fluorophores result in a number of important effects, including increased photostability, fluorescence resonance energy transfer and directional emission. The complexity of fluorophore-metal interactions is influenced by the structure of the metal nanostructures, which governs their optical response. In disordered metallic nanostructures illuminated at visible and near-infrared frequencies, the optical response can involve localized and propagating surface plasmon modes which interact individually with the fluorophores. Specifically, semicontinuous metal films are characterized by broad absorption across the visible and near-infrared frequencies. This absorption spectrum can be controllably altered by effecting structural changes via a process called photomodification, wherein sufficiently intense coherent light at a specific frequency and polarization can be used to induce “holes” in the absorption spectrum. This tailoring of the optical response can in turn be used to alter the fluorescence spectrum in a controllable manner, with applications including bio-markers and sensing. In this study, semicontinuous films were photomodified to alter the absorption spectrum. Consequently, changes in the peak position and intensity were observed in the resulting emission from fluorophores placed in proximity to the metal films. The changes were sensitive to the polarization, incident angle and excitation frequency. Directionality was also observed in the fluorescent emission, indicative of surface plasmon coupled emission due to the effective dielectric response of the films. Theoretical calculations based on the finite element frequency domain method show good correspondence with experimental data and provide a direction toward optimizing the photomodification process to effect sensitive changes to the fluorescence spectrum.

8096-118, Poster Session
Subwavelength directional SPP couplers
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Plasmonic gap-waveguides open up new dimensions for the manipulation of light on a subwavelength scale. Based on recent progress in fabrication technologies, the interest in highly integrated SPP components has grown substantially. A lot of attention has been attracted by subwavelength directional SPP couplers and waveguide loaded optical antennas; the first of which allow for connecting individual SPP transmission lines, the latter of which are used for probing sub wavelength circuitry from the far field.

Here we report on experiments, in which we investigated directional coupling between highly integrated adjacent SPP gap waveguides (~80nm gap width, ~15µm long, ~130nm pitch), in a broad wavelength range. Gap-waveguides are well known to allow for a further miniaturization compared to SPP stripe waveguides, due to their higher field confinement. Waveguides and connected plasmonic antennas were etched into plane silver films (~100 nm thickness) on a silica substrate using focused ion beam milling (FIB). For exciting the SPP waveguide, we optimized a plasmonic antenna for the NIR wavelength range of 1400 nm ≤ λ ≤ 1700 nm, where losses are expected to be small.

In the presentation, we compare experimentally measured wavelength dependent coupling parameters with those, obtained from rigorous finite element method (FEM) and finite difference time domain (FDTD) calculations. We demonstrate that the concept of directional couplers, known from integrated optics, can be transferred to the nanoscale, thus enabling future nanoplasmonic circuitry. At the same time control of plasmonic coupling is a first step towards subwavelength discrete diffraction in larger arrays.

8096-119, Poster Session

Cooperative infrared to visible upconversion and visible to near-infrared quantum cutting in Tb and Yb co-doped glass containing Ag nanoparticles

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Tb, Yb, and Ag co-doped glass nano-composites were synthesized in a glass matrix Li2O-LaF3-A12O3-SiO2 (LLAS) by a melt-quench technique. Ag nanoparticles (NPs) were formed in the glass matrix and confirmed by optical absorption. Plasmon enhanced luminescence was observed. Cooperative infrared to visible upconversion and visible to near-infrared quantum cutting were studied for glass samples with different thermal annealing times. Because the Yb3+ emission at 940 - 1020 nm is matched well with the band gap of crystalline Si, the phosphors studied using focused ion beam milling (FIB). For exciting the SPP waveguide, we optimized a plasmonic antenna for the NIR wavelength range of 1400 nm ≤ λ ≤ 1700 nm, where losses are expected to be small.

8096-120, Poster Session

Plasmon-based light enhancement from a hybrid copper-gold planar structure

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For Raman and fluorescence spectroscopy, the ability to fabricate plasmonic nanostructures using readily available materials and processes offers remarkable advantage in the development of methods to characterize trace amounts of physical, chemical, and biological substances. We report a novel configuration and an optical characterization of a copper-gold planar structure resulting in strong plasmonic enhancement of the electromagnetic field in the red region of the spectrum. The structure consists of aggregates of gold nanospheres (20 +/- 2) nm in diameter (dropped and dried from a colloidal solution) on a thin continuous copper film (50 +/- 20) nm thick (deposited on a silicon substrate using sputter deposition). We observed enhanced plasmon resonances with a peak at 665 nm and FWHM of 150 nm, measured from a light scattered from the structure using a dark-field reflection-mode microspectroscopic. We attribute the strong field enhancement to the coupling of interparticle plasmon resonances from gold nanospheres to the surface plasmons induced in the copper film. Additionally, the high reflectivity of the copper layer reflects the portion of light that would otherwise be transmitted, thus increasing the collection efficiency of the scattered light. We achieved the homogeneity and planarity of the copper-gold structure through the electrostatic attraction between the negative surface charge of gold nanospheres and a lattice of positive ions of copper oxide, formed by ionic bonds during the oxidation of copper to air. Such homogeneity and planarity cannot be achieved using gold and silver films that do not possess the lattice of ions and where the deposited nanospheres move towards the edge of the drop. We foresee that when integrated with easily available lasers emitting red wavelengths, the proposed copper-based nanostructure is a cost-effective step towards the development of lab-on-chips with applicability in public safety, global health-care, homeland security and defense.

8096-121, Poster Session

Emission control with metallic hole arrays

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Adding holes in a periodic arrangement to metallic thin films greatly affects the optical properties of the metal film. The compound structure can exert a large influence on electromagnetic fields that interact with the hole array. Many parameters affect the actual response of the hole array, such as the periodicity, the size of the holes and their shape. We will show that, for a fixed periodicity and hole area, a change in aspect ratio of rectangular holes over a narrow range is sufficient to significantly alter the lifetime and far-field radiation patterns of a single emitter, e.g., a molecule, embedded in the central hole of a hole array. Due to the complexity of the geometry, analytical results are hard - if not impossible - to obtain. Therefore, an FDTD simulation scheme is used to obtain the evolution in time of the radiated fields by a single dipole, which models the emitter. By recording the electric field and current at the location of the dipole, the relative local density of states can be obtained after Fourier-transforming the fields. From the spatially Fourier-transformed time-harmonic near fields, far-field angular emission spectra are calculated, showing a strong dependence on the aspect ratio of the holes: the directionality of the emission is radically altered with increasing aspect ratio.

8096-122, Poster Session

Growth of ultra thin silver films monitored by in situ spectroscopic ellipsometry during high power impulse magnetron sputtering

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High precision in both film thickness and optical constant of ultra thin Ag films is crucial for their application in optical coatings and plasmonic metamaterials. For such applications, very thin layers of Ag must be used to minimize optical losses; however, it is difficult to make continuous Ag films thinner than 20 nm. Deposition of noble oxides follows the Volmer-Weber island growth process with island formation.
occurring at the initial stages followed by nucleation and coalescence. Below the coalescence threshold the optical dispersion does not follow that of bulk Ag, with both the index of refraction and extinction coefficient deviated in the visible wavelength region. Since island formation results from an imbalance in cohesive energies between adatoms within the film and atoms with the substrate, one way to decrease the adatom-adatom interaction is to use highly energetic deposition techniques such as high power impulse magnetron sputtering (HiPIMS). Coalescence thresholds of thin Ag films grown by DC magnetron sputtering and HiPIMS were determined using in situ spectroscopic ellipsometry (SE) during growth. With SE, the coalescence threshold was reached when the optical dispersion of the film matched that of the bulk Ag. The high degree of ionization and low deposition rate offered by HiPIMS resulted in increased film densities, refractive indices, lower coalescence thresholds and smoother film surfaces compared to those grown with DC magnetron sputtering.

8096-123, Poster Session
Subradiant plasmonic fano resonances For ultrasensitive biomolecular detection
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We introduce an ultrasensitive label free detection technique based on asymmetric Fano resonances in plasmonic band-gap devices with far reaching implications for real time biosensing and point-of-care diagnostics. By exploiting high quality factor (Qsolution~200) sub-radiant dark modes, we experimentally demonstrate record high figures of merits (FOM~162) for intrinsic detection limits. Our experimental record high sensitivities are attributed to the nearly complete suppression of the radiative losses that are made possible by the high structural quality of the fabricated devices as well as the sub-radiant nature of the resonances. To fabricate high optical quality sensors, we introduce a novel high-throughput nanofabrication technique with extremely uniform and precisely controlled nano-features. The demonstrated label free sensing platform offers unique opportunities for point-of-care diagnostics in resource poor settings by eliminating the need for labeling as well as mechanical and light isolation.

8096-124, Poster Session
High tunability of the optical response with a metal-multiferroic composite
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Plasmon resonances in metal nanostructures depend strongly on the size, shape, composition, orientation and dielectric environment of the metal nanostructure. However, most metal nanostructures have been restricted to passive templates, with little dynamic tunability in the optical response. In the current experiment study, we demonstrate active control of the plasmonic response from Au nanostructures by the use of a novel multiferroic substrate -LuFe2O4 (LFO) - to tune the surface enhanced Raman scattering (SERS) response in real time. From both experiments and numerical simulations based on the finite-difference time-domain method, a threshold field is observed, above which the optical response of the metal nanostructure can be strongly altered through changes in the dielectric properties of LFO. This offers the potential of optimizing the SERS detection sensitivity in real-time as well as the unique functionality of detecting multiple species of Raman active molecules with the same template. We also observe evidence of interaction between the plasmon modes and polaron excitations that are inherent in multiferroic LFO. Our results indicate that the plasmons have a strong screening effect on the polaron which can be mediated by altering the dielectric response of LFO via external applied fields.

8096-125, Poster Session
Tunability of plasmonic fano resonances in nanoparticle clusters
H. Sobhani, P. J. Nordlander, Rice Univ. (United States)

Fano resonances in strongly coupled metallic nanostructures such as Heterodimers,[1] Ring/Deck cavities,[2] Heptamer and Octamer clusters [4] enable highly efficient LSPR sensing due to their narrow linewidths. They are also of significant importance in plasmonic waveguiding and light harvesting applications such as photodiodes. In this talk, we describe how plasmonic Fano resonances can be modeled using a combination of fully retarded electromagnetic simulation methods such as FDTD and FEM. We also discuss Fano resonance modeling using a simple intuitive harmonic oscillator model which expose the underlying physics, the interference between superpredendant and subradiant collective plasmon modes.


8096-126, Poster Session
Enhanced and suppressed transmission through metal gratings at the plasmonic band edges
M. Bloemer, U.S. Army Aviation and Missile Command (United States); D. de Ceglia, M. A. A. Vincenti, The AEgis Technologies Group, Inc. (United States); M. Scalora, U.S. Army Aviation and Missile Command (United States); N. Akozbek, The AEgis Technologies Group, Inc. (United States)

Extraordinary optical transmission through metallic gratings is mediated by Faby-Perot cavity modes inside the apertures and surface waves propagating along the grating. Anomalous features arise in the grating transmission spectrum when the optical period for the surface wave is equal to the grating pitch. The surface waves can be plasmonic in nature or due to diffracted orders propagating parallel to the surface. At optical frequencies, plasmonic effects are well separated from Wood-Rayleigh anomalies. The plasmonic band gap properties were determined with COMSOL by propagating a plasmon on a smooth Ag surface followed with a section containing a series of air gaps. The reflection spectrum for the plasmons shows a well defined frequency gap for plasmon propagation. The COMSOL simulations for light transmitted through the grating reveal anomalies in the vicinity of the plasmonic band gap. At the center frequency of the gap where surface waves are forbidden, the transmission through the grating is very low and the reflection is 98%. Standing waves are formed at the band edges and the fields become localized. At the high energy band edge the electric field localizes in the low index medium and the magnetic field in the high index medium. The
field localization reverses at the low energy band edge. As a result of the localization at the band edges, the surface plasmons couple strongly to the Fabry-Perot cavity modes at the high energy band edge leading to enhanced transmission through the grating with the opposite properties for the low energy band edge.

8096-127, Poster Session

Numerical investigation of the plasmonic properties of bare and cysteine-functionalized silver nanoparticles

M. Csete, A. Sipos, A. Szalai, E. Csapo, V. Hornok, I. Dekany, Univ. of Szeged (Hungary)

Theoretical and experimental studies were performed to develop silver nanoparticles (Ag NPs) based Localized Surface Plasmon Resonance sensor which can be used to determine the dependence of aggregation on pH and bio-molecule concentration, and to follow the aggregation kinetics based on spectral monitoring. The absorption spectra of different Ag NPs containing aqueous dispersions were numerically computed by Finite Element Method (FEM) applying the RF module of COMSOL software package, and compared to spectra determined by UV-Visible spectroscopy between 300 and 650 nm. This comparative study proved that the spectrum measured on citrate-stabilized bare Ag NPs aqueous dispersion with absorbance maximum at \( \lambda_{\text{meas}} = 385 \) nm corresponds to the characteristic surface plasmon band of spherical Ag NPs with 8.25\%/-1.5 nm diameter. The presence of aggregates in aqueous dispersions resulted in splitting on the spectrum, when the surface of the Ag NPs having a concentration of \( c_{\text{Ag}} = 2 \times 10^{-4} \) M was functionalized with L-cysteine (Cys) having a concentration of \( c_{\text{Cys}} = 5.7 \times 10^{-6} \) M. The FEM computation proved that the maximum at \( \lambda_{\text{meas}} = 390 \) nm corresponds to quadrupolar resonance, while the second maximum red-shifted to \( \lambda_{\text{meas}} = 574 \) nm and \( \lambda_{\text{meas}} = 625 \) nm originates from coupled dipolar plasmon resonances on extended aggregates at \( \text{pH}=2.98 \) and \( \text{pH}=4.92 \), respectively. The most simple aggregate-type that exhibits resonance at the measured absorbance maxima was determined by varying the number of Ag NPs, the thickness of the Cys shell, and the inter-particle distance in linear chains aligned along the E-field oscillation direction.

8096-128, Poster Session

Resonance behaviour of gold nanoparticles: coupled plasmonic modes

A. Mahdavi, Erlangen Graduate School in Advanced Optical Technologies (Germany); E. Tatartschk, Erlangen Graduate School in Advanced Optical Technologies (Germany) and Clemson Univ. (United States); E. Shamonina, Imperial College London (United Kingdom) and Erlangen Graduate School in Advanced Optical Technologies (SAOT) (Germany)

Metamaterials acquire their functionality from the structuring of the small building blocks, “artificial atoms”. Understanding the nature of the resonance behaviour of unit cells is crucial for designing a structure with desired properties. In this paper we study the resonant behaviour of a variety of metallic nanoparticles in the region of hundreds of THz, including square-cross-section nanorods, nanoparticles of L, U and O shapes, and split rings with a variable gap size.

The split ring, the most prominent subwavelength resonator, can be described as an LC circuit. However, if it is miniaturized to be as small as several hundreds of nanometers, its resonant behavior does not just simply scale with the size. The resonance frequency saturates and the field modes change significantly. The effects that need to be incorporated here are those of kinetic inductance due to the inertia of the electrons and of plasmon-polaritons at the metal/dielectric interface noticeable as the surface plasma frequency is being approached.

For a better understanding of the resonant behavior of plasmonic nanoparticles we investigated standing wave patterns of surface plasmon polaritons on nanoparticles of different shapes. Our numerical results (CST Microwave Studio) suggest that the resonant behavior of each of these particles is similar to that of periodic arrays of nanorods with specific lengths and periodicities. For the first time to our knowledge, the interaction of the gap edges of a split ring, previously described in terms of the self-capacitance, has been interpreted in terms of coupled plasmonic modes.

8096-129, Poster Session

Effective permittivity of concentrated random multiple component linear plasmonic composites

S. Wani, T. Cong, A. Sangani, R. Sureshkumar, Syracuse Univ. (United States)

Electromagnetic wave propagation in plasmonic media is of fundamental and practical interest. We present a new technique for calculating the effective medium properties of concentrated linear plasmonic composites containing multiple metallic (Ag, Au, Al and Cu) monodisperse spherical inclusions in a homogeneous absorbing matrix. The underlying physical motif was the separation of the space surrounding any inclusion into two regions, one immediately surrounding the particle with the properties of the matrix (the size of this region depends on the static structure factor) and an outer effective medium. Ensemble averaged Maxwell equations were derived for the system. Self consistent closure relations were found for the conditionally averaged fields by solving the vector Helmholtz equations for a layered sphere in an infinite matrix. In the quasi-static limit, predicted values of effective permittivity were in excellent agreement with those of Maxwell-Garnett theory. However, for large particle sizes and relatively high volumetric concentrations (~ 1%), the relationship between the concentration and the attenuation constant becomes nonlinear as evidenced by experimental measurements on Ag nanoparticle suspensions in ethylene glycol. Further, the resonance peak red shifted and broadened with increasing concentration.

8096-130, Poster Session

Broad band, tunable super-lenses in the visible region of electromagnetic spectrum with metalodielectric stacks (MDS)

N. C. Katte, J. Haus, A. M. Sarangan, J. Gao, Univ. of Dayton (United States); R. Jakubiai, Air Force Research Lab. (United States); M. Scalora, U.S. Army Aviation and Missile Command (United States)

We compare the two main designs based upon combinations of Ag/GaP and Au/GaP, and calculate the super-resolving band widths. The super-resolving bandwidth of the Ag/GaP design is (520nm-560nm), while that of the Au/GaP design is (630nm-660nm). We evaluate these two designs in their ability to resolve two 20nm wide apertures separated by a center-to-center distance of 80nm. We also compare two numerical techniques, used to study these systems, namely the transfer matrix method (TMM) and the finite element method (FEM). The TMM is simple and provides a first evaluation of the samples' expected performance. The FEM technique is numerically more demanding, but it is more robust for determining super-resolution. Finally we discuss the practical limitations of our super-resolving imaging devices in resolving objects that are much smaller than the incident wavelength.
Tunable surface plasmon polaritons in Ag composite films by adding dielectrics or semiconductors

D. Lu, J. Kan, E. E. Fullerton, Z. Liu, Univ. of California, San Diego (United States)

Surface plasmon polaritons (SPPs) in metal films concentrate electromagnetic energy into subwavelength scale in the optical regime. Its unique properties enable light guiding and manipulation at the nanoscale, sub-diffraction-limited optical imaging, highly-sensitive biomolecular detection, highly efficient semiconductor light emissions, and enhanced solar energy utilization, etc. However, all these useful applications rely on the fixed SPP properties associated with existing materials, which on the other hand limit their capabilities to specific conditions. By adding a small percentage of SiO\textsubscript{2} or Si into pure Ag films, we recently demonstrate SPP properties of metal films can be well tuned. Those composite films are characterized by an oil-immersion optical microscope to obtain their angular resolved reflection spectra in the Fourier space for different wavelengths. The resonance position and bandwidth of SPPs in the composite films can be well predicted by an adopted phenomenological model after taking into account both the volumetric average of the permittivities of the combined components and the size and interface effects. Their dispersion relations deviate from those of pure Ag films and have advantages to provide a larger SPP wave vector at longer wavelengths. This type of tunable composite films serves as a promising alternative to current metals for broader working frequencies.

Metallic nanoshells with semiconductor cores: optical characteristics modified by core medium properties

N. K. Grady, Institute of Physics (China) and Rice Univ. (United States); R. Bardhan, Rice Univ. (United States); T. A. Ali, Institute of Physics (China); H. Xu, N. J. Halas, Rice Univ. (United States)

It is well-known that the geometry of a nanoshell controls the resonance frequencies of its plasmon modes; however, the properties of the core material also strongly influence its optical properties. Here we report the synthesis of Au nanoshells with semiconductor cores of cuprous oxide (Cu2O) and examine their optical characteristics. This material system allows us to systematically examine the role of core material on nanoshell optical properties, comparing Cu2O core nanoshells (c = 7) to lower core dielectric constant SiO2 core nanoshells (c = 2) and higher dielectric constant mixed valency iron oxide nanoshells (c = 12). Increasing the core dielectric constant increases nanoparticle absorption efficiency, reduces plasmon line width, modifies plasmon energies and changes which mode is “bright.” We show that these effects arise from realignment of the cavity and sphere plasmon energies, changing the composition of the hybridized nanoshell plasmons. Modifying the core medium provides an additional means of tailoring both the near- and far-field optical properties in this unique nanoparticle system.

Engineering dispersion in omnidirectional single-layer plasmonic metamaterials at visible frequencies

S. P. Burgos, R. M. Briggs, H. A. Atwater, California Institute of Technology (United States)

It has recently been shown that an array of coupled coaxial metal-dielectric-metal plasmonic waveguides can serve as a wide-angle polarization insensitive metamaterial with a tunable effective index response at visible frequencies. The metamaterial index is set by the antisymmetric mode index of the constituent plasmonic waveguides, which ranges from positive to negative values in the visible frequency spectrum as set by the surface plasmon resonance of the metal-dielectric material combination and the thickness of the dielectric channel slot. Full-wave simulations and three-dimensional dispersion calculations are used to engineer the metamaterial dispersion. In-plane dispersion curves \(\omega(kx,ky)\) show that the metamaterial has an isotropic response in the x-y plane as characterized by a hyperbolic band diagram. By matching this with the mode index dispersion of the coupled waveguide array \(\omega(kz)\), we show that it is possible to access omnidirectional refractive indices ranging from negative \((n_{eff} = −2)\) to positive values \((n_{eff} = 1)\) in the \(\lambda = 400–600\) nm free space wavelength range. Further simulations investigate the structure’s imaging capabilities, and confirm the metamaterial omnidirectional response over the visible spectrum.

Metallic nanoshells with semiconductor cores: optical characteristics modified by core medium properties

E. Feigenbaum, S. P. Burgos, R. M. Briggs, H. A. Atwater, California Institute of Technology (United States)

In the last two decades, plasmonics has become an important tool for designing the optical properties of complex media due to its ability to manipulate nanoscale light-matter interactions. Recently, we reported a new class of artificial photonic materials, called resonant guided wave networks (RGWNS), which define new directions in optical dispersion control. In a RGWN, localized waves resonate in closed paths throughout a network of waveguides connected by power splitting junctions, enabling wave dispersion that is dependent on the waveguide network layout. Control of the local wave interference allows for “programming” the network to achieve a desired photonic function. Here we describe realizations of resonant guided wave networks: a two dimensional network of intersecting 200nm-wide plasmonic air channel waveguides in a Au matrix and a mesh of Si-based 500nm-wide photonic waveguides with careful designed power splitting elements introduced into their intersection junctions. In both cases, we couple \(\lambda = 1500\) nm light using a grating into a Si-on-insulator ridge waveguide that is in turn end-coupled to the network inputs. We will present concept designs of waveguides profiles, power splitting elements, and waveguide terminations. We also compare and verify NSOM measurements of near-field interference patterns of various network designs with analytical network representations and FDTD numerical simulations. These results highlight the viability of the RGWN concept, and once again the powerful design capabilities facilitated by plasmonics.
modes of different decay characters interact through the structural asymmetry, giving rise to multiple Fano resonances. An analogy to the atomic physics concept of electromagnetically induced transparency is drawn, where the eigenstates of the three-dimensional metamaterial system can be modeled as multiple three-level systems. A theoretical perturbative model taking into account both the plasmon hybridization and subradiant-radiant mode coupling is presented to provide further insight to the behavior of the multi-layered metamaterial. For experimental demonstration of this novel phenomenon, we propose a lift-off free fabrication technique, which utilizes dielectric membranes as the building blocks. This fabrication scheme allows simultaneous patterning of multi-layered structures that are automatically registered in the third-dimension. Excellent agreement between simulated and experimental results is observed. The proposed multi-layered metamaterial can be used to enhance non-linear processes at multiple frequency domains opening up new possibilities in optical information processing.

8096-137, Poster Session

PEDOT:PSS light sensor enhanced by localized surface plasmon of gold nanoparticles

S. Zeng, National Taiwan Univ. (Taiwan)

In this paper, we used PEDOT:PSS(Poly(3,4-ethylenedioxythiophene) poly(styrenesulfonate)) as light sensing material with enhanced sensitivity by localized surface Plasmon resonance generated by gold nanoparticles. PEDOT:PSS was spin coated on ITO glass substrate and 120 nm of Al were evaporated above the PEDOT:PSS. The electrical properties of PEDOT:PSS was then enhanced after adding the gold nanoparticles between the ITO glass substrate and the film of PEDOT:PSS. We observed that the sample with gold nanoparticles has lower resistance when the samples were lighted. Compared with no illumination, the sample resistance (with nanoparticles) decreased about 30%. This is not observed in the sample without gold nanoparticles. And when the density of the gold nanoparticles was increased, the total resistance of the sample was further decreased. When the sample with nanoparticles was illuminated at different wavelengths, the total resistance of the sample was distinct. We measured the current intensity at 0.5 voltage at various wavelengths, and we can obtain that the current intensity correlate with the surface Plasmon resonance frequency of gold nanoparticles.

8096-138, Poster Session

Size and periodicity effects of tuned extraordinary transmission through hole arrays in a Ag-Al2O3 metamaterial thin film

E. A. Ray, R. Lopez, The Univ. of North Carolina at Chapel Hill (United States)

We show the effects of hole shape, size, and periodicity variation on extraordinary transmission through a tuned metamaterial of 4 pairs of alternating layers of Ag-Al2O3 with 20 nm thicknesses. Transmission through cross or rectangular holes is shifted to the red by 200 nm from transmission through circular or square arrays with square arrays exhibiting a strong enhancement in the blue end of the spectrum. The advantage of a metamaterial over a Ag film of similar thickness is the tunability of the surface plasmons coupling k-vector. For the metamaterial, we are able to tune it to support surface plasmons from periodicities ranging from 130 nm to 215 nm, which effectively shifts the transmission peaks from the blue end of the spectrum in Ag films across the visible and into the red. With this adaptation, we can selectively tune the metamaterial or periodicity to exhibit enhanced transmission over a wide range of wavelengths in the visible. In a parallel vein, when the hole arrays are replaced by pillar arrays, we see the red shift more pronounced from the Ag film to the metamaterial in all shapes, and an asymmetric hole shape exhibits a 100 % increase in transmission from hole to pillar. For all shaped pillars, transmission is highest in the red end of the spectrum and exhibits a relatively small shift in transmission despite a 20 % increase in periodicity.

8096-139, Poster Session

Mapping near-field coupling effects in infrared gap antennas

P. Alonso-Gonzalez, P. Albella, L. Arzubiaga, M. Schnell, J. Chen, F. Huth, F. Golmar, F. Casanova, L. Hueso, CIC nanoGUNE Consolider (Spain); J. Aizpurua, Centro de Fisica de Materiales (Spain); R. Hillenbrand, CIC nanoGUNE Consolider (Spain)

The vector near-field distribution of infrared gap antennas (linear dipole antennas coupled via a nanometric gap) is mapped by scanning-type near-field microscopy (s-SNOM). The images provide direct experimental evidence of strong in-plane near-field localization inside a gap as small as 50 nm. By measuring the gap fields as a function of the total antenna length (near-field spectroscopy), we observe a clear resonance shift compared to uncoupled linear dipole antennas, thus verifying strong near-field coupling via the gap. We also find significant differences between near-field and far-field spectra of the antennas and discuss their implications. Vector near-field imaging of the infrared antennas [1, 2] was carried out with s-SNOM where s-polarized laser light is used for antenna excitation. A dielectric Si tip scatters the local near fields of the antennas. Interferometric and polarization-resolved detection of the tip-scattered light yields amplitude E and phase φ of the in- (x) and out-of-plane (z) near-field components (Ex, φx) and (Ez, φz).

Fig. 1 shows the near-field patterns obtained for a single gap antenna with a gap width of about 50 nm. The out-of-plane near-field component (Ez, φz) shows large near-field amplitudes at both sides of the gap, while a phase jump of about 180° occurs at the gap center [3]. The in-plane near-field component (Ex, φx), in contrast, is strongly enhanced exactly inside the gap and directly verifies field concentration inside the gap.

To provide experimental evidence of near-field coupling in the infrared gap antennas, we perform near-field spectroscopy. We fabricate gap antennas of different total length (but constant gap size) and measure the in-plane gap field as a function of the antenna length. A comparison with near-field spectra of single dipole antennas (continuous nanorods) shows a pronounced resonance shift, which clearly verifies near-field coupling across the antenna gap.

Our results show that vector near-field mapping is a powerful tool for measuring spectral resonance shifts in the near field of infrared antennas, in both amplitude and phase. This enables detailed studies of near-field coupling signatures, including the mapping of strongly localized field enhancement ("hot spots") and resonance shifts of near-field spectra, which are not accessible by far-field spectroscopy.

8096-140, Poster Session

Generalized surface plasmon modes partially coherent

J. C. Juarez-Morales, Instituto Nacional de Astrofísica, Óptica y Electrónica (Mexico)

Elementary long-range plasmon modes are described assuming an exponential dependence of the refractive index in the neighbourhood of a conductive thin film. The study is performed using coupling mode theory. The interference between long-range plasmon modes allows the synthesis of surface sinuosidal plasmon modes which can be considered as generalized plasmon modes completely coherent. These sinuosoidal plasmon modes are used for the synthesis of new surface plasmon modes partially coherent, which are obtained by means of an incoherent superposition of sinuosidal plasmon modes where each period is considered as a random variable. The kinds of surface modes generated have a profile easily tuneable which is controlled by means of
the probability density function associated to the period. The numerical simulation for sinusoidal, Bessel, Gaussian and dark hollow plasmon modes are presented.

8096-141, Poster Session

Multipoles on crescent silver nanorod excited by light with different frequencies

S. Chen, C. Yue, W. Lin, Far East Univ. (Taiwan)

In this study, we numerically analyze the interaction of a crescent silver nanorod with polarized visible light, and some specific optical properties are demonstrated. Crescent nanorod is constructed from a cylinder by removing a smaller eccentric cylinder from it, thus, the thickness of the shell has a continuous variation. In comparison with a tube-like nanorod, crescent nanorod could provide a wider freedom to electromagnetic modes. For single frequency, the electric multipoles are different with frequency expectedly. And a strong intensity of surface plasmon polarization could stay inside the chamber of the nanorod only at the resonant frequencies. For continuous wave, the types of multipoles are important evidences in understanding the optical characteristics, though it is hard to be predicted. We are studying the possibility of Fano-like resonance in a crescent nanorod if the incident light includes two or more frequencies. Due to the gradual variation of the wall thickness, a Fano-like extinction spectrum might be obtained under some specific conditions.

8096-142, Poster Session

Nanogap-engineerable Raman-active nanodumbbells for single-molecule detection

Y. D. Suh, Korea Research Institute of Chemical Technology (Korea, Republic of)

Surface-enhanced Raman scattering (SERS)-based signal amplification and detection methods using plasmonic nanostuctures have been widely investigated for imaging and sensing applications. However, SERS-based molecule detection strategies have not been practically useful because there is no straightforward method to synthesize and characterize highly sensitive SERS-active nanostructures with sufficiently high yield and efficiency, which results in an extremely low cross-section area in Raman sensing. Here, we report a high-yield synthetic method for SERS-active gold-silver core-shell nanodumbbells, where the gap between two nanoparticles and the Raman-dye position and environment can be engineered on the nanoscale. Atomic-force-microscope-correlated nano-Raman measurements of individual dumbbell structures demonstrate that Raman signals can be repeatedly detected from single-DNA-tethered nanodumbbells. These programmed nanostructure fabrication and single-DNA detection strategies open avenues for the high-yield synthesis of optically active smart nanoparticles and structurally reproducible nanostructure-based single-molecule detection and bioassays.

8096-143, Poster Session

Optical and electrical characterization of carbon nanotubes by terahertz spectroscopy: comparison between modeling and experimental results

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Electromagnetic terahertz (THz) radiation in frequency range of 0.3 to 10 THz is the next border in science and technology. The first THz-wave time-domain spectroscopy (THz-TDS) was shown in the late 1990s (Ugawa et al., Physical Review B, 60, 1999; Kang et al., Physical Review B, 75, 2007; Parrott et al., Advanced Materials, 21, 2009). Following then, carbon nanotubes have been widely investigated to find their unique properties and structure in electronic and mechanic fields. Their structures and properties have been applied for numerous applications in photonic emission, scanning, microscopy and tuning fields (Dresselhaus et al., 2001). The study of the plasma frequency of carbon nanotube films in high frequency range of THz-TDS is increasingly interested topic since the THz-TDS uses coherent electromagnetic pulse and does need the complicated numerical solution compared to Fourier transformation infrared (FTIR) (Kim et al., Journal of the Korean Physical Society, 50, 2007).

This paper studies about the optical and electrical properties of carbon nanotubes by utilizing THz electromagnetic wave spectroscopy. Absorption and dispersion of single-walled carbon nanotubes (SWNT) films are investigated by Terahertz time-domain spectroscopy (THz-TDS) in order to recognize the electrical and optical characteristics of carbon nanotube films. Measured data and pure and F-doped single-walled carbon nanotubes in the frequency range of 0.2-3 THz. To fit well results based on the Jeon et al. (Journal of Applied Physics, 98, 2005) experimental setup, this study combines the Maxwell-Garnett with Drude models. It allows us to better understand a sequence numerical modelling of carbon nanotubes for different devices based on the experimental data.

This work is supported by MITEPHO project (http://www.uc3m.es/portal/page/portal/grupos_investigacion/optoelectronics/european_projects/mitephos) which is coordinated by oddL research group in Carlos III de Madrid University with foundation grant agreement number 283893 (EU FP7) in order to develop compact tunable dual-mode diode lasers and terahertz spectroscopy in sensing and biomedical applications.

8096-144, Poster Session

Nano laser optoacoustic spectroscopy (LOS) system to quantify gold nanoparticles in a liquid tissue phantom for biomedical applications

H. Lamela, V. Cunningham, D. C. Gallego, Univ. Carlos III de Madrid (Spain)

The increasing demand for new techniques to enhance the spectroscopic characterisation and contrast of in-vivo unhealthy tissue is at the forefront of new innovations in nanomedicine. Such novel optical based medical techniques can provide physiological definition, enhanced therapeutic efficiency and aid in early and effective diagnostic decisions. Targeted gold nanostructures are forming an integral part in solving current demands for biomedical applications, already providing numerous advances in fields of high sensitive diagnostic imaging (Eghtedari et al., Nano Letters, 7, 2007; Eghtedari et al., Nano Letters, 9, 2009), optical enhanced targeted drug delivery (Yih et al., Journal of Cellular Biochemistry, 97, 2006; Han et al., Angewandte Chemie-International Edition, 45, 2006) and localized cancer cell destruction by means of phototherapy (Rozanova et al., Science in China Series B-Chemistry, 52, 2009; Huang et al., Nanomedicine, 2, 2007). Knowledge of the optical properties of such nanostructures is vital for efficient medical procedures.

In this paper, a novel real-time Laser Optoacoustic Spectrometer (LOS) prototype which demonstrates the potential of the photon to ultrasound conversion, via optoacoustics, is presented and proven to be a valuable technique for characterisation of gold nanoparticles within the visible range from 410 to 650 nm (Lamela et al., Optics and Laser Technology, 2010), and spectroscopic characterisation of spherical nanoparticles within the visible range from 410 to 1000 nm. The optical source used is a Q-switched Nd:YAG pumped Optical Parametric Oscillator (OPO) controlled by specifically designed software. A comparative analysis of results obtained from a parallel reference measurement scheme,
based on standard collimated optical transmission and standard UV-VIS spectrophotometry will be provided.

8096-145, Poster Session

Analyzing symmetry in phononic band structure of gyro-magnetic photonic crystals
S. Khorasani, A. Najafi, Sharif Univ. of Technology (Iran, Islamic Republic of)

In the band structure analysis of photonic crystals it is normally assumed that the full photonic gaps could be found by scanning high-symmetry paths along the edges of Irreducible Brillouin Zones (IBZ). We have recently shown [1] that this assumption is wrong in general for sufficiently symmetric breaking geometries, so that the IBZ is only half of the complete BZ. That minimal required symmetry arises from the requirement on time-reversal symmetry. In this paper we show that even if requirement might be broken by using gyro-magnetic materials in the composition of photonic structures, under which the time-reversal symmetry no longer holds. As a result, for sufficiently asymmetric structures we can observe that the IBZ extends fully to the boundaries of the complete BZ, that is IBZ must be taken to be as the same as the BZ.


8096-146, Poster Session

Surface enhanced coherent anti-Stokes Raman scattering on nanostructured gold surfaces
C. Steuwe, J. J. Baumberg, S. Mahajan, Univ. of Cambridge (United Kingdom)

In this paper, we demonstrate a novel method for combining plasmonic surface enhancement with Coherent anti-Stokes Raman Scattering (CARS) on gold sphere segment void substrates. We show that Surface-Enhanced CARS (SECARS) allows for a 10^5 enhancement within our nanostructures, which is a key approach towards reliable single molecule Raman spectroscopy.

Plasmonic enhancement of Raman scattering and fluorescence on surfaces has been a topic of strong interest over the last three decades. However, so far only a few attempts of plasmonic-enhanced nonlinear Raman scattering have been reported, on colloidal spheres [1]. Here colloidal-crystal templated electrodeposition is used to fabricate sphere segment void (SSV) substrates that show large, reproducible enhancements in surface-enhanced Raman spectroscopy (SERS) [2]. Since the plasmonic properties of nanostructures are extremely sensitive to geometry, it is possible to optimize the substrates for SERS by fine tuning the structural architecture. With these substrates, enhancement factors exceeding 10^6 in SERS have been shown [3]. Since CARS is a third-order effect, it overcomes the weak scattering cross section of spontaneous Raman scattering by coherently converting three photons of two different frequencies into an anti-Stokes photon. Hence, combining plasmonic enhancement and CARS gives rise to strong Raman scattering in SECARS.

Here we demonstrate SECARS of a monolayer of benzenethiol molecules on a plasmonic SSV substrate using a single laser approach (in combination with nonlinear wavelength conversion). SECARS spectra in presence of Raman active bonds coincide with spontaneous Raman spectra of the same sample.

We compare the SECARS enhancement to SERS and CARS on a variety of structures and show that the enhancement is strongly dependent on the structural geometry of the sample.


8096-147, Poster Session

Broadband optical antenna with a disk structure
I. Wang, The Hong Kong Polytechnic Univ. (Hong Kong, China)

Broadband optical antennas are of interest as they can transmit more information like traditional microwave UWB antennas. This paper presents a design of broadband optical antennas with a concentric disk structure. An equivalent circuit for the optical antenna with a disk structure is introduced. The broadband radiation at optical frequencies was demonstrated via the computer simulation.

8096-149, Poster Session

Investigation of cross-dipole metallic infrared frequency selective surfaces
J. Zhou, L. Wang, W. Zeng, Y. Y. Wang, Wuhan Univ. of Technology (China)

In this paper, we investigate cross-dipole infrared frequency selective surfaces using the finite element method (FEM). The Lorentz-Drude model is used to model the metallic film plasmonic effect at near infrared frequencies (1 - 5 um). The transmission spectrum is obtained and compared to those without considering the plasmonic effect. The filter transmissivity and ohmic loss as a function of metallic film thickness are also studied. The results show that the plasmonic effect of metallic film reduces the filter transmissivity and shifts the resonant frequency to longer wavelength while the increased metal film thickness reduces both amplitude and bandwidth of the transmitted signal at infrared frequency.

Key words: cross-dipole, infrared frequency selective surfaces, finite element method, Lorentz-Drude model
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8096-151, Poster Session

Surface plasmon propagation and coupling in silver nanowires
Y. Peng, K. Kempa, Boston College (United States)

Nanowire plasmonics have attracted a lot of research attention recently [Takahara et al, 1997; Liu et al, 2008; Ma et al, 2010]. In our study, we simulate surface plasmons in nanowires using the FDTD method. We investigate the details of the surface plasmon propagation, including the dispersion, field profiles, and the material and radiative dumping. We also investigate the radiative emission from plasmons at nanowire ends, as well as the coupling of plasmons between nanowires. These results are compared with experiments, and are used to validate the idea of employing these nanowires as transmission lines in the discretely guided electromagnetic effective medium [Kempa et al, 2008]. These results could also be important to the nanocircuit design [Assefa et al, 2010], and in the field of the nanostructure fabrication [Nah et al, 2010].

8096-152, Poster Session

Fabrication and test of an optical magnetic mirror
J. G. Hagopian, P. A. Roman, S. Shiri, E. J. Wollack, NASA Goddard Space Flight Ctr. (United States); M. Roy, U.S. Army Research Lab. (United States)
Plasmons in nanoscale, metal junctions: optical rectification and thermometry (Keynote Presentation)

D. Natelson, D. R. Ward, Rice Univ. (United States); F. Heuser, F. Pauly, Karlsruhe Institut für Technologie (Germany); J. C. Cuevas, Univ. Autónoma de Madrid (Spain); D. A. Corley, J. M. Tour, Rice Univ. (United States)

For more than 15 years, physicists (and chemists) have been able to perform experimental studies of electronic transport through single molecules in nanoscale junctions, looking at current as a function of voltage. These studies have revealed rich physics, including evidence for quantum entanglement (the Kondo effect) and inelastic processes involving vibrations. However, there are limits to how much one can learn from dc conduction. Fortunately, we have found that some of the same nanoscale metal structures used to perform the electronic measurements have tremendous utility in optical studies. Thanks to plasmons, the collective modes of the electronic fluid, these metal structures act like an optical antenna, channeling optical energy into and out of precisely the region of interest. We use simultaneous electronic transport and optical characterization measurements to reveal new information about electronic and optical processes in nanoscale junctions fabricated by electromigration. Comparing electronic tunneling and photocurrents allows us to infer the optical frequency potential difference produced by the plasmon response of the junction. Together with the measured tunneling conductance, we can then determine the locally enhanced electric field within the junction. In similar structures containing molecules, anti-Stokes and Stokes Raman emission allow us to infer the effective local vibrational and electronic temperatures as a function of DC current. This permits new fundamental studies of heating and dissipation at the nanometer scale.

Digital plasmonics

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No abstract available
and the far-field zones, to induce the properties of the coupled system. We numerically validate our model for structures that are currently under extensive investigation in the plasmonic and metamaterial communities. The insights into the physical comprehension of Fano resonances gained this way will be of great interest for the design of plasmonic sensing platforms and metamaterials.

8096-64, Session 15
Wide-angle spectrally selective plasmonic metamaterials for energy applications
G. Shvets, B. Neuner Ill, C. Wu, The Univ. of Texas at Austin (United States); S. Savoy, J. John, A. Milder, Nanohmics, Inc. (United States)
The infrared part of the spectrum is of particular interest for a broad range of applications, including thermal photovoltaics, thermal signature camouflage, and solar thermal applications. It is also a very appealing optical spectral range for plasmonic metamaterials because metallic losses are significantly lower in the infrared than in the visible part of the optical spectrum. I will describe the concept and the first experimental demonstration of a large-area spectrally-selective wide-angle infrared absorber based on a single-layer plasmonic metamaterial. This large-area structure is fabricated using the Nano Imprint Lithography (NIL) and tested using angle-resolved spectroscopy. By changing the dimensions and material composition of this metamaterial, we demonstrate the ability to control its spectral properties. Angle-resolved spectroscopy of these structures reveals a wide-angle response, including complete absorption at the resonant frequency due to the excitation of the short-range plasmon. The short propagation length of the plasmon is used for engineering a more sophisticated (broadband) spectral response by designing sub-wavelength macro-cells consisting of several base unit cells. We will also describe a simple design paradigm of engineering the spectral response of the macro-cell by analytically expressing its characteristic impedance in terms of the impedances of the base unit cells. Applications to thermal photovoltaics will be addressed by designing a plasmonic structure that compresses the broad solar spectrum into a spectrally-narrow infrared photons which are emitted with the peak emissivity approaching that of the black body.

8096-65, Session 16
Optical spin-Hall effects in plasmonics
E. Hasman, Technion-Israel Institute of Technology (Israel)
Spin-Hall effect is a basic phenomenon arising from the spin-orbit coupling of electrons. In particular, the spatial trajectory of the moving electrons is affected by their intrinsic angular momentum. The optical spin-Hall effect (OSHE) - beam deflection due to the optical spin (polarization helicity) - was recently presented. The effect was attributed to the optical spin-orbit interaction occurring when the light passes through an anisotropic and inhomogeneous medium. Here, we present and experimentally observe the OSHE in coupled localized plasmonic chains. The OSHE is due to the interaction between the optical spin and the path of the plasmonic chain with an isotropic plasmonic mode. In addition, OSHE was observed due to the interaction between the optical spin and the local anisotropy plasmonic mode, which is independent on the chain path. A spin-dependent orbital angular momentum was observed in a circular path. Moreover, a wavefront phase dislocation due to the scattering of surface plasmons from a topological defect in space. The OSHE in the nanoscale provides an additional degree of freedom in spin-based optics.

8096-66, Session 16
Plasmon propagation in gold and silver nanowires
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Noble-metal nanowires can serve as plasmonic waveguides, efficiently transporting optical energy along the wire while confining electromagnetic fields laterally on dimensions much smaller than the diffraction limit. Nanoplasmonic waveguides fabricated using top-down lithographic methods suffer from significant losses due to scattering from edge roughness and grain boundaries. Chemically synthesized silver nanowires have been demonstrated to overcome this limitation. However, these structures have limited chemical and physical stability: they degrade in ambient environments, and they are easily damaged by intense radiation. We therefore investigate plasmon propagation in individual chemically synthesized gold nanowires and compare to propagation in silver nanowires. Propagation length is measured as a function of wavelength using a fluorescence-imaging technique, and group-velocity dispersion is measured using an interferometric spectroscopic technique. By comparing measurement results to electromagnetic simulations based on the finite-difference time-domain method, we find that plasmon propagation is determined by the intrinsic properties of the metal for both gold and silver wires. Although inherent absorption means that propagation lengths in gold are shorter than in silver, the greater stability of the gold wires opens up new scientific and technical possibilities, including detailed structural characterization using x-ray diffraction and nonlinear-optical effects at high field strengths.

8096-67, Session 16
Reversed diffraction laws and anomalous scaling properties in plasmonic systems
G. Bartal, Technion-Israel Institute of Technology (Israel)
Periodic nanostructures made of metals and dielectrics have shown the ability to guide and transmit optical information much smaller than the wavelength of the carrier wave, overriding the fundamentals limits of diffraction. Owing to the plasma-like nature of the metallic constituents, manifested as negative dielectric function, these nano-structures enable the formation of surface plasmons on the metal-dielectric interfaces and exhibit strong mode confinement and anomalous propagation characteristics, such as negative refraction, anomalous diffraction and enhanced transmission through hole arrays. The strong metal dispersion, along with the loss inherent in such systems, also results in unique scaling of the diffraction and resolution properties with the wavelength which can even be opposite to those found in conventional dielectrics. We study those anomalous scaling phenomena in both resonant and non-resonant plasmonic nano-structures. We show how the resolution and diffraction in periodic metal-dielectric systems scale anomalously with the wavelengths, where longer wavelengths exhibit better resolution power and weaker diffraction - opposite to those found in conventional dielectrics. Likewise, resonant plasmonic systems like silver superlens also show interesting scaling properties where the angular frequency spectrum of a thin silver slab sandwiched between dielectric layers scales in a super-linear manner with the refractive index of the dielectrics, comparing to linear scaling of the dielectric media alone.
8096-68, Session 16

**Plasmonic logic gates and devices in silver nanowire networks (Keynote Presentation)**

H. Xu, Institute of Physics (China)

Here we show that the local electric field distribution of propagating SPs along Ag NWs can be imaged by coating the NWs with a layer of quantum dots. In Ag NW networks of simple geometries, plasmons launched along a NW can be controllably routed to a specific NW output. The underlying physical mechanism, interference between SPs launched at different positions along a primary NW, is clearly observable, as is the detailed evolution of the plasmon field along the device. The addition of a second plasmon input makes it possible to turn on or off emission paths, resulting in combinations of optical signals that execute specific interferometric Boolean logic operations. This primary NW can thus be viewed as the plasmonic equivalent of a bus in a central processing unit. By loading the primary NW with plasmons launched with specific input properties at the secondary input NWs, the resulting plasmonic interference enables routing and output-coupling to specific output NWs. We believe this concept can be further generalized and expanded to more complex structures that can combine optical signals in various ways, and that a multiple-input, multiple-output plasmonic bus may serve as an efficient splitter, router, switcher and/or multiplexer in future complex plasmonic networks designed for computation and information processing functions. These findings shed new light onto both fundamental understanding of propagating plasmons in complex networks and may advance the development of integrated plasmonic devices for new generation information technologies.

8096-70, Session 16

**Localized field enhancements in two-dimensional V-groove metal arrays**

J. Beermann, S. M. Novikov, Univ. of Southern Denmark (Denmark); T. Søndergaard, J. Rafaelsen, K. Pedersen, Aalborg Univ. (Denmark); S. I. Bozhevolnyi, Univ. of Southern Denmark (Denmark)

We investigate field enhancements in two-dimensional 800-nm-periodic arrays of (108 - 121 nm deep) V-grooves (opening angles 38 -75 degrees) fabricated using focused ion beam milling in a 190 nm thick gold film on top of a fused silica substrate. Simulated and experimental reflection spectra, high-resolution two-photon luminescence (TPL) images, and microscopy of surface enhanced Raman scattering (SERS) obtained from the V-groove metal arrays are compared revealing good correspondence in the spectral dependences of reflection and local TPL as well as SERS measured at the groove bottom. We relate the obtained field intensity enhancements reaching 85 with nanofocusing and expanded to more complex structures that can combine optical signals in various ways, and that a multiple-input, multiple-output plasmonic bus may serve as an efficient splitter, router, switcher and/or multiplexer in future complex plasmonic networks designed for computation and information processing functions. These findings shed new light onto both fundamental understanding of propagating plasmons in complex networks and may advance the development of integrated plasmonic devices for new generation information technologies.

8096-71, Session 17

**Biosensing based on plasmon resonance energy transfer (PRET)**


In 2009, Choi et al. introduced the concept of plasmon resonance energy transfer (PRET, Nano Letters vol. 9, p. 85, 2009) to enhance the absorption of cytochrome c for measuring oxidative stress in living cells. In this contribution, we study in detail both theoretically and experimentally the conditions under which strong coupling can exist between cytochrome c and plasmon nanoparticles. By monitoring the plasmon absorption of cytochrome c, we introduce a non-invasive way of monitoring the release of oxidative stress, which plays a complex and multifaceted role in cell physiology. Such oxidative stress occurs for example when cells are exposed to toxic agents. The technique is extremely sensitive and enables measuring hydrogen peroxide released by micro-organisms with an unprecedented sensitivity. The versatility of this approach is illustrated by two series of experiments on aquatic micro-organisms and on cancerous cells. For aquatic micro-organism, the ability to monitor PRET over long periods provides insights into the relation between toxicity and photosynthesis. The proposed scheme is not limited to cytochrome c and detection of reactive oxygen species, but can also find a broad range of applications in strongly coupled bio-plasmonic system, such as for example oxygen sensing using hemoglobin.

8096-72, Session 17

**Design of hybrid plasmonic materials for SERS direct and indirect sensing**

R. A. Álvarez-Puebla, Univ. de Vigo (Spain)

Surface-enhanced Raman scattering (SERS) is gaining prominence as an ultrasensitive and ultrarapid detection technique. In the recent years many applications involving both direct and indirect sensing has been developed in biomedicine, biolabelling, medical imaging, multiplex high-throughput screening, pollutant monitoring or molecular and material characterization. Notwithstanding, several aspects such as colloidal stability, plasmon tunability, detection of molecular species with low affinity for gold or silver surfaces, low SERS cross-sections of aliphatic molecules or transition metals detection are still challenging. Here we demonstrate how the rational design in materials from controlling shape, size and composition of the initial colloidal nanoparticles, that will act as optical enhancers, to their integration into hybrid materials for advanced sensing, may resolve most of those SERS shortcomings.1-5 Furthermore we disuse the advantages or disadvantages of the different SERS approaches (direct sensing with single particles, generation of hot spots and indirect sensing with biological interfaces and encoded nanoparticles) to the different analytical and bioanalytical problems.

References

Experimental demonstration of n=0 in metal-insulator-metal waveguides at cutoff

E. J. R. Vesseur, T. Coenen, FOM Institute for Atomic and Molecular Physics (Netherlands); N. Engheta, Univ. of Pennsylvania (United States); A. Polman, FOM Institute for Atomic and Molecular Physics (Netherlands)

The spatial advance of the phase of light is controlled by the refractive index, essential to many if not all optical applications. Surface plasmons enable a strong modification of the dispersion of light, allowing to taylor effective refractive indices that are very large or even negative. A special case occurs when the refractive index reaches a value close to 0. This condition can be met in waveguides near cutoff, which was experimentally demonstrated in the microwave regime and was also predicted for plasmonic waveguides. So far, it was impossible to reach this condition at visible wavelengths due to limitations in nanofabrication and the difficulty of probing the n = 0 condition in a buried waveguide.

Here, we present a metal-insulator-metal plasmon waveguide that shows an effective n = 0 at cutoff. Waveguides with accurately controlled dimensions were fabricated using a sequence of steps including focused ion beam milling. Modes of the waveguides were excited using a 30 keV electron beam penetrating through the layer stack. By collecting the emitted radiation as a function of electron beam position we directly observe the spatial mode profiles and determine the dispersion relation of plasmon modes near cutoff. At cutoff, the enhanced density of optical states is directly observed from a peak in the electron-beam induced emission spectrum.
We present an imaging technique using an optically trapped cigar-shaped probe controlled using holographic optical tweezers. The probe is raster scanned over a surface, allowing an image to be taken in a manner analogous to scanning probe microscopy (SPM), with automatic feedback control provided by analysis of the probe position recorded using a high speed CMOS camera. The probe is held using two optical traps centred at least 10µm from the ends, minimising laser illumination of the tip, so lowering the chance of optical damage to delicate samples. The technique imparts less force on samples than contact SPM techniques, and allows highly curved and strongly scattering sample to be imaged, which present difficulties for imaging using photonic force microscopy. To calibrate our technique, we first image a known sample - the interface between two 8µm diameter polystyrene beads. We then demonstrate the advantages of this technique by imaging the surface of the soft algae Pseudopediastrum. The scattering force of our laser applied directly onto this sample is enough to remove it from the surface, however we can use our technique to image the algae surface with minimal disruption while it is alive, un-adhered and in physiological conditions. The resolution is currently equivalent to confocal microscopy, but as our technique is not diffraction limited, there is scope for significant improvement by reducing the tip diameter and limiting the thermal motion of the probe.

Profile measurement using standing wave trapping

T. Washitani, M. Michihata, T. Hayashi, Y. Takaya, Osaka Univ. (Japan)

We proposed a new measurement technique for surface profile using the standing wave trapping in air condition. The high-accuracy scale and the high-sensitive sensor are required in the profile measurement. In our measurement system, the optical trapping particle is used as the sensor. The standing wave pattern is used as the measurement scale, which has wavelength-determined interference pitch (λ/2). Therefore, this measurement technique is expected to perform the high-accuracy measurement. It was experimentally found that the vertical measurement range is about 250 µm. The uncertainty of the sensor is ±λ/100. Thus, this technique is capable of measuring large objects in height. When measuring the continuous surface, the sensor particle is scanned in the horizontal direction above the measured surface. The trapped sensor particle in the standing wave field axially moves to follow the measured surface topography. The particle jumps when the surface profile exceeds the pitch of the standing wave pattern. Therefore, the surface profile can be calculated based on the measurement of the particle motional variation. At first, we realized to measure the smooth surface profile such as micro-lens. As pre-measurement, the dependency of the scale pitch on measured surface angles was investigated. A micro-lens was measured with the angle dependency correction. This shows the improvement of the measurement accuracy. When measuring the discontinuous surface, the sensor particle is scanned in the vertical direction on the measured surface. Cross-correlation of sensor signals reveals the step height distance of the discontinuous surface.

Surface imaging of biological samples using holographic optical tweezers

D. B. Phillips, J. A. Grieve, S. Olof, S. Kocher, Univ. of Bristol (United Kingdom); R. W. Bowman, M. J. Padgett, Univ. of Glasgow (United Kingdom); M. J. Miles, D. M. Carberry, Univ. of Bristol (United Kingdom)

We present an imaging technique using an optically trapped cigar-shaped probe controlled using holographic optical tweezers. The probe is raster scanned over a surface, allowing an image to be taken in a manner analogous to scanning probe microscopy (SPM), with automatic feedback control provided by analysis of the probe position recorded using a high speed CMOS camera. The probe is held using two optical traps centred at least 10µm from the ends, minimising laser illumination of the tip, so lowering the chance of optical damage to delicate samples. The technique imparts less force on samples than contact SPM techniques, and allows highly curved and strongly scattering sample to be imaged, which present difficulties for imaging using photonic force microscopy. To calibrate our technique, we first image a known sample - the interface between two 8µm diameter polystyrene beads. We then demonstrate the advantages of this technique by imaging the surface of the soft algae Pseudopediastrum. The scattering force of our laser applied directly onto this sample is enough to remove it from the surface, however we can use our technique to image the algae surface with minimal disruption while it is alive, un-adhered and in physiological conditions. The resolution is currently equivalent to confocal microscopy, but as our technique is not diffraction limited, there is scope for significant improvement by reducing the tip diameter and limiting the thermal motion of the probe.
Optical Trapping and Optical Micromanipulation VIII

8097-07, Session 2

Hydrodynamic synchronization of light driven propellers

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Hydrodynamic interactions are believed to be responsible for the coordinated motion of cilia and flagella in motile microorganisms. Very recently numerical simulations and macroscopic experiments have begun to provide insights in this phenomenon of hydrodynamic synchronization. We investigate a simple microscopic system of independently light driven propellers coupled by hydrodynamic interactions. Microscopic propellers are fabricated by using two photon polymerization while holographic optical tweezers are used to trap and drive them by radiation pressure. Hydrodynamic synchronization is clearly observed when the applied optical forces are finely tuned and disappears progressively as the two propellers are brought far apart. Due to the unavoidable presence of noise in any micron sized system, we discuss hydrodynamic synchronization as a stochastic phenomenon.

8097-08, Session 2

A microsyringe controlled using a triple beam optical trap

W. T. Ramsay, M. Bechu, L. Paterson, Heriot-Watt Univ. (United Kingdom)

A limited range of instruments are available which allow the controlled injection of sub-picoliter volumes; cumbersome, commercially produced mechanical microinjection systems and microfluidic, lab-on-a-chip devices account for the majority. We present an optically controlled microsyringe capable of dispensing femtolitres of liquid. Triple beam optical tweezers are used to manipulate hollow glass microneedles and also polymer microspheres which were used as ‘handles’ to assist the manipulation of microneedles and ‘plungers’ to dispense liquid from the microneedle.

Standard optical tweezers were used with the addition of a Ronchi ruling (250 lines per inch) mounted in the image relay telescope. The diffraction pattern generated by the Ronchi ruling produced three optical traps in the sample chamber. Trap spacing was controlled by translating the ruling along the axis of beam propagation within the image relay telescope.

Utilizing the three-beam trap, it was possible to manipulate pulled, borosilicate capillaries (5-50µm in length, 1-5µm in diameter) both perpendicular and parallel to the axis of the capillary. Rolled SO/SO2 microlutes (4µm diameter, 50µm long) were also manipulated, however in this case polymer microspheres were used as ‘handles’. In both cases the microneedles did not align vertically along the propagation axis; an advantage over using a single beam optical trap. Tweezing a microsphere within a microneedle dispenses femtolitres of liquid from the needle. The force exerted on microneedles is calculated to be in the order of picoNewtons so may have applications where femtolitre volumes must be controllably delivered beyond a barrier, such as single cell microinjection.

8097-09, Session 2

Fast optical force based cell sorter assisted with CUDA and computer vision techniques

G. Xu, W. Qin, N. L. Johnson, Z. Ma, Clemson Univ. (United States); X. Peng, Shenzhen Univ. (China); B. Z. Gao, Clemson Univ. (United States)

Optical force and microfluidics based cell sorting is a newly developed cell manipulation technique. It is non-invasive and easy to control comparing with conventional flow cytometry methods. We investigate a novel high speed, computer vision assisted cell sorting device that utilizes the optical force generated by a weakly focused laser beam to move individual cells and direct cell separation in a microfluidics system. This paper focus on the computer vision based detecting cell, tracking cell position, and estimating moving speed, which are the core of the cell sorting components. In order to distinguish cells by their size and moving speed that indicates cells’ physiological characteristics, high speed computer-vision techniques are first introduced. We use sobel edge detector to find potential edges of moving objects (cells or other noises) in each video frame captured by a high speed camera first. Then Hough transform (HT) is used to calculate parameters (center and radius) of the real moving cell’s contour. Finally particle filter (PF) is selected to realize cell tracking and its speed measurement. Because HT and PF are all time consuming, in our study we use CUDA compatible GPU-Tesla 1060 and Quadro FX 1800 and program on it to implement real-time processing.

The experimental results show that this method can track five to nine cells at approximately 130 to 170 frames per second. The signals from the imaging system are used to trigger a laser beam to laterally move the cells in the microfluidic channel to achieve cell separation.

8097-10, Session 2

Active matter on asymmetric substrates

C. J. Olson Reichhardt, J. Drocco, T. Mai, C. M. Reichhardt, Los Alamos National Lab. (United States)

We investigate the dynamics of self-driven particles on symmetric and asymmetric substrates. This system could be realized using self-driven colloids on optical traps or swimming microorganisms such as bacteria in microstructures. In an asymmetric array of funnel-shaped barriers, particles that undergo only Brownian motion experience no net flow; however, if the particles are undergoing run and tumble type dynamics we find a net flow of particles or a ratchet effect. We investigate the effect of different particle dynamics on the ratchet effect. For example, if the particles reorient to follow the barrier walls they encounter, we observe a ratchet effect; however, if the particles reflect or scatter off the barrier walls, the rectification is reversed or destroyed. We also consider particle-particle interactions which can either promote or decrease the ratchet effect in accordance with different rules. In certain swarming moddies the ratchet effect can even be reduced.

8097-11, Session 3

Direct force and ionic-current measurements on DNA in a nanocapillary

O. Otto, L. J. Steinbock, R. Skarstam, J. L. Gornall, U. F. Keyser, Univ. of Cambridge (United Kingdom)

We demonstrate for the first time combined optical tweezers and ionic-current measurements in which the nanopore is located perpendicular to the trapping laser. Traditionally, quadrant photo-detectors are used to measure the displacement of a trapped colloid while the attached DNA is
8097-12, Session 3
Sequence dependent effect on DNA elasticity
K. Raghunathan, J. Milstein, Univ. of Michigan (United States); Y. Chen, Cornell Univ. (United States); J. D. Meiners, Univ. of Michigan (United States)
We have used constant force axial optical tweezers to understand the subtle effects of DNA sequence variations on its mechanical properties. Sequence variations in the DNA can affect two fundamental properties, namely the intrinsic curvature and the elasticity of the molecule. To delineate the effects of curvature from elasticity, we have designed sequences of DNA which have nearly identical curvatures but varied AT content and measured their elasticity. We have verified the similarity of curvatures of these sequences computationally and using polyacrylamide gels. Our experiments have shown that the persistence length is highly dependent on the elasticity of DNA; in fact it varied almost two fold between sequences containing 67% AT and 40% AT content region. Thus, the cost of bending a GC rich region of the DNA is energetically much costly compared to an AT rich sequence. The biological implications of this may be substantial, as the need to bend DNA is involved in a host of regulatory schemes, ranging from nucleosome positioning to the formation of protein-mediated repressor and enhancer loops.

8097-13, Session 3
Laser microbeam - kinetic studies combined with molecule - structures reveal mechanisms of DNA repair
B. Altenberg, European Molecular Biology Lab. (Germany); P. Grigaravicius, Deutsches Krebsforschungszentrum DKFZ (Germany); K. O. Greulich, Fritz Lipmann Institute (Germany)
Kinetic studies on double strand DNA damages induced by a laser microbeam have allowed a precise definition of the temporal order of recruitment of repair molecules. The order is Ku70/80 - XRCC4 --- NBS1 --- Rad51. Ku70/80 and XRCC4 molecules represent the inaccurate NHEJ pathway, NBS1 a switch and Rad51 the almost error free HRR pathway. These kinetic studies are now complemented by studies on molecular structures of the repair proteins, using the program YASARA which does not only give molecular structures but also physicochemical details on forces involved in binding processes. It turns out that the earliest of these repair proteins, the Ku70/80 dimer, has a hole with high DNA affinity. The next molecule, XRCC4, has a body with two arms, the latter with extremely high DNA affinity at their ends and a binding site for Ligase 4. Together with the laser microbeam results this provides a detailed view on the early steps of DNA double strand break repair. The sequence of DNA repair events is presented as a movie.

8097-14, Session 3
Ultrafast Imaging of Microbubble Cavitation using Integrated Optical Trapping for Spatial Control: Progress and Prospects
P. A. Campbell, Univ. of Dundee (United Kingdom)
Cavitation, which involves the formation and dynamic evolution of bubbles, is a ubiquitous phenomenon in fluids. Recently, the area has received heightened interest in medical contexts due to the utility of [shelled] bubbles for exploitation both as contrast agents for clinical diagnostic ultrasound imaging, and increasingly, for their emerging potential as microscopic drug delivery systems. Micrometer-sized bubbles [microbubbles (µBs)] are most clinically relevant as their small size allows them to flow easily within even the smallest vessels of the vascular system. This size constraint results in bubble resonant frequencies lying in the MHz range, and in turn, requires [ultrasonic] driving frequencies in a comparable range. Accurate monitoring of µB response at sampling rates greater than the Nyquist limit thus requires the use of ultra-high speed microphotography. Moreover, in order to develop a fundamental understanding of bubble behavior over a range of clinically relevant scenarios, it is imperative that spatial control be exercised over their whereabouts relative to any proximal surfaces, and indeed, to other bubbles, so that the effects of any boundary constraints and acoustic cross-talk can be discriminated. Only one technique can be applied readily to this situation, that neither interferes with the incident ultrasound wave, nor perturbs any resultant hydrodynamical response in the surrounding fluid: that technique is optical trapping.

Interestingly, the first demonstration of such optical trapping for low-index µBs occurred in 1988 [1], however it was not until 2005, when the first fully integrated study incorporating high speed imaging sequences of optically trapped µBs activated by ultrasound was published [2]. This was followed in 2007 by an independent study, using an alternative architecture, and which demonstrated the explicit role of proximal walls on the dynamic of shelled µB for the first time [3]. Both of these latter studies underscored the flexibility and power of combining optical trapping and high speed imaging as an innovative new approach to cavitation studies. In this review paper, the lead authors and architects of those latter two studies [2,3] bring their collective experience together for the first time, assessing the process of how their respective integrative solutions converged, and moreover how emerging technologies such as the use of spatial light modulators can be exploited fully in this context. A full reference list, including all conference papers in this area, is included, so that this review represents a completely up-to-date snapshot of the state of the art, as well as a sober assessment of where the most fruitful future directions may lie, given the rapidly evolving CCD industry that underpins modern high speed imaging systems.

8097-15, Session 4
Characterization of oil-producing microalgae using Raman tweezers
In order to utilize algae for efficient fuel production, the optimal cultivation
parameters have to be determined which, in turn lead to high production of oil in the selected cell line. Therefore, rapid techniques allowing for the characterisation/identification of algal species, and consequently for the determination of the unsaturation degree of the constituent fatty acids in the algal lipid bodies are required. Thus, Raman spectroscopy can offer an attractive alternative for lipid characterization that has not yet been sufficiently exploited in algae investigations.

We present that Raman spectroscopy can be combined with optical tweezers and with microfluidic chips so that this instrument is capable to measure algal nutrient dynamics and metabolism in vivo, in real-time, and label free, making it possible to detect population variability as a biosensor. Moreover, employing an active sorting switch, cells can be sorted depending on input parameters obtained from Raman spectra.

8097-16, Session 4

High speed tracking of intracellular structures: understanding the transport mechanisms in living plant cells

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Intracellular transport in plant cells is governed by an internal flux, known as cytoplasmatic streaming, which facilitates the exchange of materials between organelles and between the cell and its surroundings. Recent studies have shown that this directed flow of the cytosol is dependent on the actin filament integrity and requires the proper action of myosin XI molecular motors. However, the role that myosins play in the movement of particular intracellular organelles remains unclear. These may be directly pulled by myosin motors or carried away by the flux in the cytosol produced by the active movement of another organelle. In order to elucidate the underlying mechanism by which cytoplasmatic streaming is generated, we analysed the motion both protein bodies, which are membranous structures that are artificially induced in transgenic tobacco leaves. In addition, these synthetic organelles can be used as a handle to exert large forces by means of optical tweezers, which may be important for the study of the mechanics of the cell transport system in living cells. In vitro myosin XI motors move processively along actin filaments with a fixed step size of 35 nm. These transporters, which are the fastest known molecular motors, stride along the actin tracks at velocities up to 7 µm/s. In order to determine whether a particular transported cargo moves in a stepwise mode, a high-speed, highly accurate tracking method is required, such as FIONA. Large temporal resolution is guaranteed by using a fast back-illuminated EM-CCD camera (Ixon-860, Andor Technologies), which is characterized by its high frame rate and sensitivity. Our results reveal that cargo moves in a stepwise mode, suggesting that myosin XI directly pulls these structures through cell’s cytosol.

8097-17, Session 4

The viscoelastic properties of the vitreous humour measured using an optically trapped local probe

F. Watts, L. E. Tan, Univ. of Strathclyde (United Kingdom); M. Tassieri, Univ. of Glasgow (United Kingdom); C. G. Wilson, Univ. of Strathclyde (United Kingdom); J. M. Girkin, Durham Univ. (United Kingdom); A. J. Wright, Univ. of Strathclyde (United Kingdom)

We present results demonstrating for the first time that optical tweezers can be used as a local probe to measure the variation in the viscoelastic properties of the vitreous humour of a rabbit eye. The beads were injected into a dissected vitreous and optically trapped using a 532 nm wavelength laser beam and an inverted microscope. The quasi-Brownian motion of the optically trapped bead was monitored on a fast CCD camera on the millisecond timescale. Analysis of the bead trajectory provides local information about the viscoelastic properties of the medium surrounding the particle [1]. The linear viscoelastic properties of a material can be represented by the frequency-dependent dynamic compliance modulus , where G’ (ω) is the storage (elastic) modulus and G” (ω) the loss (viscous) modulus. Previous methods for measuring the viscoelastic properties of the vitreous destroy the sample and allow only a single averaged measurement to be taken per eye, whereas, with our approach, we were able to observe the variation in G’ (ω) and G” (ω) across the sample and the inhomogeneous nature of the vitreous. The motivation behind these measurements is to gain a better understanding of the structure of the vitreous humour in order to design effective drug delivery techniques. In particular, we are interested in methods for delivering drug to the retina of the eye in order to treat sight threatening diseases such as age related macular degeneration.


8097-18, Session 4

Investigating the interaction forces between T-cells and antigen-presenting cells using an optical trapping system

A. J. Wright, Univ. of Strathclyde (United Kingdom); R. Benson, R. W. Bowman, G. M. Gibson, M. J. Padgett, Univ of Glasgow (United Kingdom); J. M. Girkin, Durham Univ. (United Kingdom); J. M. Brewer, F. Garside, Univ. of Glasgow (United Kingdom)

The interactions between T-cells and antigen-presenting cells (APCs) are crucial in triggering a successful antigen-specific, adaptive immune response leading to protection against a particular pathogen or disease. At present very little is known about the magnitudes of the forces involved in these interactions. We present results showing for the first time that optical tweezers can be used to measure these cell-cell interaction forces. We were able to see a clear difference in the interaction force depending on the presence or absence of specific antigen. The optical trapping system incorporated a fast camera to provide sensitive position detection and was developed to be stable and vibration free, allowing interaction forces to be measured on a time scale of several minutes. We combined two Laguerre-Gaussian beams, with equal but opposite handedness, to create a trapping beam with a ‘petal pattern’ intensity profile that had no net orbital angular momentum and therefore did not cause the trapped object to rotate. The T cell of interest was trapped directly with this beam and no exogenous beads were added to the sample. Interaction forces between T cells and APCs in the presence of specific antigen ranged from 0-6.5pN, whereas, when the specific antigen was absent the interaction forces ranged from 0-1.5pN. The accuracy of the system will be discussed in terms of how accurately we can track the position of the optically trapped cell and the methods we used for limiting cell roll.

8097-19, Session 4

Viability studies of optically trapped T-cells

N. McAlinden, D. Glass, O. Millington, A. J. Wright, Univ. of Strathclyde (United Kingdom)

We present a viability study of optically trapped live T cells and T cell hybridomas. T cells form an important part of the adaptive immune response system which is responsible for fighting particular pathogens or diseases. The cells of interest were directly trapped by a laser operating at a wavelength of 1064 nm and their viability was measured as a function of time. Cell death was monitored using an inverted fluorescent microscope to observe the uptake by the cell of the fluorescent dyes propidium iodide and trypan blue. Studies were undertaken at various laser powers and beam profiles and the data compared to results taken...
using a laser beam with a wavelength of 532nm to optical trap the cells. There is growing interest in optically trapping immune cells and this is the first study that investigates the viability of a T cell when trapped using a conventional optical trapping system. In such experiments it is crucial that the T cell remains viable and trapping the cell directly means that any artefacts due to a cell-bead interface are removed. Our motivation behind this experiment is to use optical tweezers to gain a greater understanding of the interaction forces between T cells and antigen presenting cells. Measuring these interactions has become important due to recent theories which indicate that the strength of this interaction may underlie the activation of the T-cell and subsequent immune response.

8097-20, Session 4
Elastic light scattering measurements from multiple red blood cells in line tweezers
A. Kauppila, M. Kinnunen, Univ. of Oulu (Finland); A. Karmenyan, National Yang-Ming Univ. (Taiwan); R. Myllylä, Univ. of Oulu (Finland)

Different theoretical models have been developed to understand light scattering processes in biological medium and for helping in analysis of experimental data, both at a cellular level and in bulk tissues. Experimental verification of the simulation models is difficult at a cellular level. Optical tweezers, combined with a light scattering measurement facility, has enabled the measurement of elastic light scattering distributions from single particles and cells. The aim of this paper is to present elastic light scattering measurement results from several red blood cells (RBC) and compare the results with the theoretical ones found in literature. Elliptical optical tweezers is used to keep one, two and three RBCs next to each other and stable in place during the measurements. Face-on and rim-on incidences of He-Ne laser light (vertical polarization) in relation to the RBCs are used. In the face-on case, light scattering intensity is larger from two RBCs than from one RBC, but no difference was found when using 3 RBCs instead of two RBCs. In the rim-on case, clear changes in the shape of scattering light intensity field were found when the number of RBCs was increased from one to two. Those results are in agreement with modelling, where it was found that scattering patterns are almost independent of the lateral distance of the RBCs in the face-on case, and, the multiple scattering effect needs to be taken into account when several RBCs are along the direction of the incident wave.

8097-21, Session 5
Plasmonic nanogels with robustly tunable optical properties
T. Cong, S. Wani, R. Sureshkumar, Syracuse Univ. (United States)

Metal nanoparticles (e.g. Ag and Au) are widely investigated as attractive candidates for inorganic-organic assemblies because of their unique optical and electronic properties. Fluids with metal nanoparticles can be used to manufacture thin films and interfaces for applications such as light trapping in photovoltaic devices, microelectric devices and biosensor technology. In this study, plasmonic nanogels were produced by self-assembly of wormlike surfactant micelle and metal nanoparticles in an aqueous solution at room temperature. The structure of the nanogel was studied by cryogenic transmission electron microscopy and rheological measurements. The optical absorbance of the gels could be robustly tuned by varying the nanoparticle type (Au or Ag), size, shape and/or concentration. Specifically, multicomponent nanogels capable of broadband absorption of the solar radiation were synthesized. These gels had relatively low viscosity (~ 1), long shelf-life (~ weeks), thermal stability up to 80 degree C and are thermoreversible. Hence, they can be easily processed to make thin films and interfaces with tunable optical properties. Structure, rheology and optical properties of these plasmonic nanogels as well as their potential application to high efficiency photovoltaics design will be discussed.

8097-22, Session 5
 Femtosecond laser structured surfaces for opto-fluidics and sensing
R. Buvidas, D. J. Day, S. Juodkazis, Swinburne Univ. of Technology (Australia)

Surface patterning by ripples, the self-organized quasi-periodic sub-wavelength relief structures, is demonstrated on large areas with sub-millimeter cross section using femtosecond laser pulses. The period of ripples, L, is determined by the wavelength of irradiation, w, and the refractive index of materials, n, as L = w/2n in (sem)transparent materials and is close to L = w on the metallic and absorbing surfaces for normal incidence. We choose high refractive index materials such as Si, TiO2, GaF GaAs, Al2O3 ITO for creating patterns where the width of a groove/ridge is between 100 - 200 nm. Such patterns are prospective for surface enhanced Raman scattering (SERS) after coating them by plasmonic metals. The orientation of the ripples, their wavevector, is determined by the orientation of the linearly polarized light. In the case of elliptical and circular polarization, patterns of a more complex geometry but with similar feature sizes are obtained. SERS activity of samples has been confirmed. Such directly written SERS sensors do not require multi-processing lithographic fabrication steps which are not practical or expensive for the large sub-1mm regions. The complex sub-wavelength roughening of the surface by ripples is found to change wetting conditions as revealed by video monitoring water droplet put in touch with the rippled regions. Application potential of ripples in applications of electrowetting on ITO substrates is discussed.

8097-23, Session 5
Electrowetting-controlled bio-inspired artificial iridophores
S. Manakasettharn, J. A. Taylor, T. Krupenkin, Univ. of Wisconsin-Madison (United States)

Many marine organisms have evolved complex optical mechanisms of dynamic skin color control that allow them to drastically change their visual appearance. In particular, cephalopods have developed especially effective dynamic color control mechanism based on the mechanical actuation of the micro-scale optical structures, which produce either variable degrees of area coverage by a given color (chromatophores) or variations in spatial orientation of the reflective and diffractive surfaces (iridophores). In this work we describe the design, fabrication and characterization of electrowetting-controlled bio-inspired artificial iridophores. The developed iridophores geometrically resemble microflowers with the flexible reflective petals. The microflowers are fabricated on a silicon substrate using surface micromachining techniques. After fabrication a small droplet of conductive liquid is deposited at the center of each microflower. This causes the flower petals to partially wrap around the droplet forming a capillary origami structure. The dynamic control over the degree of wrapping is achieved by applying a voltage differential between the conductive core of the petals and the droplet. The applied voltage causes dynamic contact angle change between the droplet and each of the petals due to the electrowetting effect. We have characterized mechanical and optical properties of the microstructures and discuss their electrowetting-based actuation. These experimental results are in good agreement with a simple theoretical model based on electrocapillarity and elasticity theory. This work forms the basis for a broad range of novel optical devices.

8097-25, Session 5
Femtosecond laser structuring of waveguides for sensing applications
D. J. Day, R. Buvidas, G. Gervinskas, S. Juodkazis, Swinburne Univ. of Technology (Australia); M. Mikutis, G. Slekys, ALTECHNA
Co. Ltd. (Lithuania)

Tightly focused femtosecond laser pulses were used to open cavities and drill-through holes in the optical single and multi-mode fibers. The cross section of the holes and cavities ranging from 10 to 50 micrometers. This direct laser writing approach makes it possible to minimize the amount of waveguide material which should be removed for uncompromised mechanical performance. The proof-of-the-principle demonstration of incorporating fibers into a microfluidic chip is demonstrated. We show that fabricated open cavities and holes in the waveguides can be used for direct monitoring of absorption changes. Simple design and integration possibility of laser-fabricated waveguide sensors is prospective for optofluidic applications.

8097-79, Session 5

A thiol-ene/methacrylate-based polymer for creating integrated optofluidic devices

M. Baylor, Carleton College (United States); R. R. McLeod, R. Boyne, N. Cramer, C. N. Bowman, Univ. of Colorado at Boulder (United States)

We present a new photopolymer that allows the creation of physical features (e.g. micro-fluidic channels) and optical index features (e.g. waveguides) as coplanar components in an optofluidic device using standard photolithography techniques. The polymer consists of two monomer species that polymerize at different rates. The methacrylate gels rapidly to create a scaffolding structure. The thiol-ene is a high-index polymer that cures more slowly. An initial exposure of the fluidic-structure mask brings the polymer to a rubbery gel point. Any unexposed monomer is a liquid and can be removed using a solvent wash leaving physical structures in the polymer. A second short exposure of the waveguide mask initiates the creation of index structures resulting from diffusion of high-index monomer into the exposed region. A final flood-cure permanently fixes the optical structures.

Using the above process we create an integrated refractometer that includes a polymer waveguide cross by a micro-fluidic channel, a butt-coupled fiber source and a detector attached to a single base. Waveguide loss for a 12 mm x 60 micron x 60 micron waveguide-only sample was 0.28 dB which includes material absorption, scattering losses, and coupling losses. When the 160.5 micron fluid channel was introduced in a waveguide plus channel device, the total loss of the waveguide plus the channel was 4.2 dB decreasing to 1.8 dB when filled with water due to improved index-matching between the channel and the waveguide. Using direct-write and contact liquid photopolymerization techniques, we believe this work can be extended to make 3D optofluidic structures.

8097-26, Session 6

Hydrodynamic assisted barrier escape

A. Curran, M. Lee, Univ. of Glasgow (United Kingdom); R. Di Leonardo, Univ. degli Studi di Roma La Sapienza (Italy); M. J. Padgett, Univ. of Glasgow (United Kingdom)

We present experimental evidence of hydrodynamic assisted escape from a potential barrier. Holographic optical tweezers are used to landscape a bistable system composed of two optical traps, separated by 400nm as seen by a Si colloid of radius 400nm. We observe thermally activated transitions between the two metastable states in the system with transition rates that are in agreement with Kramers’ theory. Introducing a second bistable system into our experiment allows us to study the behavior of thermally activated transitions in the presence of hydrodynamic interactions.

The two bistable systems are placed in a line separated by a few micrometers. Using camera tracking technologies we track each of the two beads as they hop back and forth within their respective system. The escape events are recorded and any correlation between the two systems are then computed. We consistently find that the number of observed correlations are as expected and that the number of correlations having a positive coefficient are greater than the number of correlations having a negative coefficient. The hydrodynamic interactions assist in the escape from a metastable potential.

Our results are particularly relevant in the context of concentrated colloidal suspensions where hydrodynamic interactions could lead to the formation of higher mobility paths along which it is easier to overcome barriers to structural rearrangement.

8097-27, Session 6

Probability distribution of colloidal nanoparticles in an optical trap

Y. Hu, X. Cheng, D. H. Ou-Yang, Lehigh Univ. (United States)

In a colloidal suspension of nanoparticles, the presence of an optical trap can exponentially enhance the probability of finding the particles in the vicinity of the trap. Intriguing questions arise regarding whether the probability distribution of particle number in the trap follows Poisson approximation, and if so, what is the upper limit of the trapping energy at which Poisson is followed. To answer these questions, we conduct experiments to determine directly the variance and the mean particle number in the trap at different trapping energies and compare with the predictions of the probability theory.

8097-28, Session 6

Particle interactions in colloids are revealed in a nonlinear effect in light transmission

J. Song, D. H. Ou-Yang, Lehigh Univ. (United States)

Studies on interactions between particles in highly concentrated suspensions are rare because the solutions are opaque and the interpretations from methods such as diffusing wave spectroscopy are often complicated.

We propose a simple method of probing particle interactions in opaque solutions by measuring light transmission affected by optically induced particle concentration enhancement. The increase in the particle concentration with the input light intensity depends on the interactions between particles. We demonstrate how this method can be used to determine the single particle trapping energy and the virial coefficients in aqueous suspensions of 190 nm polystyrene spheres.

8097-29, Session 6

Experimental and theoretical study of optical binding forces between two colloidal particles

M. Wei, Lehigh Univ. (United States); J. Ng, C. Chan, Hong Kong Univ. of Science and Technology (Hong Kong, China); D. H. Ou-Yang, Lehigh Univ. (United States)

Optical binding has been proposed to be responsible for the cluster formation of micron size dielectric spheres in coherent light fields. However, the measurement of the forces involved in binding is challenging due to overcome thermal fluctuations. In order to measure these forces, we trap two particles in two highly focusing laser beams created from a coherent laser source. We track the displacement of a particle in the stationary trap when the other trapping beam is blinking. The stationary trapping laser served as a force sensor which is able to isolate non-blinking signals. We report an experimental and theoretical study of optical binding forces between two optically trapped dielectric spheres. Results for optical forces are presented as a function of inter-particle separation and respective polarizations. The results are useful to understand various inter-particle effects in dual trapping beams system.
Tunable multidimensional optical binding of particles in laser beams.

P. Zemanek, O. Brzobohaty, V. Karasek, M. Siler, J. Trojek, Institute of Scientific Instruments of the ASCR, v.v.i. (Czech Republic)

We will present a method that provides flexible real-time modifications of the spatial positions of self-arranged particles in optically bound structures. Particularly we will focus on tuning of the inter-particle distances in one-dimensional array of particles in counter-propagating Gaussian or Bessel laser beams and we will also present the first examples of two-dimensional and three-dimensional self-arranged optically bound structures far from the surfaces.

Dynamics and Directional Locking of Colloids on Quasicrystalline Substrates

C. M. Reichhardt, Los Alamos National Lab. (United States)

Recent experiments on colloids interacting with a quasiperiodic Penrose lattice created by an optical substrates have found that although for strong substrates the colloids have a quasicrystalline ordering, at intermediate substrate strengths the colloids order into what is called an Archimedean tiling consisting of triangles and squares, while for weak substrates the colloids have a triangular ordering [1]. Here we examine particles such as colloids driven over a quasiperiodic Penrose substrate. For strong substrates and low external drives the colloids form a quasiperiodic pinned state, while at higher drives the moving system exhibits a dynamically induced Archimedean ordering which is aligned with the driving direction [2]. The dynamically induced Archimedean ordering only occurs for driving along the five orientationally ordered directions of the Penrose lattice. For driving along other directions, the particles form either a moving liquid or a moving triangular lattice. We also find that the driving angles at which the Archimedean ordering occurs are associated with a directional locking effect in which the colloids remain aligned with lattice substrate symmetry directions even when the driving force is rotated away from these directions. This directional locking is similar the locking steps observed for particles driven over periodic substrates [3], indicating that orientational ordering of the substrate is sufficient to induce directional locking effects and that translational ordering is not required. Our results have implications for various systems including colloids moving through optical lattices, vortices moving in nanostructured superconductors, and frictional studies of particles on substrates.


Using optical tweezers to investigate colloidal phenomena

I. Cohen, Cornell Univ. (United States)

Colloids are micron scale particles that are suspended in a fluid. The large size and relatively slow motions of the particles, make these suspensions convenient to image in 3D using confocal microscopy and manipulate at the single particle level using optical tweezers. These tools are revolutionizing our ability to link the microscopic structure of the suspension with the large scale macroscopic material properties. In this talk, I will discuss how we are using these systems to study a vast array of phenomena ranging from statistical mechanics problems including crystallization, defect motion in crystals, and the mechanics of glasses.

Message in a bottle: the statistical behavior of nanoparticles in optical confinement

D. H. Ou-Yang, L. Zhou, J. Junio, Lehigh Univ. (United States)

In an aqueous medium, container surfaces can significantly alter the behavior of suspended nanoparticles. We propose a method to investigate nanoparticle behavior in a boundary-free environment by transiently trapping them with a focused laser beam. While optically confined, as in an optical bottle, these particles are affected by both particle-light and particle-particle interactions. Time-averaged fluorescence imaging produces results in 3D mapping of the nanoparticle concentration in the bottle. We report how we analyze the messages in the bottle, i.e. the statistical behavior of these particles and the optical field intensity distribution.

Rotational micro-rheology with rotational optical tweezers

G. Maucort, D. C. Preece, T. A. Nieminen, N. R. Heckenberg, H. H. Rubinsztain-Dunlop, The Univ. of Queensland (Australia)

Recently the measurement of the visco-elastic properties of materials at the micron scale has received much interest. However, for biological experiments where the properities of the materials change drastically from point to point a localized measurement is necessary. Such measurement is complicated however by the need to obtain a measurement of the viscoelastic response of the material over sufficient frequency range. Optical tweezers represent one way in which such measurements may be achieved. However, it has proved difficult to take measurements of the visco-elastic properties of biological systems due to often complicated biological structures which may lead to differing measurements of visco-elasticity in different parts of the system. We present a method for localized measurement of the complex visco-elastic moduli of fluids utilizing the optical torque created when a birefringent Vaterite particle is exposed to light with modulated polarization. We use this method to acquire the frequency dependent, visco-elastic moduli while minimizing the associated interaction volume. Though a number of studies have looked at the possibility of using optical tweezers for the measurement of visco-elasticity this is the first time to our knowledge that birefringent properties have been utilized to perform such a measurement.

References:
[2] A. Bishop, T. Nieminen, N.R. Heckenberg, and H. Rubinsztain-Dunlop,
Optical manipulation of aerosol particle arrays

J. P. Reid, J. S. Walker, R. Power, A. E. Carruthers, Univ. of Bristol (United Kingdom)

Aerosols play a crucial role in many areas of science, ranging from atmospheric chemistry and physics, to drug delivery to the lungs, combustion science and spray drying. The development of new methods to characterise the properties and dynamics of aerosol particles is of crucial importance if the complex role that particles play is to be more fully understood. Optical tweezers provide a valuable new tool to address fundamental questions in aerosol science. Single or multiple particles 1-15 micrometres in diameter can be manipulated for indefinite timescales using optical tweezing. Linear and non-linear Raman and fluorescence spectroscopies can be used to probe particles composition and size. In this paper we will report on the latest developments in the use of holographic optical trapping (HOT) to study aerosols. Although widely used to trap and manipulate arrays of particles in the condensed phase, the application of HOT to aerosols is still in its infancy. We will explore the opportunities provided by the formation of complex optical landscapes for controlling aerosol flow, for comparing the properties of multiple particles, for performing the first ever digital microfluidic operations in the aerosol phase, and for examining interparticle interactions that can lead to coalescence/coagulation. Although aerosol coagulation is the primary process driving the evolution of particle size distributions, it remains very poorly understood. Resolving the time-dependent motion of trapped particles and the light scattering from particles during the coalescence process, we see how HOT can be used to study this fundamental process.

Optical manipulation of ‘drops on rails’ in two dimensional microfluidic devices

C. McDougall, Univ. of Dundee (United Kingdom); E. Fradet, C. Baroud, Ecole Polytechnique (France); D. McGlinn, Univ. of Dundee (United Kingdom)

In the context of using microfluidic droplets as isolated biological or chemical micro-reactors, control over droplet placement is crucial to successful device implementation. Previously we have demonstrated that optically induced heating of droplets from a focused laser beam can be used to control the formation of aqueous droplets in oil, merge or sort them. We have also demonstrated that more complex operations such as buffing droplets and mixing their contents are made possible by use of holographic or mobile laser beams. The localised heating produced by the focused laser beam causes localised variations of the interfacial tension of the droplet. Consequently Marangoni flows are generated and exert a force upon the droplet. It is this optically driven force that can be used to move the drop in a controlled manner.

Here we demonstrate a combined mechanical and optical approach to bring a water-in-oil droplet to any desired position on a two-dimensional plane and hold it stationary against a mean flow. This is achieved using far lower laser powers than those required for purely optical manipulation. The technique makes use of the “drops on rails” technique, which mechanically forces droplets to follow predetermined paths on “rails” or holds them stationary on “holes”. The laser induced optical forcing is employed for intelligent operations such as stopping, guiding or derailing droplets as they pass through the chip. In this way a droplets under study can be selectively sorted and then held stationary against the flow for prolonged observation.

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It has been recently demonstrated that a dielectric semi-cylinder, exposed to plane wave radiation, will rotate into a stable orientation thereafter it will experience a force that is not, in general, parallel to the flow of the momentum carried by the incident light. By analogy with aeronautics, the transverse component of this force can be thought of as “optical lift”, and the semi-cylinder itself, as a “light-foil”. We present a comprehensive examination of this effect using finite difference time domain (FDTD) and discrete dipole approximation (DDA) calculations. The effect of variations in particle size, shape and refractive index on the conditions for stable optical lift are considered. It is found that the phenomenon is common to particles containing precisely two mutually perpendicular mirror planes. For a particular shape of particle in this class the optical size determines the strength of the effect and is associated with Mie type resonances apparent in the magnitude of the lift force. Conversely, the shape itself influences the angular behavior in terms of the stable orientation and the direction of the equilibrium force. Finally, we examine the motion of a light-foil in a viscous medium. The symmetry required to generate optical lift also gives rise to hydrodynamic coupling between translational and rotational motion. As a consequence the conditions for orientational equilibrium are modified and the object acquires a steady velocity. These issues are examined for a range of novel geometries and ways of optimizing the effect are described.

8097-44, Session 9

Pulling particles backward using a forward propagating beam

J. Ng, Hong Kong Univ. of Science and Technology (Hong Kong, China); J. Chen, Z. Lin, Fudan Univ. (China); C. Chan, Hong Kong Univ. of Science and Technology (Hong Kong, China)

Can the scattering force of a forward propagating beam pull a particle backward? A photon carries momentum, so one may expect light will push against any object standing in its path. However, light can indeed “attract” in some cases. For example, small particles will be attracted towards a strongly focused spot in optical tweezers due to the gradient force. But it is probably more appropriate to say that the gradient force “grabs” rather than “pulls”, as the particle will remain stable in the optical trap after being drawn to the focus. Here, we discuss another possibility—a backward scattering force which is always opposite to the propagation direction of the beam so that the beam keeps on pulling an object towards the source without an equilibrium point.

In the absence of intensity gradient, using a light beam to pull a particle backwards is counter intuitive. Indeed, this is not possible with a plane wave. However, the situation is more subtle for certain optical beams. Here, we show that it is possible to realize a backward scattering force which pulls a particle all the way towards the source without an equilibrium point. The underlying physics is the maximization of forward scattering via interference of the radiation multipoles. We show explicitly that the necessary condition to realize a pulling force is the simultaneous excitation of multipoles in the particle and if the projection of the total photon momentum along the propagation direction is small, attractive optical force is possible.

8097-45, Session 9

Theoretical studies of nonlinear resonance radiation force exerted on nano-sized objects

T. Kudo, H. Ishihara, Osaka Prefecture Univ. (Japan)

Laser manipulation (LM) is a technique for the mechanical control of small objects using radiation force (RF) [1]. We have previously proposed the LM by using electronically resonant optical response of nanostructures to enhance the RF and to select particular kinds of nanoparticles via quantum confinement effect [2], which has been demonstrated experimentally [3]. This scheme is effective for travelling- and standing-waves, while it is not the case of the trapping by a single focused laser beam because the enhanced dissipative force strongly pushes objects...
toward outside the focal point. However, recent relevant experiments report positive results for trapping, showing puzzling phenomena contradicting our conventional understanding of the trapping mechanism [4].


Spin and orbital angular momenta of light reflected from a cone
M. Mansuripur, College of Optical Sciences, The Univ. of Arizona (United States); A. R. Zakharion, Corning Incorporated (United States); E. M. Wright, College of Optical Sciences, The Univ. of Arizona (United States)

We have examined several retro-reflecting optical elements, each involving two reflections. In the case of a hollow metallic cone having an apex angle of 90°, a circularly-polarized incident beam acquires, upon reflection, the opposite spin angular momentum. However, no angular momentum is transferred to the cone, because the reflected beam picks up an additional angular momentum (this one orbital) that is twice as large but opposite in direction to that of its spin. A 90° cone made of a transparent material in which the incident light suffers two total internal reflections before returning, may be designed to endow the retro-reflecting beam with different mixtures of orbital and spin angular momenta. Under no circumstances, however, does it seem possible to transfer any angular momentum from the light beam to the cone without either allowing absorption or breaking the circular symmetry of the system.

Optimized optical manipulation
M. Mazilu, J. Baumgartl, M. Ploschner, A. C. De Luca, S. Kosmeier, K. Dholakia, Univ. of St. Andrews (United Kingdom)

Special beams such as Bessel beams, Laguerre Gaussian beams or Airy beams are each interesting for various applications in micromanipulation. But which beam shape, what polarization and back aperture fill-factor is the optimum for trapping, sorting, manipulating or focusing? Here, we present a general method based on optical eigenmodes, that allows the determination of the beam shape optimizing each of the cases considered. The method is applied to optimize trapping, plasmonic based sorting and enhanced whispering gallery mode coupling enabling the Doppler cooling of mesoscopic particles. More precisely, optical eigenmodes (OEi) are solutions of Maxwell’s equation that are orthogonal with respect to a quadratic measure of the electromagnetic field. The intensity, the focal spot size, the linear/ angular momentum of the light field are such quadratic measures. Each eigenmode is associated with an eigenvalue corresponding to its measure. Ordering these eigenvalues delivers the field with largest/smallest measure enabling the determination of the optimal beam shape for any specific case.

Theory of resonant radiation force exerted on single organic molecules near metallic nanogap
H. Ishihara, Y. Mizumoto, Osaka Prefecture Univ. (Japan)

The targets of the laser manipulation have been shifting to nanoscale objects including single molecules. For manipulating nano-objects, we have proposed to utilize an electronic resonance[1], and recently its feasibility has been experimentally demonstrated[2]. On the other hand, there has been growing attention to the nanoparticle trapping by using gap plasmons[3]. A localized electric field with a steep gradient strongly attracts nanoparticles. Since such light electric field has a spatial structure with a single molecular scale, the spatial interplay between the electric field and molecular wavefunctions plays an essential role for the molecular manipulation, and hence, the resonant manipulation by using nanogap is expected to become a powerful tool to control molecular alignment and orientation.


Enhanced optical forces in hybrid plasmonic waveguides
X. Yang, Y. Liu, R. F. Oulton, X. Yin, X. Zhang, Univ. of California, Berkeley (United States)

Gradient optical forces have been broadly exploited in dielectric waveguides and cavities for realizing many exciting applications in optomechanics. Metallic nanostructures, with subwavelength optical confinement arising from surface plasmon polaritons, bring new capabilities in optical forces enhancement. Here we numerically demonstrate that the optical force applied on the silicon dielectric waveguide by the silver substrate in hybrid plasmonic waveguide system can be enhanced by more than one order of magnitude compared to the optical force generated between the silicon waveguide and the glass substrate in conventional photonic waveguide system, at wavelength of 1,550 nm. This enhancement arises from the deep subwavelength optical energy confinement and the small mode propagation loss of the hybrid plasmonic mode. The structural dependence of the optical forces and the optimized waveguide design are analyzed with both Maxwell’s stress tensor formalism and the coupled mode theory, in order to reveal the mechanism of this enhanced optical force. We also demonstrate that the optical trapping force applied on a single dielectric nanoparticle with size of 5 nm in water can be strongly enhanced utilizing the hybrid plasmonic mode. The optical trapping potential for the nanoparticle from the hybrid plasmonic mode is approximately 30 times stronger than the one in the photonic mode, due to its strong localization of the optical field in the gap region. Such an interesting result may be useful to design nanoscale optical tweezers to manipulate individual nanoscale objects such as single biomolecules or quantum dots.
Optical binding with anisotropic particles: Resolving the forces and torques
M. M. Coles, S. N. A. Smith, D. L. Andrews, Univ. of East Anglia Norwich (United Kingdom)

In the phenomenon known as optical binding, optical fields induce significant forces between microparticles of dielectric matter. Most experimental studies have centred on particles of spherical morphology, assumed to be isotropic and able to tumble freely in a fluid. However, when birefringent microcrystals and anisotropic nanoparticles such as carbon nanotubes are held in an optical trap, it is essential to account for their orientation. These particles are susceptible not only to optical forces but also torques, and there is considerable interest in their response to light that conveys angular momentum – especially optical vortices. Before the full effects of such interactions can be fully understood, however, it is necessary to cultivate a thorough understanding of the rotational effects that operate in optical binding with conventional laser radiation. Here, the orienting effect of the radiation on each individual particle, as well as the orienting influences they exert on each other, need robust theory to account for partial alignment with throughput radiation.

The aim of this paper is to develop, using quantum electrodynamics and perturbation theory, analytical expressions for the observables associated with pair-wise optical binding in anisotropic, non-polar particles. The intricacies of weighted rotational averaging and tensor analysis are tackled, deploying newly devised methods to resolve results into forms amenable to experimental application. Analysing the resulting equations allows the identification of terms corresponding to specific properties of the considered particles, including terms reflecting the degree of anisotropy. It is then straightforward to recognise criteria for the validity of commonly held approximations.

Biophotonics in turbid environments.
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We review recent advancements in laser field optimization within turbid environments. Before laser light enters random, turbid and scattering media its wavefront can be pre-shaped to form latter high intensity focal spots after or within the turbid layers to be further exploited for biophotonics methods such as optical trapping or nano-surgery to name a few.

The method is based on the field decomposition into a series of orthogonal modes. One of them is selected as a phase reference whilst the remaining ones are interferometrically tested for particular phase giving the highest intensity signal when interfering with the reference mode at an intensity probe such as fluorescent particle. When applying the optimal phase for all the modes simultaneously the optimal focus is produced at the intensity probe as all the modes meet in phase. The remaining once are interferometrically tested for particular phase giving the highest intensity signal when interfering with the reference mode at an intensity probe such as fluorescent particle. When applying the optimal phase for all the modes simultaneously the optimal focus is produced at the intensity probe as all the modes meet in phase.

Digital holography through multimode fibers
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Optical fibers can guide a light beam across long distances or through turbid media like biological tissues. Multimode fibers can propagate a light beam carrying a large information encoded in the complex coefficients of its expansion in the propagating modes. The main obstacle in using such a set of degrees of freedom comes from the fact that one always ends up having a random speckle pattern at a multimode fiber output. It is natural then to ask whether such a structured noisy pattern could be shaped with a spatial resolution of a single speckle size. Spatial light modulators seem to be the ideal tool for achieving this. We recently demonstrated that phase only modulation can be used to shape a light beam in such a way that, after propagation along a multimode fiber, most of the outgoing light will flow through one or few target spots having the size of a single speckle and arbitrarily located in space. By directly extracting the fiber’s end-to-end field propagator we can infer the optimal phase modulation for a desired output, which means that we can have few dynamically reconfigurable target spots. We show that such light spots can optically trap dielectric objects allowing holographic optical micromanipulation with a single multimode fiber. We will also discuss the possibility of imaging using a single multimode fiber endoscope.

Comparison of design algorithms for fast hologram generation in CUDA
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We have implemented different algorithms for fast hologram generation, aimed for holographic optical tweezers applications, using the parallel computing architecture CUDA. We compare the performance of different implementations of the Gerchberg-Saxton algorithm and provide guidelines for choosing the best suited version with respect to the application. Included in the comparison are three versions of the Gerchberg-Saxton algorithm, one using fast Fourier transforms for propagation and two different implementations using direct summations. The latter two are mathematically equivalent but show radically different dependence on the number of traps in terms of calculation time. Included is also a “lenses and prisms” algorithm for extremely fast hologram generation. It is found that optimized holograms producing hundreds of traps using an FFT based- or tens of traps using direct summation based Gerchberg-Saxton algorithms may be generated in less than 10 ms. This is well below the response time of most commercially available spatial light modulators and thus the use of non-optimizing algorithms such as the “lenses and prisms” algorithm is no longer motivated in many applications. Accompanying this work is a software package including the implementations used in the comparison. The software is made available free of charge under the GNU General Public License (GPL) along with a graphical user interface for interactive control of holographic optical traps.

Optical trapping using conical refraction of light

Conical diffraction of linearly polarised light in a biaxial crystal produces a beam with a crescent-shaped intensity profile. Rotation of the plane of
Polarization produces the unique effect of spatially moving the crescent-shaped beam around a ring. We use this effect to trap microspheres and white blood cells and to position them at any angular position on the ring. Continuous motion around the circle is also demonstrated simply by rotating the polarizer continuously. This crescent beam does not require an interferometric arrangement to form it, nor does it carry optical angular momentum. The ability to spatially locate a beam and an associated trapped object simply by varying the polarisation of light suggests that this optical process should find application in the manipulation and actuation of micro- and nano-scale physical and biological objects. Using the process of cascade conical refraction in which light travels through two biaxial crystals in succession, we can produce a ring beam with a Gaussian spot at the centre of the ring. We show using this geometry that we can trap a particle in the Gaussian beam and in the ring trap simultaneously. We can control both the separation of the particles and also their relative angular position using the linearly polarized conical refraction case.

**8097-54, Session 12**

**Reconfigurable 3-dimensional optical route formed by fiber-optic pseudo-Bessel beam arrays**

J. Kim, S. Lee, Y. Jeong, J. Shin, K. Oh, Yonsei Univ. (Korea, Republic of)

Due to its unique non-diffracting and self-reconstructing nature, Bessel beam has been successfully adopted to expand the single optical trap into multiple traps along the longitudinal direction. Here we present a novel implementation of Fourier optics along a single strand of hybrid optical fiber in a monolithic manner that can generate a pseudo-Bessel beam. The incident fundamental mode of an optical fiber is adiabatically transformed to a ring mode by a hollow optical fiber, which serves as a micro annulus aperture in the Fourier transformation. Multiple trapping experiments for both polystyrene beads and living Jurkat cells were performed along the beam. Especially, four living Jurkat cells were trapped in a row, which can be applied to cellular level spectroscopy. Furthermore, optical transport of the trapped particles along a 3-dimensional curvilinear optical route was demonstrated by spatially multiplexing pseudo-Bessel beams. The radius curvature of the optical route was smaller than the particle size, which has not been possible in prior micro-fluidic channel technologies. The novel concept to spatially multiplex the fibre optic arrays could form a new all-optical building block to realize reconfigurable transportation of particles in true 3-dimensional space overcoming the prior microfluidic routes. Detailed discussion of optical route formation using fiber optic couplers and fiber lasers will be discussed along with explanation on device fabrication.

**8097-55, Session 12**

**Optical chaining of dielectric particles by two counter-propagating all-fiber Bessel-like beams**

S. Lee, J. Kim, Y. Jeong, J. Park, K. Oh, Yonsei Univ. (Korea, Republic of)

Optical chaining of multiple dielectric beads was experimentally demonstrated using two counter-propagating Bessel-like beam generated by multimode interference in optical fibers embedded in polydimethylsiloxane (PDMS) channel. The Bessel-like beam generator was composed of a single mode fiber concatenated with a segment of coreless silica fiber of 1600 um length and a fiberized focusing lens. A Bessel-like beam was achieved by multimode interference along the coreless silica fiber, and the beam maintained an average center beam diameter of 4.9 um over an axial length of 300 um, having a nearly uniform output power within a variation of ±0.25%. The proposed device was designed to be compatible with a continuous wave Yb-doped fiber laser oscillating at the wavelength of 1084 nm in order to provide all-fiber solution. A micro-fluidic system of cross-channel was fabricated using PDMS to embed two counter-propagating fiber probes, which provided an accurate beam alignment and stable delivery of dielectric beads. One dimensional optical potential well was formed along the counter propagating beams, where the dielectric beads were trapped. For the particles with the diameter in the range of 2 to 4.5 um, which is smaller than the central beam diameter, unique chaining of multiple particles was observed, whereas particles were assembled in a form of chain. By adjusting the optical power we could transport the whole chain of particles along the optical beams. Detailed discussion of the optical chaining of particles is presented along with characterization the optical force.

**8097-56, Session 12**

**Generation of high efficiency vector beams with synthetic phase holograms**

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Recently, vector beams (VB) have attracted significant interest due to its unique characteristics. In particular, the presence of a strong longitudinal component of the electric field and tighter focusing in comparison to homogeneously polarized beam when the VB have axial symmetry in amplitude and polarization. Several generation methods for obtaining VB have been reported. However, most of them are unstable, complicated and the output efficiency is small.

In 2007, Wang et al. proposed a method to produce arbitrary VB using an amplitude spatial light modulator (SLM) and a common path interferometric arrangement. They use an amplitude hologram to generate VB and they only encode VB with constant intensity distribution. Recently we published two novel phase synthetic holograms (Arrizón et al. 2007) that allow us to encode arbitrary complex scalar fields into phase-only function with high quality reconstruction and efficiency of the encoded field. In this work we present a novel method to generate reconfigurable vector beams with arbitrary polarization states employing these phase synthetic holograms. The method is based on the linear recombination of two orthogonally homogeneous polarized scalar modes, that allow the generation of vector fields with arbitrary spatial varying polarization. The two orthogonally polarized modes are superposed by using a common path interferometer which consists of a 4-f system and a phase SLM. We demonstrate the generation of high efficiency and quality Bessel and Laguerre-Gaussian vector beams of different orders with radial and azimuthal (or any other combination) polarization distributions.

**8097-57, Session 12**

**Vector fields with hybrid states of polarization and their orbital angular momentum**

X. Wang, B. Gu, J. Chen, Y. Li, Nankai Univ. (China); J. Ding, Nanjing Univ. (China); C. Guo, Shandong Normal Univ. (China); H. Wang, Nankai Univ. (China)

Vector fields with spatially inhomogeneous states of polarization (SoPs) have become a subject of rapidly growing interest, due to its unique features and novel applications in various realms, such as optical trapping and particle manipulation, micromechanics, and biology. However, the generation of arbitrary vector fields is still a challenge. We describe a convenient approach for generating arbitrary vector fields in a 4f system with a spatial light modulator (SLM) and a common path interferometric arrangement. A computer-generated hologram is indirectly onto SLM for phase fields. Realization of a variety of polarization configurations confirms the reliability and flexibility of our method. As examples, we experimentally demonstrate the typical radially and azimuthally polarized fields, high order cylindrical vector fields and vector fields with hybrid SoPs.

It is generally accepted that optically isotropic materials are not
influenced by polarization, whereas anisotropic materials can be. However, we validate that the polarization feature can also influence isotropic materials. We predict a new category of optical orbital angular momentum that is associated with the curl of polarization and a kind of vector field with radial-variant hybrid states of polarization that can carry such novel optical orbital angular momentum. We present a scheme for creating the desired vector fields. Optical trapping experiments validate that the vector fields, which have no additional phase vortex, exert torques to drive the orbital motion of the trapped isotropic microspheres.

8097-58, Session 12

The sonic screwdriver

G. C. Spalding, Illinois Wesleyan Univ. (United States); A. Volovich, Z. Yang, C. Demore, M. P. MacDonald, S. Cochran, Institute for Medical Science & Technology (United Kingdom)

When samples of interest are small enough, even the relatively weak forces and torques associated with light can be sufficient for mechanical manipulation, can offer extraordinary position control, and can measure interactions with three orders of magnitude better resolution than atomic force microscopy. However, as the components of interest grow to slightly larger length scales (which may yet be of interest for microfluidic, “lab-on-a-chip” technologies and for research involving biomedical imaging), other approaches gain strength. This talk includes discussion of the angular momentum carried by sonic beams that we have implemented both to levitate and controllably rotate disks as large as four inches (!) across. Discussion of such acoustic beams complements the discussion of the angular momentum carried by light. Also, these beams are useful for a variety of reasons (not least for aberration correction). Methods, including the use of holographically structured fields, will be discussed.

8097-72, Session 12

Flexible dual-beam optical trapping

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We present an advanced configuration for optical manipulation of micro- and nano-objects employing adaptive optical element to control properties of more counter-propagating beams overlapping in a sample chamber. This system can eliminate optical aberrations in both pathways, online re-align the system remotely from a computer interface, arbitrarily switch in real time between various beams types (vortex, Gauss, Bessel etc.) and their spatial intensity distributions (beam width, vorticity etc.). We demonstrate variety of applications of this setup ranging from formation of spatial solitons, longitudinal optical binding, precise particle delivery via optical conveyor belt, stable confinement of low-index particles, and controlled rotation or swing of heterogeneous objects.

8097-64, Poster Session

Optical manipulation of aerosols using Surface Acoustic Wave Nebulisation

S. Anand, J. Nylk, C. D. Dodds, Univ. of Dundee (United Kingdom); J. M. Cooper, S. L. Neale, Univ. of Glasgow (United Kingdom); D. McGlone, Univ. of Dundee (United Kingdom)

High density micron sized aerosols from liquid surfaces were generated using surface acoustic wave (SAW) nebulisation. The SAWs are made from a set of interdigitated electrodes (IDT) deposited on a lithium niobate (LiNbO3) substrate and are designed to operate around 12MHz. RF powers of ~235mW are used to achieve nebulisation. Powers below this results in droplet motion across the substrate surface. The nebulisation process generated aerosols of a narrow size distribution with diameter ranging from 0.5-2 µm. We consider ways in which these aerosols can be loaded into optical traps for further study. In particular we look at how SAW nebulisation can be used to load particles into a trap in a far more robust manner than a conventional nebuliser device. We demonstrate trapping of a range of particle types and sizes and analyse the size distribution of particles as a function of the applied frequency to the SAW device. We show that it is simpler to load, in particular, solid particles into optical traps using this technique compared to conventional nebulisation. We also consider the possibilities for loading nanoparticles into aerosol optical tweezers.

8097-65, Poster Session

Brownian movement rectification of microparticles using pulsating ratchets

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In recent years, particle transport at microscopic level has become an important research topic which has led to the understanding of directed particle transport subjected to thermal fluctuations. Brownian motors (also called ratchet mechanism) are one of the most interesting phenomena of work generation in nonequilibrium systems under random external forces. In this work, we report Brownian movement rectification of 0.5 micron diameter latex particles using pulsating ratchets. In order to implement the asymmetric potential, a 2D asymmetrical saw tooth phase pattern is displayed on a spatial phase modulator and then transformed into an intensity pattern by using the phase contrast method. This pattern is focused down with a 100x microscope objective obtaining a pattern of ~40x40 square microns at the focal plane. The pattern’s parameters can be dynamically controlled: periodicity, asymmetry, and on/off rate which allows optimization of directed transport. We found that there is an optimum value for the on/off rate and particle diameter/spatial period obtaining an average speed of 0.6 microns/s. The 2D pattern allow us to manipulate a large number of particles, in contrast to previous studies were only one particle has been studied, opening the opportunity to massive sorting of particles.

8097-66, Poster Session

Optically induced zinc nanoparticles selective deposition on single-mode fiber end

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Metal particles manipulation with radiation pressure of laser light is possible, only if the diameters of these particles are much smaller those of the wavelength of the laser light (Rayleigh particles). In this case, the gradient force is larger than both the scattering and absorption forces. We have made a numerical study considering a Gaussian beam with a fundamental mode that interacts with zinc spherical nanoparticles with different diameters (< 44 um), and submerged into isopropyl alcohol in order to examine the behavior of the radiation pressure (scattering, absorption and gradient force). The results of this study show that the gradient force is greater than other forces only by ast method. This certain diameter. Moreover, by using the gradient force of the laser light, the zinc nanoparticles were deposited on a single-mode fiber end. The images obtained by optical microscope and atomic force microscope.
show that the particles deposited on the optic fiber end exhibit a uniform distribution of nanoparticles in the core which can be used as optical mirrors, sensors, saturable absorbers, etc.

8097-67, Poster Session

**Trapping of nanoparticles in water by evanescent wave near a NSOM probe**

B. Liu, L. Yang, Y. Wang, Harbin Institute of Technology (China)

Applying Maxwell stress tensor and 3D FDTD methods, physical properties of nanoparticle trapping by evanescent wave near the NSOM probe, including trapping size, trapping position and role of other forces versus optical trapping force, are revealed. From the distribution of trapping force acted on a nanoparticle along three axis directions, it is found that the nanoparticle tends to be trapped to the aperture edge and center surface of the probe tip. In experiments 120 nm polystyrene particles are trapped in a multi-circular shape and two circles of polystyrene particles are arranged to different positions on the substrate. The results indicate that the NSOM probe is able to trap nanoparticles with lower laser intensity than that required by conventional optical manipulator.

8097-68, Poster Session

**Optical trapping of semi-conducting nanowires**

S. H. Simpson, S. Hanna, Univ. of Bristol (United Kingdom)

Semi-conducting nanowires lend themselves to a variety of applications. For example, they are ideal candidates for components in novel electronic and optical devices. Evidently, optical trapping has a part to play in the assembly of such structures and there is much experimental work directed toward this goal. Theoretical work, however, is relatively sparse. One reason for this is that the very high aspect ratios involved, prohibiting the use exact methods. Here we investigate the use of the discrete dipole approximation to calculate optical forces on nanowires. Where possible, results are compared with available analytical and semi-analytical techniques. The accuracy is assessed and possible modifications to the algorithm are suggested. Subsequently we investigate the optical forces on nanowires trapped in single and multiple Gaussian beams. The domain between trapping and non-trapping behavior is demarcated, and observed to be highly dependent on the optical environment. Thus, a nanowire which will trap in a single beam, may not trap horizontally in a dual beam system, and a nanowire which will trap in this way may cease to do so if the polarization states of the beam are altered. For single beam trapping, with the nanowire vertically oriented, it is shown that the vertical stiffness decreases exponentially with increasing length, whilst it remains tightly trapped in other respects. Such systems can therefore be used as highly sensitive force or mass sensors. Finally, we show simulations of the thermal motion of optically trapped nanowires and investigate its impact on trap stability.

8097-69, Poster Session

**Optical trapping of single gold nanoparticles with higher order laser modes**

A. Huss, R. Jäger, A. M. Chizhik, J. Mihaljevic, A. J. Meixner, Eberhard Karls Univ. Tübingen (Germany)

Optical trapping is one of the most promising tools for nanochemistry and nanoengeneering. Since Arthur Ashkin [1] brought optical trapping to life, many steps forward have been made. To form a stable trap it is required to overcome the scattering and absorption forces, therefore metallic and magnetic nanoparticles cannot be trapped easily. Recently, trapping of single gold nanoparticles in aqueous solutions with a linearly polarized Gaussian beam and fixing them in controlled pattern on the sample surface has been experimentally shown [2,3]. However, to increase the trapping force and stability of the trap the use of cylindrical vector beams (also known as doughnut-modes) has been suggested according to theoretical calculations [4]. Since a focused radially polarized laser mode has higher electric field component in the propagation direction with respect to the linearly polarized Gaussian beam, it provides an advantage for optical trapping. Moreover, the weak in-plane component of the radially polarized laser mode pushes passing nanoparticles into the focus of the beam.

In this work we present our recent experimental and theoretical results upon optical tweezers using a radially polarized light. A home-built confocal microscope setup has been used for focusing a radially polarized laser beam with a high numerical aperture immersion oil objective lens. This allowed us to use the advantages of high-resolution confocal microscopy and cylindrical vector beams for trapping nanometer-size gold spheres.


8097-70, Poster Session

**Micro- and Nanoparticle Optical Trapping Using Cylindrical Vector Beams**

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The vast majority of optical tweezers use a trapping laser beam with a spatially homogeneous state of polarization, such as linear, elliptical and circular polarizations. However, spatial modulation of the polarization of the trapping beam has the potential to add a further degree of control to trapping parameters and allow further optimization of the trap for certain particle types.

Laser beams in which the polarization is directed radially outwards from the beam axis have received significant recent attention due to their interesting focusing properties. These beams contain a polarization singularity along the beam axis where the electric field amplitude is identically zero, and thus exhibit an annular intensity distribution in the far-field. The polarization configuration and ‘donut’ intensity profile result in tighter focusing of the radially polarized beam when compared to a linearly polarized Gaussian beam, producing a smaller transverse size of the focal spot. Furthermore, due to symmetries in the polarization components, the time-averaged axial component of the Poynting vector is zero, thus the scattering force vanishes, making the radially polarized tweezer an ideal candidate for trapping nano-particles.

We investigate the use of radially polarized laser beams for optical trapping of micro- and nano-particles. We present quantitative experimental measurements of the trap spring constants for a wide range of parameters and particle sizes and compare the results to those obtained using the more conventional linearly- and circularly- polarized trapping beams. Additionally, we investigate shaping of the trapping volume for trapping of elongated micro and nanostructures (nanotubes, nanowires).

8097-71, Poster Session

**Discrete complex amplitude filter for ultra long optical tube**

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In this paper, a discrete complex amplitude filter is designed to obtain the focused hollow field with ultra long depth of focus (DOF). As for a high numerical aperture (NA=0.95) objective lens obeying the sine condition, the distribution of the focused field in the focal region can be engineered into a field like a long “tube” with flat wall through manipulating the transmitted amplitude and the phase delay of the field at the incident pupil plane. This complex amplitude of the pupil plane can be discretized into multiple zones with different radius, transmitted amplitude and phase delay. A focused tube field with 9, depth of focus can be created as an example through separating and averaging of the projected pupil radiation field of dipole array in the focal region. Imperfections of the designed filter will influence the quality of the generated optical tube field. Deviation of the radius, transmitted amplitude and phase in each zone will influence the profiles of the tube field to some extent and these are discussed (Fig.1 (a) and (b)). For the optical trapping and manipulation, this created tube field can expand the manipulated distance and increase the trapped particles’ numbers.

8097-73, Poster Session
Femtosecond laser pulses for chemical-free embryonic and mesenchymal stem cell differentiation
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Owing to their self renewal and pluripotency properties, stem cells can efficiently advance current therapies in tissue regeneration and/or engineering. Under appropriate culture conditions in vitro, pluripotent stem cells can be primed to differentiate into any cell type some examples including neural, cardiac and blood cells. However, there still remains a pressing necessity to answer the biological questions concerning how stem cell renewal and how differentiation programs are operated and regulated at the genetic level. Indeed, Uchugonova et al, 2008 [1] reported on an urgent requirement in stem cell research on technologies for non-invasive, marker-free observation of growth, proliferation and stability of living stem cells under physiological conditions. In their studies, through the detection of second-harmonic generation signal, they investigated two-photon excited auto-fluorescence of human stem cells and the onset of collagen production of differentiated cells.

Femtosecond (fs) laser pulses have been reported to non-invasively deliver exogenous materials, including foreign genetic species into both multipotent and pluripotent stem cells successfully [2, 3]. Through this multi-photon facilitated technique, directly administering fs laser pulses onto the cell plasma membrane induces transient submicrometer holes, thereby promoting cytosolic uptake of the surrounding extracellular matter [4]. To display a chemical-free method of stem cell differentiation that utilises micro-litre scale volumes of reagents, we report on using a multi-photon facilitated technique, directly administering fs laser pulses onto the cell plasma membrane induces transient submicrometer holes, thereby promoting cytosolic uptake of the surrounding extracellular matter. In their studies, through the detection of second-harmonic generation signal, they investigated two-photon excited auto-fluorescence of human stem cells and the onset of collagen production of differentiated cells.

References:

8097-74, Poster Session
Heating effects on NG108 cells induced by laser trapping
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Optical tweezers (OT) are an innovative and powerful technique with a wide range of applications in the physical and biological sciences. This novel novel microtool uses a highly focused laser beam to trap and manipulate microscopic neutral objects. Typical traps in cell biology are generally based on lasers producing from 25 mW to 2 W in the specimen plane. Non-contact force for cell manipulation, force resolution as accurate as 0.1 pN and amiability to liquid medium environments are the main advantages of this technique.

Nevertheless, the response of living matter to the interaction with laser light still remains unclear. Previous studies evaluating the cell response to laser irradiation with OT have already been performed. Several parameters (laser power, irradiation time, wavelength...) have been tested in various types of cells and organisms and different cell functions (cloning efficiency, ability to grow, motility...) and reactions (viability, apoptosis and stress response) have been used to assess damage. However, conclusions do not seem to be unanimous yet.

Photon absorption is a major detrimental process when laser radiation interacts with cells, consequently, generating both photodamage and thermodamage. Particularly, this work is focused on the damage induced by heating of the sample or thermodamage. The heat shock or stress response is the earliest defence mechanism of cells when subjected to physiologically relevant changes in the environment. This mechanism gives the stressed cell added protection, thus, allowing for continued cell survival. However, high levels of thermodamage can lead to other type of reactions in the cell such as apoptosis or necrosis.

This work aims at assessing the induced laser heating effects on NG108 cells by studying the induction of apoptosis and necrosis on these cells. Furthermore, quantification of the local temperature increase in the focus of the optical trap with the back-focal-plane interferometry technique is also one of the main goals.

8097-75, Poster Session
Optical tweezers used to assess the effects of viscosity on sperm motility
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The purpose of this study was to analyze sperm motility in a range of viscous media. Viscous media solutions were made by using varying concentration of methylcellulose yielding 3, 6, 9, and 15 centipoises. Motility parameters were collected using customized tracking software that measures the curvilinear velocity (VCL) and the escape force (Pesc) of an individual sperm. The Pesc was measured by using a 1064 nm Nd:YVO4 continuous wave laser that optically traps motile sperm at a maximum power of 450 mW in the focused trap spot. The VCL was measured frame by frame before trapping. Multiple experiments were performed to collect motility parameters in increasing viscosity media. To complement our motility data, sperm were labeled with the fluorescent dyes DiOC6(3) and JC-1 to measure mitochondria membrane potential and during trapping in to provide insight to the sperm energetics under various viscous conditions.

The preliminary results showed that there was a correlation between swimming speed (VCL) vs. viscosity and escape force (Pesc) vs. viscosity. The relationship between VCL and viscosity showed that there was a decreased VCL with increasing viscosity; however there was an increase in Pesc with increasing viscosity. There was no change in
is trapped by a traditional optical tweezer, whereas the wider ‘main
chip’, a shield structure divides a microfluidic channel into two parallel
microscopic environments. In our device, termed a “manometer-on-a-
channel” conveys fluids whose behavior we are interested in studying.
Because parallel channels always share the same pressure drop when
a flow is applied, the displacement of the bead in the ‘side channel’,
which we monitor using a video camera, reflects the pressure variation
over both channels. The pressure-displacement relation is calibrated by
measuring the extension of a bead trapped in a test chip containing a
channel with the same cross section as the ‘side channel’ of the actual
device. This test chip is connected to an external pressure source. To
demonstrate the device, we send oil droplets in water, generated by a T
junction structure treated to be hydrophilic, through the manometer, and
record the position of the bead trapped in the side channel. Our results
illustrate that the device can detect single droplets and differentiate them
based on size. The droplets are detected by monitoring the bead position
with time. Comparison with calibration show that our device is sensitive
enough to resolve a pressure variation below 0.1 Pa. We anticipate that
our device will be useful for understanding the behavior of emulsions and
multiphase flows.

8097-59, Session 13

Plasmonic nanopillar arrays for optical trapping, biosensing, and spectroscopy
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In this work, we propose a plasmonic platform based on monopole antenna arrays that can enable high sensitive biosensing, vibrational spectroscopy and high precision optical trapping at the same time. Perpendicular incident light is coupled to Surface Plasmon (SP) modes through the system. This is one of the significant advantageous over other sensing/trapping platforms based on angled illumination source. The tight localization of plasmonic excitation in nanopillar structure leads to narrow resonances in the spectrum. Hence, we achieve high refractive index sensitivity, ~675 nm/RIU with high figure of merit (FOM), ~112.5. This FOM value is higher than the preceding plasmonic structures based on the localized SP modes. SPs are localized at specific hot spots on the top surface of the gold nanopillars which lead large near-field intensities with enhancement factors of ~9000 highly desirable for surface Raman spectroscopy. The hot spots with high near-field enhancement depend on the polarization of the incident source. We also achieve high optical force, ~350 pN/μm^2, from these hot spots which allows optical trapping of nanoparticles with excitation source of low power. Since the location of the hot spots highly depends on the direction of polarization, we can always get the strongest directional force we can achieve from the system. Our proposed structure serves for optical trapping of bioparticles, spectroscopy measurement and real-time biodetection at the same platform which could attract many attentions from wide range of researches and studies.

8097-60, Session 13

Controlling and utilizing optical forces at the nanoscale with plasmonic antennas
A. Lovera, O. J. F. Martin, Ecole Polytechnique Fédérale de
Lausanne (Switzerland)

Plasmonic dipole antennas are powerful optical devices for many applications since they combine a high field enhancement with outstanding tunability of their resonance frequency. The field enhancement, which is mainly localized inside the nanogap between both arms, is strong enough to generate attractive forces for trapping extremely small objects flowing nearby. Furthermore it dramatically enhances their Raman scattering cross-section generating SERS emission. In this talk, we demonstrate how plasmonic antennas provide unique means for bringing analyze directly into hot-spots by merely controlling the optical force generated by the plasmon resonance. This technique is very suitable for immobilizing objects smaller that the

8097-76, Poster Session

Measuring stall forces in vivo with optical tweezers through light momentum changes
J. Mas, A. Farré, C. López-Quesada, E. Martín-Badosa, M.
Montes-Usategui, Univ. de Barcelona (Spain)

The stall forces of processive molecular motors have been widely studied in vitro. Even so, in vivo experiments are required for determining the actual performance of each molecular motor in its natural environment. We report the direct measurement of light momentum changes in single beam optical tweezers as a suitable technique for measuring forces inside living cells, where few alternatives exist. The simplicity of this method makes it convenient for measuring the forces involved in fast dynamic biological processes. We present our measurements of stalling events showing the pulling force of processive molecular motors inside living cells.

8097-77, Poster Session

Temporal evolution of thermocavitation bubbles using high speed video camera
J. P. Padilla-Martinez, J. C. Ramirez-San-Juan, Instituto Nacional
de Astrofísica, Óptica y Electrónica (Mexico); G. Aguilar, Univ. of
California, Riverside (United States); R. Ramos-Garcia, Instituto Nacional de Astrofísica, Óptica y Electrónica (Mexico)

Thermocavitation induced by CW low laser powers in highly-absorbing solution is new field of research that may have useful applications in lithography, micro patterning of metallic thin films and sonoporation among others. Thermocavitation bubbles are always in contact with the substrate due to the high absorption coefficient of the solution. The temporal evolution of these bubbles is quite complex as it has been already demonstrated in short pulsed-laser cavitation. In a previous work, we reported its temporal evolution using indirect methods; however details information cannot be obtained. In this work, a precise description of the bubble dynamics is achieved using a high speed video camera (Phantom V7, Version: 9.1) running to 111,111 frames per second of 64 × 64 pixels resolution. These videos give valuable information on the dynamics like bubble lifetime, maximum radius and collapse time as a function of laser power (62 to 200 mW) and beam waist. For a power laser of 150 mW (at the exit of the microscope objective) the bubble grows regularly without any significant modification of its half-hemisphere shape, reach its maximum radius (~1037 micron) in 180 microseconds and then collapses rapidly in 135 microseconds. Near the collapse, the bubble departs from its semi-spherical shape taking a step-like shape. Bubble’s rebound is weak and not always is observed. The bubble’s radius can be controlled with the beam waist, obtaining larger bubbles for larger beam waist.

8097-78, Poster Session

An optical manometer-on-a-chip
Y. Jin, K. Crozier, Harvard Univ. (United States)

We present a novel pressure-based approach combining optical trapping with microfluidics to investigate the properties of complex fluids in microscopic environments. In our device, termed a “manometer-on-a-
chip”, a shield structure divides a microfluidic channel into two parallel parts. In the center of the narrower ‘side channel’, a polystyrene bead is trapped by a traditional optical tweezer, whereas the wider ‘main
channel’ conveys fluids whose behavior we are interested in studying. Because parallel channels always share the same pressure drop when
a flow is applied, the displacement of the bead in the ‘side channel’,
which we monitor using a video camera, reflects the pressure variation
over both channels. The pressure-displacement relation is calibrated by
measuring the extension of a bead trapped in a test chip containing a
channel with the same cross section as the ‘side channel’ of the actual
device. This test chip is connected to an external pressure source. To
demonstrate the device, we send oil droplets in water, generated by a T
junction structure treated to be hydrophilic, through the manometer, and
record the position of the bead trapped in the side channel. Our results
illustrate that the device can detect single droplets and differentiate them
based on size. The droplets are detected by monitoring the bead position
with time. Comparison with calibration show that our device is sensitive
enough to resolve a pressure variation below 0.1 Pa. We anticipate that
our device will be useful for understanding the behavior of emulsions and
multiphase flows.
Holographic tweezers: a platform for plasmonics

M. Dienerowitz, G. M. Gibson, R. W. Bowman, A. Curran, M. J. Padgett, Univ. of Glasgow (United Kingdom)

Optical manipulation of metal nanoparticles has attracted a lot of interest over the past years yet it is still considered challenging1-4. The nanoscale size of the particles as well as their enhanced absorption and reflectivity render them hard to control with standard trapping techniques. A well-known phenomenon from plasmonics is the strong interaction between adjacent plamson resonances when exited by laser light. In the case of freely floating particles this results in a complex force mechanism displacing metal nanoparticles. It is possible to exploit the resonance to induce attractive as well as repulsive forces expanding the manipulation toolkit for metal nanoparticles5.

We present a nanoparticle workstation incorporating holographic tweezers to manipulate several trapped metal nanoparticles simultaneously. The versatility of the holographic tweezers and the submicron control of our sample stage allow precise particle positioning. In addition we assess each trapped particle by monitoring its specific spectral properties. By changing the distance between two trapped particles we monitor the interaction of their particle plasmons when brought close enough. This in situ monitoring of the changing plasmon resonances has provided new insights into plasmon coupling6. We focus particularly on nanoparticle imaging in our experiments and present a new darkfield microscopy technique which does not limit the numerical aperture of the trapping objective.

Metal nanoparticles have become popular tools for biological applications and enhanced spectroscopy techniques because of their biocompatibility. Improving the manipulation skills available and facilitate measurement techniques helps to advance the controllability of metal nanoparticles employing them as nanometric sensors and antennas.

Optical trapping in a microfluidic device via surface plasmon resonance on patterned hole arrays

S. Weber, D. J. Day, M. Gu, Swinburne Univ. of Technology (Australia)

The manipulation of polystyrene microspheres via the application of Surface Plasmon Resonance (SPR) based optical effects inside patterned and non-patterned microfluidic device was investigated. Using the Kretschmann geometry, light from a Nd:YAG laser ($\lambda = 1064$ nm) is coupled into a $40 \pm 2$ nm gold film coated onto a glass slide, resting on a glass prism ($n = 1.785$) via an index matching liquid ($n = 1.516$). The SPR angle is calculated to occur at $63.0 \pm 1.0^\circ$ for an incident wavelength $\lambda = 1064$ nm, this is confirmed via experimental observation. A $200 \times 200 \mu m$ array of $4 \mu m$ holes was etched into the microfluidic devices gold surface using an amplified femtosecond pulse laser (Spitfire, Spectra Physics, 800 nm 1 kHz) and direct multiphoton etching using a 0.70 N.A. NIR objective lens. 15, 10, and 4.3 $\mu m$ sized microspheres were placed in a sample of phosphorus buffer solution and pumped into the microfluidic chamber using a gravity pump system. The incident light illuminated the patterned region with the power being varied between 20 and 70 mW, both on the SPR angle and when the incident angle is de-turned by $4^\circ$ off the resonance position. We’ve observed that via the patterning of the gold surface layer the trapping efficiency can be increased compared to the unpatterned case. We have also demonstrated that the number of trapped microspheres can be controlled by either changing the power of the incident light or by changing the size of the microspheres being trapped.

Opto-mechanical force measurement of deep sub-wavelength plasmonic modes

J. Kohoutek, D. A. Dey, A. Bonakdar, A. Sklar, O. G. Memis, R. Gelfand, H. Mohseni, Northwestern Univ. (United States)

We show that the radiation force of a plasmonic antenna can be confined to an extremely small volume. We produce very high field intensities using compression of optical modes by orders of magnitude below their diffraction-limited volume using said antennae, and show significant radiation forces produced by these plasmonic modes. As a source we use a room temperature operated quantum cascade laser (QCL) working in the mid-infrared region of the optical spectrum as well as a commercially available fiber coupled laser operating at 1550 nm. We have used a finite-difference time domain method to simulate the plasmonic antenna to find the optimal resonance conditions, as well as the radiation force map computed by stress tensor method. We have then used electron beam evaporation and focused ion beam milling to fabricate the plasmonic antenna on the facet of the lasers. In parallel, we have developed a method capable of mapping the force with high sensitivity and nanometer spatial resolution, over the device. We have also used a lock-in to get the phase signal from the AFM in non-contact mode. We show that an external force can cause a change in phase of the AFM tip. We will compare our measured data with our FDTD simulation results.

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Ultrafast single and multiple electron transfer from quantum dots

T. T. Lian, Emory Univ. (United States)

Charge transfer to and from quantum dots (QDs) is of intense interest because of its important roles in QD-based devices, such as solar cells and light emitting diodes. Recent reports of multiple exciton generation (MEG) by one absorbed photon in some QDs offer an exciting new approach to improve the efficiency of QD-based solar cells and to design novel multi-electron/hole photocatalysts. However, two main challenges remain. First, the efficiency of MEG process needs to be significantly improved for practical applications. Second, the utilization of the MEG process requires ultrafast exciton dissociation prior to the exciton-exciton annihilation process, which occurs on the 10s to 100s ps time scale. In this presentation we report a series of studies of exciton dissociation in quantum dots by electron transfer to adsorbed electron acceptors. We show that excitons in CdSe and PbS QDs can be dissociated on the picosecond timescale to various adsorbates. As a proof of principle, we demonstrate that multiple excitons per QD (generated by multiple photons) can be transferred to adsorbed acceptors (J. Am. Chem. Soc. 2010, 132, 4858-4864). We will discuss the dependence of the electron transfer rates on the size and the nature of the quantum dots and possible approaches to optimize the multiple exciton dissociation efficiency.

Interfacial electron transfer in colloidal nanocrystals.

M. Jones, D. Woodall, S. Johnson, E. Williams, A. K. Tobias, Jr., K. J. Major, D. Woolford, The Univ. of North Carolina at Charlotte (United States)

Quantum confinement of photo-generated electrons and holes in colloidal semiconductor nanoparticles is well understood and results in a wide array of potentially important properties. Application of nanocrystals in photovoltaics requires rapid and efficient generation of separated charges, which must be transported away from the chromophore to do useful work. These charge separation processes originate from highly delocalized exciton states and can be understood in terms of electron transfer reactions that can localize an electron or hole into a ligand orbital or a nanocrystal trap state.

Electronic coupling of nanocrystal exciton states with states in the surrounding environment strongly influences relaxation dynamics. Nanocrystal charge transfer states typically have low absorption cross-sections, so it is hard to directly probe their role and relative impact on the underlying dynamics. Time resolved fluorescence spectroscopy reflects both radiative exciton recombination rates and non-radiative transitions rates to extrinsic surface or ligand states; however, interpretation of fluorescence transients is not trivial and typical multi- or stretched exponential decay models yield little specific photophysical insight.

I will describe a quantitative analysis method for temperature-dependent time-resolved fluorescence data applied to a series of nanocrystal systems and demonstrate how these data can be used to understand electron transfer dynamics. In addition I will present data obtained using a pulse-rate modulation technique with which we are able to unravel the contribution to these electron transfer dynamics from multi-exciton states. General features of charge transfer reactions are emerging from these analyses, which will be discussed in the context of future photovoltaic materials.

Nonlinear infrared spectroscopy of interface

W. Xiong, Univ. of Wisconsin-Madison (United States)

In this talk, I am going to cover two topics. First I will discuss our discovery of multiple conformations of Re dyes on nanocrystalline TiO2 film and the different charge transfer mechanisms we observed using 2D IR spectroscopy. Secondly, I will show some results of our recently developed heterodyned time domain SFG spectroscopy. It is a technique with higher sensitivity and better resolution and lineshape fidelity than the popular broadband frequency domain SFG technique. These improvements are critical for measuring spectra of non-compact, low surface coverage and disordered surfaces such as the dye-TiO2 interface.

Charge transfer across interfaces is an important step in many solar energy capture devices, such as dye-sensitized solar cells. Since the charge transfer happens right at the interface, the conformation of the molecules on the surface play a key role on their charge transfer behavior. Using 2D IR spectroscopy we found that there are at least three conformations of the dye molecules on the TiO2 nanoparticle surface. Further, using a transient 2D IR pulse sequence which can correlate the ground and excited electronic states of the dye, we showed that all three conformations participate in the charge transfer process but one of the conformations has a completely different charge transfer pathway. Further research will include monitoring the electron transfer dynamics of each conformation and determining the dye orientations using Sum Frequency Generation Spectroscopy (SFG), which is related to the second topic of my talk.

SFG is an interface specific second order infrared spectroscopy. One of its advantages is the ability to measure the dipole orientation relative to the surface. In the second half of my talk, I will discuss our newly developed heterodyned time domain SFG spectroscopy technique. It is a Fourier transform based technique that has better resolution and lineshape fidelity than the popular broadband frequency domain SFG spectroscopy. Moreover, heterodyned detection significantly improves the sensitivity and also allows a much more intuitive interpretation of the spectra by acquiring the real and imaginary part of it, which is not available using the homodyned detection method. Using heterodyned time domain SFG, we showed there is an inhomogenous binding distribution of a simple aryldiisocyanide molecule on the gold surface, and this result agrees well with recent theoretical work. The sensitivity, resolution, and lineshape improvements using the heterodyned time domain SFG spectroscopy are critical for applying SFG on a non-compact, low surface coverage, and disordered monolayer surface such as the dye-TiO2 surface in our charge transfer study.

Reference:

AC conductivity of nanoporous metal-oxide photoanodes for solar energy conversion

S. J. Koneczy, V. S. Batista, Yale Univ. (United States)

The temperature- and frequency-dependent ac conductivity of nanoporous metal-oxide semiconductors commonly used in technologies for solar photoconversion is analyzed using a model based on

Calculations of interface states between two polymers: polythiophene and polyselenophene

M. Côté, Univ. de Montréal (Canada)

Organic photovoltaic devices are presently the subject of intense research since they could eventually propose solar energy solutions at a much reduced cost compared to inorganic devices. Presently, electron transport in organic photovoltaic devices is achieved with a fullerene derivative (PCBM) but this solution has some disadvantages. First, the ratio of PCBM to polymer has to be quite high to assume good electronic transport, and second, the relatively high cost of PCBM is not ideal with the goal to reduce the cost of the device. For these reasons, a replacement for PCBM is desirable and an all polymer device solution is viewed as the best avenue. Since polythiophene (P3HT) is ideal for hole transport, its insolvent polyselenophene (P3HS) where sulfur atoms are replaced with selenium atoms might offer an interesting alternative to PCBM. The physical processes in organic devices are quite different from those of inorganic devices. Charge separation in organic devices is achieved by forming an interface between two organic materials with type 2 level alignment. However, because of the large binging energies observed in organic compounds, there is often the presence of H-aggregate states at the junction between the two organic materials. In this presentation, we will report the results of interface states in a blend of polythiophene and polyselenophene. Photoluminescence spectra will be presented along with calculations of these states with the help of the time-dependent density-functional theory.

Use of nucleating agents for microstructure manipulation of organic photovoltaic blends

N. Stingelin-Stutzmann, Imperial College London (United Kingdom) and ETH Zurich (Switzerland) and Freiburg Institute for Advanced Studies (Germany); J. Nekuda-Malik, Imperial College London (United Kingdom); P. Smith, ETH Zurich (Switzerland)

Poly(3-hexylthiophene) / phenyl-C60-butyric acid methyl ester (PCBM) bulk heterojunction (BHJ) blends are a promising organic photovoltaic system. However, lack of understanding of relevant fundamental relationships between the blend and electronic processes is hampering further improvement in device performance, and renders straightforward implementation of even the most simple fabrication protocols to other BHJ binaries challenging. The origin of this complexity is the fact that P3HT/PCBM active photovoltaic layers, as well as many other BHJ systems, consist of a multiphase architecture comprising: 1) phase-separated crystalline P3HT and crystalline PCBM phase regions, and 2) a highly intermixed P3HT/PCBM amorphous phase. While it is well known that charge separation in these structures occurs at the interface between the P3HT donor and PCBM acceptor material, to date, it is unclear at which boundaries (crystalline or amorphous) this process predominantly takes place. We present use of well known clarifiers for the bulk commodity polymer isotactic polypropylene (i-PP), including 1,3,2,4-bis(3,4-dimethyl benzylidene) sorbitol (DMDBS) and an alkyl-substituted 1,3,5-benzenetrisamide, to nucleate P3HT. This nucleation process allows us to modify and control the size of the crystalline regions in P3HT/PCBM blends in an attempt to elucidate the primary region of charge separation. Details of the methods used to manipulate the P3HT/PCBM blend microstructure will be discussed and the correlation between microstructural changes and device characteristics will be presented.

Ultrafast kinetics in polycrystalline pentacene: Exciton fission

M. W. B. Wilson, A. Rao, Univ. of Cambridge (United Kingdom); R. S. S. Kumar, Istituto Italiano di Tecnologia (Italy); D. Brida, G. Cerullo, Politecnico di Milano (Italy); R. H. Friend, Univ. of Cambridge (United Kingdom)

We report the use of ultrafast transient absorption spectroscopy with sub-20 fs time resolution to directly probe the process of exciton fission in polycrystalline thin films of pentacene. We observe that the overwhelmingly majority of initially photogenerated singlet excitons evolve into triplet excitons on an ~80 fs timescale independent of the excitation wavelength. This implies that exciton fission occurs at a rate comparable to phonon-mediated exciton localization processes, and may proceed directly from an initial delocalized state. The singlet population is identified due to the brief presence of stimulated emission, which is emitted at wavelengths which vary with the photon energy of the excitation pulse, a violation of Kasha’s Rule that confirms that the lowest-lying singlet state is extremely short-lived. This direct demonstration that triplet generation is both rapid and efficient establishes multiple exciton generation by exciton fission as an attractive route to increased efficiency in organic solar cells. However, these results bear significantly on the task of realizing such a solar cell, as it would appear necessary to ensure the formation of ordered molecular aggregates that can support delocalized excitations, as opposed to simply including pentacene moieties in a disordered system.

On the correlation between structure, morphology, and charge transport in organic molecular films: the tetracene case

G. Tarabella, Consiglio Nazionale delle Ricerche (Italy); L. Lutterotti, Univ. di Trento (Italy); S. Bertolazzi, Univ. di Trento (Italy); S. Iannotta, Consiglio Nazionale delle Ricerche (Italy); C. Santato, Ecole Polytechnique de Montréal (Canada)

Dielectric surface engineering is a tool to control organic molecular semiconducting films’ morphology and structure, which in turn play a pivotal role in establishing films’ functional properties. We report an extended correlation between films morphology, studied by Atomic Force Microscopy, structure, investigated by Grazing Incidence X-ray diffraction (GIXRD), and charge carrier transport in Field Effect Transistor configuration for tetracene films vacuum sublimed on six different dielectric substrates, namely bare SiO2 (reference substrate), OTS, HMDS, parylene C, polystyrene and PMMA. Tetracene is a model molecule exhibiting good charge transport and electroluminescence, attractive for applications such as Light Emitting Transistors. Films on polystyrene showed a mobility of 2·10-1 cm2V-1s-1, the highest reported up to now for tetracene. Films on polystyrene showed the earliest complete substrate surface coverage: at 10 nm of nominal thickness tetracene islands appeared tightly packed and well interconnected. GIXRD patterns, collected at different grazing incidence angles in reflection mode, were analyzed using the Maud software, based on the Rietveld method extended to gain an unprecedented insight on the texture, phases amount, crystallites sizes and r.m.s. microstrains. Two different tetracene phases were identified: the beta phase showed a longer c axis with respect to the alpha one. A strong fiber texture perpendicular to the
sample surface was observed for both phases. Tetracene films grown on polystyrene showed the highest amount of alpha phase and the strongest grain alignment, in agreement with the highest mobility measured.

8098-10, Session 3
Charge transport and recombination in organic solar cells
R. A. Street, Palo Alto Research Center, Inc. (United States)

Organic solar cells have reached about 8% efficiency, but need to be more efficient to compete with other materials. An understanding of the losses of organic bulk heterojunction solar cells requires knowledge of how the heterojunction interface influences the electronic transport and recombination mechanisms. We describe how transient photoc conductivity measurements and the cell spectral response provide information about the carrier mobility, recombination mechanisms and the electronic structure. We find that geminate recombination is not a dominant recombination process in P3HT:PCBM or PCDTBT:PCBM cells. Instead, there is good evidence that recombination through interface traps is important. The measurement of the electronic structure show band tail effects attributed to the material disorder. The band tails contribute to suppressing geminate recombination and allowing trap recombination. The role of the interface on the electronic structure and the electronic properties will be discussed.

8098-11, Session 3
Charge generation dynamics at nano-scale interfaces in all-organic and hybrid materials
L. M. Herz, Univ. of Oxford (United Kingdom)

Conjugated polymers and molecules are increasingly used as cheap artificial light-harvesting materials in photovoltaic devices. The large exciton binding energy in these systems necessitates the use of blends comprising at least two materials at whose interface a type-II heterojunction is formed, thus making charge separation energetically favourable. Examples of all-organic materials are blends of conjugated polymers with single-walled carbon nanotubes (SWNTs) with the latter promising large electron mobilities and percolation paths. We have investigated the charge photogeneration dynamics at the interface formed between SWNTs and poly(3-hexylthiophene) (P3HT) using a combination of femtosecond spectroscopic techniques [1]. We demonstrate that photoexcitation of P3HT forming a single molecular layer around a SWNT leads to an ultrafast (430 fs) charge transfer between the materials. The addition of excess P3HT leads to long-term charge separation in which free polarons remain separated at room temperature. Our results suggest that SWNT-P3HT blends incorporating only small fractions (1%) of SWNTs allow photon-to-charge conversion with efficiencies comparable to those for conventional (60:40) P3HT–fullerene blends, provided that small-diameter tubes are individually embedded in the P3HT matrix. In addition, hybrid interfaces comprising organic dyes as sensitizer monolayers on metal-oxide mesostructures films have been highly successful when implemented in so-called dye-sensitized solar cells (DSSCs). We have used optical-pump terahertz-probe spectroscopy to explore the photinduced conductivity dynamics in such mesoporous metal-oxide films [2]. We extract early-time mobility values and compare these to bulk values in order to determine factors limiting electron movement in these systems. In addition, we have utilized terahertz spectroscopy to investigate the influence of surface treatments for the metal oxide on early-time charge dynamics. For example, surface treatment of the mesoporous TiO2 with TiC4 has been found to be critical to enable efficient operation of DSSCs. However, we find that neither early-time charge mobility nor charge injection rate or decay times are significantly affected by the treatment, which suggests that it may, instead, have an impact on phenomena occurring on longer time scales.


8098-12, Session 4
Modifying the fluorescence properties and determining the quantum yield of a single molecule with a tunable optical subwavelength microcavity
A. I. Chizhik, A. M. Chizhik, D. Khopyar, S. Bär, Eberhard Karls Univ. Tübingen (Germany); J. Enderlein, Georg-August-Univ. Göttingen (Germany); A. J. Meixner, Eberhard Karls Univ. Tübingen (Germany)

We present experimental and theoretical results on changing the fluorescence emission spectrum of a single molecule by embedding it within a tunable planar microcavity with subwavelength spacing [1]. The cavity length is changed with nanometer precision by using a piezoelectric actuator. By varying its length, the local mode structure of the electromagnetic field is changed together with the radiative coupling of the emitting molecule to the field. Because mode structure and coupling are both frequency dependent, this leads to a renormalization of the emission spectrum of the molecule. We develop a theoretical model for these spectral changes and find excellent agreement between theoretical prediction and experimental results. We also demonstrate controlled modulation of the radiative transition rate.
of a single molecule, which is measured by monitoring its fluorescence lifetime [2]. By comparing the experimental data with a theoretical model, we extract both the pure radiative transition rate as well as the quantum yield of individual molecules. We observe a broad scattering of quantum yield values from molecule to molecule, which reflects the strong variation of the local interaction of the observed molecules with their host environment.

Our technique can be applied to any single quantum emitter of interest, such as dye molecules, semiconductor nanoparticles, carbon nanotubes, etc. Thus, the tunable cavity method makes it a versatile tool for single molecule spectroscopy and quantum yield measurements of individual quantum emitters.


8098-13, Session 4

Electric-field dependent spectroscopy of single nanocrystal systems

S. Johnson, A. K. Tobias, Jr., E. Williams, M. Jones, P. Moyer, The Univ. of North Carolina at Charlotte (United States)

The most common explanation of spectral diffusion and fluorescence intermittency in nanocrystals (NCs) is biexciton annihilation via an Auger ionization process. In this charge-separated state, one electron or hole carrier is trapped on or near the surface while the other remains in the core. The effect of the electric field generated by this charge-separated state has been implicated in a number of studies as the cause of observed dynamics, but remains scarcely explored. The spectra of single CdSe/ZnS nanocrystals at low temperature have shown random spectral diffusion up to tens of meV. Similar shifts were induced under the presence of an applied electric field. This relation suggests that local electric fields could be responsible for spectral phenomena. More recent work shows an electric field effect on blinking and the photoluminescence quantum yield, which suggests modulation of surface trap sites with applied field.

We have designed experiments to explore the complex role of surface states in carrier dynamics. CdSe nanocrystals, with a variety of shells and surface ligands, were patterned onto a glass-mounted interdigitated electrode using electron beam evaporation. A modulated electric field was applied using a function generator. Using our homebuilt confocal microscope, we were able to locate individual nanocrystals, and simultaneously collect fluorescence trajectories, lifetimes, and spectra. I will discuss the analysis of these data from which we obtained field-dependent dynamic information about a range of nanocrystal systems. These experimental results and modeling of the charge transfer and relaxation dynamics of confined excitons will advance nanostructure applications.

8098-14, Session 4

Conformation and interactions in single polythiophene polymer chains

D. A. Vanden Bout, T. Adachi, J. Brazard, R. J. Ono, G. Lakhwani, M. C. Traub, J. C. Bolinger, P. F. Barbara, C. W. Bielawski, The Univ. of Texas at Austin (United States)

Morphology of conjugated polymer films is one of the most important parameters determining physical, electrical and optical properties that are crucial for many types of device application including organic solar cells. Although major obstacle for morphological research of these materials is their complexity and heterogeneity, single molecule spectroscopy enables us to simplify the system and make it tractable. Various experiments examined the conformation of polythiophene (P3HT) chains utilizing polarization modulation spectroscopy. Both the excitation and emission anisotropy are examined to directly probe energy transfer to emitting sites along the chains. The measurements show that regioregularity of the polymer side chains has a profound effect on the ordering of the polymer chain even at the single molecule level. Studies will also be presented that examine interchain interactions utilizing model tri-block copolymer which consist of two P3HT chains connected by either a flexible or rigid linker.

8098-15, Session 4

Imaging of photoinduced tautomerism in single porphyrin molecules


Porphyrins play an important role in nature, e.g. as chlorophyll in photosynthesis. To understand how these processes work and could be imitated, first the basic structures and properties of the porphyrin-molecules have to be understood. Metal-free porphyrins serve as a very important modelsystem in theoretical chemistry to improve computational methods and help to develop such efficient energetic processes as they occur in nature. Although tautomerization has been studied for decades, it is still difficult to say what happens within one single molecule undergoing this basic process. When the tautomers are chemically equivalent, such as is the case for porphyrins and similar symmetric molecules, few experimental methods can be employed for studying ground-state and especially photoinduced tautomerism. Using the technique of optical imaging combined with cylindrical vector beams, we can determine the 3D-orientation of the excitation transition dipole moment (TDM) of single molecules. [1] As the TDM-orientation changes when the molecule converts from one trans-tautomer into another, we can distinguish between both of them. Recently we were able to visualize the conversion of one single molecule between its trans-forms. [2] Our method allows us to get a closer insight into the photoinduced tautomerism and the difference to the ground-state-process. By varying the substituents of the molecules, its environment and the excitation-wavelength, we are able to reveal new fundamental details of the excited-state tautomerization in single molecules.


8098-16, Session 4

Imaging the transition dipole moment for single CdSe/ZnS quantum dots and SiO2 nanoparticles

A. M. Chizhik, A. I. Chizhik, Eberhard Karls Univ. Tübingen (Germany); T. Schmidt, F. Huisken, Friedrich-Schiller-Univ. Jena (Germany); A. J. Meixner, Eberhard Karls Univ. Tübingen (Germany)

We study the dimensionality, orientation and dynamical effects of the excitation-transition dipole moment for single CdSe/ZnS core-shell nanocrystals [1] and SiO2 nanoparticles [2]. Using an argon ion laser at 488 nm with higher-order laser modes (azimuthally and radially polarized laser modes) for excitation, the three-dimensional orientation of the nanoparticles’ transition dipole moment was investigated in a confocal microscope. The comparison of measured and simulated single nanocrystal excitation patterns shows that single CdSe/ZnS quantum dots possess a spherically degenerated excitation-transition dipole. We show that the dimensionality of the excitation-transition dipole moment distribution is the same for all individual CdSe/ZnS nanocrystals, disregarding the difference in core size and irrespective of variations in the local environment. In contrast to the emission-transition dipole moment, which is oriented in one plane, the excitation-transition dipole moment of a single CdSe/ZnS quantum dots possesses an isotropy in
three dimensions.

SiO2 nanoparticles exhibiting strong red-orange photoluminescence were obtained by full oxidation in water of the silicon nanopowder synthesized by CO2 laser pyrolysis of SiH4. Samples of SiO2 NPs embedded in low concentration in a thin polymer layer were prepared by spin-coating a dedicated solution on glass cover slides. The linear transition dipole moment was found to be rather stable and randomly oriented. However, dynamical effects such as fluorescence intermittency and transition dipole moment flipping could also be observed.


8098-17, Session 5

The nature of bound charge pairs at donor-acceptor interfaces

G. D. Scholes, Univ. of Toronto (Canada); G. Rumbles, National Renewable Energy Lab. (United States)

The primary product of exciton photodissociation at a donor-acceptor interface is a bound charge pair, known by various names including bound radical pair, polaron pair, exciplex, etc. The microscopic nature and properties of these species will be discussed and defined. Organic and inorganic heterostructures will be compared. We will ask whether a deeper understanding of bound charge pairs suggests new designs for organic photovoltaics.

8098-18, Session 5

Charge transfer processes at intra- and intermolecular heterojunctions

E. Da Como, Ludwig-Maximilians-Univ. München (Germany)

Photoinduced charge transfer is the primary process in photovoltaics. Here we probe the first steps of charge separation in a series of low-bandgap donor-acceptor copolymers by femtosecond infrared pump-probe spectroscopy. The results are discussed considering the donor acceptor strength of the units within the chain and how this influences the yield of polaron generation. In the second part we will combine the pump-probe experiments with time resolved luminescence to study charge separation at polymer/fullerene intermolecular heterojunctions. Upon doping of the conjugated polymer we report reduced recombination via charge transfer excitons and enhanced polaron formation.

8098-19, Session 5

Beyond the adiabatic limit: charge separation in organic photovoltaic materials

J. B. Asbury, R. D. Pensack, The Pennsylvania State Univ. (United States)

The dynamics of charge separation in photovoltaic polymer blends following photoinduced electron transfer from the conjugated polymer, CN-MEH-PPV, to the electron accepting functionalized fullerene, PCBM, are observed with ultrafast vibrational spectroscopy. The investigations take advantage of a solvatochromic shift of the vibrational frequency of the carbon (C=O) stretch of PCBM to directly measure the rate of escape of electrons from their Coulombically bound charge transfer (CT) excitons at donor/acceptor interfaces on ultrafast time scales. The data reveal that the rate of dissociation of CT excitons is temperature independent from 200 to 350 K indicating that excess energy in hot CT excitons plays an important role in mediating charge separation. These observations suggest that conceptual and theoretical descriptions properly taking into account the strong coupling of electronic and nuclear degrees of freedom in organic semiconductors are essential to understand the mechanism of charge separation in organic photovoltaic materials. From a practical stand-point, efforts to develop new low band-gap polymers for organic solar cells should target electron donor and acceptor pairs capable of advantageously redistributing excess energy in hot CT excitons to enable efficient charge separation with minimal donor-acceptor energy level offsets.

8098-20, Session 5

Charge-transfer excitons at semiconductor polymer heterojunctions in efficient organic photovoltaic diodes

F. Provencher, C. Silva, Univ. de Montréal (Canada)

In organic photovoltaic (OPV) diodes based on blends of semiconductor polymers and fullerene derivatives, singlet intrachain excitons on the polymer created by the absorption of light dissociate into gaseous polaron pairs (GPP) at the heterojonction. These are bound by a Coulomb potential, so they must then dissociate endothermically to form photocarriers. Alternatively, GPP can relax to form charge transfer excitons (CTX), where the electron and the hole sit on different molecules but are coulombically bound to form excitonic states across the interface. Since CTX can limit the internal quantum efficiency as well as the open-circuit voltage of OPV cells, our focus is to unravel the dynamics of branching from GPP to CTX, and subsequent recombination processes to re-generate intrachain singlet excitons in an efficient OPV blend.

A careful temperature-dependent study of combined spectroscopic methods of time-resolved photoluminescence, transient absorption and quasi-steady-state photoinduced absorption unravels the dynamics of those species on timescales ranging from picoseconds to milliseconds in films of poly(carbazole)/fullerene derivative blend (PCDTBT/PC70BM). We find that GPP are precursors to photocarriers and act as a dark reservoir that feeds the CTX. At low temperature, the GPP are easily trapped and they feed the CTX via tunneling, but not the free photocarriers (polarons). At room temperature, the GPP overcome the Coulomb barrier and dissociate more easily into free polarons.

8098-21, Session 6

Excitonic charge separation at organic semiconductor interfaces

X. Zhu, The Univ. of Texas at Austin (United States)

Solar photovoltaics based on organic semiconductors commonly involve excitons. This results from strong Coulomb attraction between an electron and a hole due to the low dielectric constants of molecular materials. In this lecture, I will address the question of how excitons form, relax, multiple, and dissociate in organic semiconductor materials and at their interfaces. My group uses two experimental techniques to probe interfacial exciton dynamics: time-resolved two-photon photoemission spectroscopy (TR-2PPE) and time-resolved electric field induced second harmonic generation (TR-EFISH). The TR-2PPE technique tracks the electron in time and energy domains at it is initial excited, and as it relaxes, multiplies, and transfers. The complementary TR-EFISH technique monitors the transient electric field formed from exciton dissociation and charge separation at the interface. A particularly exciting aspect is the possibility of harvesting these excitons in dynamic time windows that may allow us to design solar cells with efficiency exceeding the so-called Shockley-Queisser limit, which is the thermodynamic limit of conventional solar cells.
8098-22, Session 6

**Photogenerated charges in neat poly(3-hexylthiophene) films**

G. Rumbles, National Renewable Energy Lab. (United States) and Univ. of Colorado, Boulder (United States); O. Reid, N. Kopidakis, National Renewable Energy Lab. (United States); N. Stingelin-Stutzmann, Imperial College London (United Kingdom); J. Nekuda-Malik, London Ctr. for Nanotechnology (United Kingdom); G. Latini, Consiglio Nazionale delle Ricerche (Italy); C. Silva, Univ. de Montréal (Canada)

The nature of the primary photoexcitation in conjugated polymers has been a subject of interest for a number of years, and two models have emerged: neutral excitons and free charge carriers. While excitons are recognized as the dominant of the two species, there are a small fraction of carriers that appear directly upon photoexcitation that have been detected experimentally either spectroscopically or through conductivity measurements. The fraction of near-instantaneous free charge carriers produced depends both on the chemical structure of the polymer and on the time-scale on which the study is performed. For example, poly(3-hexylthiophene) (P3HT) thin films have been reported to have free carrier yields as high as 15%, when measured on a fast time scale, but as low as 3% when measured on a slow time scale. It is unclear why these numbers are so different, and from where these carriers originate.

This presentation will report studies using flash photolysis, time-resolved microwave conductivity (fp-TRMC) to probe carriers produced in a number of thin films of P3HT of differing molecular weights. By correlating the free carrier yield with the solid-state microstructure of the polymer, and the corresponding electronic absorption spectra, we will propose a model that explains the origins of these carriers.

8098-23, Session 6

**The mechanism of ultrafast exciton dissociation in neat regioregular poly(3-hexylthiophene)**

G. Latini, Istituto Italiano di Tecnologia (Italy); F. Paquin, P. Karsenti, M. Sakowicz, Univ. de Montréal (Canada); N. Stingelin-Stutzmann, Imperial College London (United Kingdom); C. Silva, Univ. de Montréal (Canada)

Semiconductor polymer films with high molecular order display high apparent intrinsic charge photogeneration yields by a mechanism that has not been unravelled by contemporary literature. We address charge photogeneration dynamics in neat regioregular poly(3-hexylthiophene) by means of transient photoluminescence (PL) and absorption spectroscopies at 10 K. Charges are generated over ultrafast timescales, but furthermore over timescales that compete with the exciton lifetime (~1 ns) by a mechanism that excludes diffusion-limited exciton dissociation. They recombine with distributed rates that lead to delayed PL over microsecond timescales, accounting for >12% of the time-integrated emission intensity in the studied im microstructure. By analyzing the spectral bands/hape of delayed PL, we conclude that charges recombine primarily at interfaces between photophysical aggregates comprised of lamellar polymer stacks and electronically uncoupled chains. This highlights the extrinsic role of boundaries between domains of contrasting microstructure in charge photogeneration processes in this important class of materials.

8098-24, Session 6

**Ultrafast conformational readjustment through non-adiabatic state crossings in oligofluorenes**

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A molecule’s conformation in terms of whether it is twisted, planar or bent reflects a complex equilibrium resulting from thermodynamic, nuclear, and electronic degrees of freedom. Changing electronic state (by absorption, for example) can dramatically alter the conformational minima of the multidimensional potential energy surface (PES). Readjustment to the new equilibrium position generally occurs on the 10-100 ps time scale, depending on the involved vibrational mode frequencies and the dissipation paths. This relaxation can be thought of in the classical picture as a damped oscillator. Here, we apply an ultrafast pump-push-probe experiment and advanced computational techniques to investigate energy relaxation in oligofluorenes in solution. Results suggest direct observation in the time domain of ultrafast photoinduced planarization of oligofluorenes via internal conversion through non-adiabatic state crossings. By studying dynamic shifts in the stimulated emission band, we observe that conformational relaxation (planarization) in the first excited state (S1) takes place - as expected - on the 10s of picosecond time-scale. This conformational relaxation time is reduced by over two orders of magnitude when exciting a higher-lying (Ag) state as the wavepacket arrives at the S1 state within 100fs already planar. Calculations elucidate the path in configurational space taken by the wavefunction and highlight the role of non-adiabatic state crossings in dissipating the energy. We find a clear correlation between the ultrafast planarization and an intramolecular charge transfer state whose ultrashort lifetime is exploited in realizing all optical switching in plastic media.

8098-34, Poster Session

**Nonlinear optical properties of two dimensional ferroelectric polymer film at the air/water interface**

C. Jung, P. Jang, S. Kyu, K. H. Kim, Cheongju Univ. (Korea, Republic of)

Organic materials are generally attractive because of the possibility having exceptionally high nonlinear optic (NLO) coefficient. The most straightforward approach to increase the NLO coefficient is the development of new material through the systematic chemical design of the molecules. Even though the lack of amphiphilicity, the copolymer of vinylidene fluoride and trifluoroethylene, P(VDF-TrFE) makes its monomolecular (Langmuir) layer on the water surface. By stacking these layers onto a solid substrate with appropriate transfer technique, one can establish a well organized two dimensional films with a good noncentrosymmetric crystallinity. In this study, we focused our attention on the formation of polar monolayer on the air/water interface by using nonlinear optical technique, such as second harmonic generation method. Up to now, many research group have reported the NLO properties of amphiphilic two dimensional films. However, the NLO study from this kind of poor amphiphilic film has not been reported yet. In this work, a copolymer of vinylidene fluoride(70%) and trifluoroethylene (30%) were prepared on the water subphase and the time dependent NLO properties was studied by second harmonic generation method.
Modeling interfacial charge transport of Quantum dots using Cyclic Voltammetry

A. K. Tobias, Jr., E. Williams, M. Jones, The Univ. of North Carolina at Charlotte (United States)

Quantum dot applications are numerous and range from photovoltaic devices and lasers, to bio labeling. Complexities in the electronic band structure of quantum dots create the necessity for analysis techniques that can accurately and reproducibly provide these band energies. Cyclic voltammetry (CV) has been used to estimate HOMO/LUMO levels in molecular species and, similarly, can also be used to estimate valence and conduction band levels in quantum dots. Energy and charge transfer between quantum dots and other electron/hole accepting materials can be tuned and optimized according to this data. CV has been utilized in recent research to study effects of electron and hole insertion on quantum dot ensembles and also investigate their band gap energies. These experiments can be done on quantum dots in solution, as thin films, or coated on metal electrodes. CV has potential to become a useful tool in designing new nanocrystal technology, by providing information necessary for predicting and modeling interfacial charge transfer and from quantum dots. Despite the potential use of CV analysis, limitations arise due to the physical nature of nanocrystals. Solubility and diffusion come into play in solution-state experiments, while sample degradation is an issue in thin films. Carbon paste electrodes have been used in electrochemical studies to eliminate these issues. I will present data obtained using a carbon paste electrode to investigate energy levels in core CdSe and core/shell CdSe/CdS quantum dots. Importantly, the results of this work allow us to determine HOMO-LUMO energy differences for candidate nanocrystal-molecule electron transfer systems.

Effect of alloying on the photoluminescence of the CuInS2 nanocrystals

Y. Kim, C. Choi, Korea Institute of Materials Science (Korea, Republic of)

We have developed a novel route to highly luminescent Cd-free core-shell nanocrystals. By simply refluxing as-synthesized CuInS2 nanocrystals with zinc acetate and palmitic acid, highly luminescent CuInS2/ZnS nanocrystals were synthesized. We modified the photoluminescence of the grown nanocrystal by alloying foreign atoms. Nanocrystals with alloyed cores were synthesized by adding selenium and nanocrystals with alloyed shell layers were synthesized by refluxing the as-synthesized CuInS2 nanocrystals with mixture of cadmium acetate, zinc acetate and palmitic acid. It was found that the emission wavelength of the nanocrystals was shifted to longer wavelength side by alloying. The photoluminescence spectra showed clear red-shift without significant minimization of emission intensity. A Detailed study on the emission process of nanocrystals implies that the formation of shell layers with small lattice mismatch minimized mismatch strain generated from the shell layers in contrast to core alloyed nanocrystals.

Modeling exciton dynamics of type II nanocrystals

D. Woodall, A. K. Tobias, Jr., E. Williams, P. Moyer, M. Jones, The Univ. of North Carolina at Charlotte (United States)

Semiconducting nanocrystals are becoming more important in light harvesting devices because of their tunable optical properties, stability, and ease of synthesis. In order to design high efficiency optoelectronic devices, the movement of charges within these nanocrystals needs to be fully understood. Electron transfer models such as Marcus theory exist for molecular systems, but critical parameters such as potential energy curves and electronic coupling strengths of Marcus theory have yet to be applied to nanocrystals. The development of such a model for nanocrystals is problematic because they are complex. Nanocrystals are complex because of inhomogeneities in size and shape, surface trap states, and ligand effects, all of which affect electron transfer rates in different ways. Nanocrystals consisting of type II core/shell CdSe/CdS with varying shell thicknesses were synthesized using a colloidal synthesis method. Each sample was characterized by various optical spectroscopies including UV-Vis absorption, steady state fluorescence, and time resolved photoluminescence. Lifetimes were measured at a range of temperatures and were directly analyzed using software previously shown to be effective in predicting carrier trapping and detrapping rates for CdSe/CdZnS core/shell nanocrystals. Computational modeling based on the premises of Marcus theory was performed to simulate experimental results. By combining lifetime measurements with simulations, we establish a kinetic model of nanocrystal exciton dynamics predicting electron transfer rates over a range of temperatures. The development of this model is critical for future design and fabrication of optoelectronic devices such as photovoltaics, photodetectors, and chemical sensors.

Noise and current-voltage characteristics of structures with porous silicon layer in different gas environments

Z. Mkhitaryan, V. Aroutiounian, S. Geghamyan, Yerevan State Univ. (Armenia)

The experimental research of current-voltage characteristics and low-frequency noise in dry air, dry air+0.1%ammonia, dry air+0.1%(butane+propane), dry air+0.1%spirit (C2H5OH) were done. PS layers were formed using the electrochemical etching of heavily doped (p=0.01 Ωcm) p+ type (100)-oriented silicon wafers. The thickness of the PS layer was 3 micro-meters; the porosity was equal to 80 %. The diameter of nanometrical filaments was equal to ~5nm; sizes of pores were equal up to 50nm approximately.

Measurements of noise characteristics were carried out by the method of direct filtration at room temperature in the range of frequencies 3 Hz - 500 Hz. Measuring setup for research of the noise in the semiconductor-gas system included the input chain, a gas cell, low noise preliminary amplifier SR 560 (SRS, USA), the analyzer of the spectrum realized by HANDYSCOPE 2 (Tie Pie Engineering).

Sensitivity diagrams for explored samples are shown after traditional (resistance) and noise measurement, correspondingly. We have shown that the noise sensitivity in the presence of target gas in air is much higher than the sensitivity of the sensor after the measurement of ohmic resistance. The largest change in the characteristics of our samples occurs in the environment of dry air+0.1%ammonia. The possible reason for this is the molecule size of target gas and its adsorption properties. The physical reasons of sensing properties of the investigated samples are detailed discussed in paper.
The multiple resistance to treatment, acquired by bacteria and malignant tumors requires finding alternatives to the existing medicines and treatment procedures. One of them is strengthening the effects of cytostatics by modifying their molecular structures through exposure to laser radiation. A method associated with this is the generation of micro-droplets which contain medicines solutions; the droplets are utilized/produced as vectors to transport the medicines to targets.

In our studies we try to combine these two methods in order to obtain a new technique to deliver the efficient medicines to targets that can be applied for a relative large number of chemicals. For this purpose we have developed an experimental set-up containing a liquid droplets generator, a tunable laser source used to irradiate droplets, a subunit to measure the laser induced fluorescence signals and a real time recording system for droplet image analysis.

Measurements on different probes, like ultrapure water, commercial grade medicines, newly developed medicines and laser dyes were performed. For some of these samples, the wetting properties were also studied. All these measurements were performed on water-based solutions.

First we show the laser induced fluorescence measurements results on micro-droplets, that exhibit important modifications after the exposure at laser radiation. It was evidenced that the exposures to laser beams/coherent optical radiation of some medicines solutions in ultrapure water may produce molecular modifications in solutions. These slight modifications of the molecules made them more efficient against bacteria strains.

Secondly, we present results concerning the micro droplets behavior at laser beam interaction for different laser energies and impact geometries. The laser beam incident on the droplet was emitted at 10 pulses per second or in single pulse regime at 540nm (green) with 6ns FWHM. The beam focus diameter was 0.1mm and the irradiance in the focus was about 3kW/cm². The processes which might take place at the interaction of the laser beam with water microdroplets are: a. Droplet vibration; b. Generation/expulsion of micro/nano droplets at high speed by the initial droplet through loss of material; c. Microdroplet destruction by lossing the contact with the capillary used to generate it; d. Possible heating of the droplet’s material although the laser beam wavelength was emitted in green, where the water absorption is negligible; e. Total sputtering in 4π of the droplet, when exposed to a single high power pulse. The effect of the mechanical pressure of light on the microdroplets is investigated in correlation with the superficial tension values for such droplets.

8098-41, Poster Session

Structure and optical properties of noble-metal and oxide nanoparticles dispersed in various polysaccharide biopolymers

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The hybrids based on nanostructured noble-metal and polymers have been investigated for almost two decades but this subject is enjoying a constant resurgence of interest and activity as a result of the exceptional properties which can be realized from such nanocomposite materials. Since a polymer can be easily designed into almost any shape required by a particular application, the properties of the nanoparticles can be successfully utilized by incorporation of the nanoparticles into polymer matrices. Polymers can also influence the growth and spatial arrangement of the nanoparticles formed within the matrix that makes them convenient templates for the preparation of nanoparticles of different morphologies. Because of possible applications in biotechnology and environmental protection, biopolymers and particularly polysaccharides were recently employed as host materials for metal and semiconductor nanoparticles. The macromolecular chains of these biopolymers possess a large number of hydroxyl groups and they can complex well with metal ions, which in turn enable a good control of size, shape and dispersion of the nanoparticles formed. Here we present the results on the structure and the optical properties of noble metal (Ag, Au), oxide (ZnO) and composite (Ag-Ag2S) nanoparticles synthesized by various methods in different polysaccharide matrices such as chitosan, glycogen, alginate, and starch. The structure of the obtained nanoparticles was studied in detail with microscopic techniques (TEM, HRTEM, HAADF-STEM), while the XPS spectroscopy was used to investigate the effects at the nanoparticle biomolecule interfaces. The antimicrobial activity of the nanocomposite films with Ag and ZnO nanoparticles was tested against the Staphylococcus aureus, Escherichia coli and Candida albicans pathogens. In addition, we will present the results on the structure and optical properties of the tryptophan amino acid functionalized silver and gold nanoparticles dispersed in polyvinyl alcohol matrix.

8098-25, Session 7

Physical chemistry of acridine adsorption onto gold surface: The influence of nanostructure as revealed by near-infrared and tip-enhanced Raman spectroscopy (TERS)

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The surface science of aromatic molecules has long been of interest, both on semiconductor and on metal surfaces, due to their high importance for industry. For example, catalytic purification of petroleum (crude oil) fractions is based on the adsorption/reaction behaviour of sulphur- and nitrogen-containing molecules. In this view, a systematic study of the adsorption and transformation of sulfur and nitrogen compounds on different solids (applicable as catalysts, catalyst components, or adsorbants) is needed. Here we report a detailed study of adsorption of acridine (C13H9N) and a number of its derivatives: benz[a]acridine, benz[c]acridine, etc. Thermodynamic and kinetic data, obtained by solution-phase near-infrared spectroscopy (NIRS), clearly show a great difference of adsorption behavior for flat and nanorough (~4 nm) gold surfaces. Gibbs free energies of -4.57±0.10 vs. -7.67±0.13 kcal mol⁻¹ and adsorption kinetic constants of 26±3 vs. 4160±220 min⁻¹ M⁻¹ were determined for flat and SERS-type surfaces, respectively. This result could be interpreted in terms of the type of adsorption model: adsorption by the conjugated pi-electron system or by the lone pair of the nitrogen atom in the former and latter cases, respectively. The characterization of the polyaromatic monolayer directly at the Au surface, as measured by tip-enhanced Raman spectroscopy in scanning tunneling microscope mode (STM-TERS), has confirmed the dependence of the adsorption parameters on the (nano)roughness of the metal surface. The shift of Raman active vibrations (by 2-8 cm⁻¹) of the molecules at the surface and the appearance of new bands were used as a direct indicator of the adsorption model type. Density functional theory calculations (DFT-B3LYP, DFT-M06) were used to confirm the assignment. A unique possibility of TERS to enhance the molecular Raman signal independent on the surface structure and type was fully realized. The importance of the findings for industry and nanotechnology are discussed.

8098-26, Session 7

Investigation of the influence of surface and heterogeneous radical stages on oscillation modes of methane oxidation

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The goal of our work is investigating the role of heterogeneous radical stages in the initiation oscillation modes of methane oxidation at flow conditions.

There is evidence of the existence of oscillations in the process of thermal oxidation of methane, which is accompanied by luminescence. However the mechanism of their appearance is little known. We
supposed and then proved, with the method of mathematical modeling, that one of its reasons could be the influence of nature of the state of the surface on character of dynamic regimes of process.

The short model of chain radical process was considered. The system of differential equations for changes of reagents concentration was solved in quasi-stationary approach for the concentration of some radicals at initial stage of the reaction, when the consumption of methane and oxygen can be neglected.

The luminescence during oxidation of organic compounds is routinely attributed to the recombination of radicals. In an oscillatory mode of methane oxidation of concentration oscillations of radicals will naturally cause oscillations of intensity of a luminescence. When we were varying the rate constants of heterogeneous stages of reaction process as a result we observed damping or swinging oscillations. Summarizing results it is possible to conclude, that oscillatory regimes of thermal oxidation of methane is strictly connected with the heterogeneous factors that is with the nature of the surface and also revealed conditions, which they can be regulated.

8098-27, Session 7

**Nanostructured silicon for surface passivation of solid-state photodetectors**

M. E. Hoenk, Jet Propulsion Lab. (United States)

Surface-related instabilities, including especially quantum efficiency hysteresis, have plagued scientific solid-state imaging detectors since the 1970’s, when NASA first invested in charge-coupled devices (CCDs) for astronomical instruments in space. Such instabilities are especially problematic in the deep ultraviolet, where photons carry sufficient energy to damage surface coatings, creating defects and traps associated with surface charging, carrier recombination, and dark current generation. Using molecular beam epitaxy to grow a 2 to 3 nm epitaxial layer of delta-doped silicon, we have created a highly stable surface passivation layer that uniquely enables reflection-limited quantum efficiency and completely eliminates quantum efficiency hysteresis in back-illuminated CCDs and CMOS imaging arrays. In this paper we study the physics of surface passivation in delta-doped, back-illuminated silicon imaging detectors. The silicon surface in these detectors is modified by epitaxial growth of silicon, within which a partial monolayer of boron is embedded in the silicon lattice, creating a delta-doped surface. In a delta-doped surface, the highly-localized sheet of dopant atoms creates a quantum well for majority carriers within a few nm of the surface. Here, the bandstructure of the delta-doped surface is calculated using self-consistent calculations of Poisson’s equation and the Schrödinger equation, using an eight band k·p model of the valence band. Calculations affirm that the potential barrier formed by the delta-doped layer isolates the surface from the bulk. Thus a delta-doped silicon surface is virtually immune to environmentally induced changes in the surface charge that are known to degrade conventional silicon-based detectors. This immunity to surface charge is consistent with the absence of measurable quantum efficiency hysteresis in delta-doped imaging detectors.

8098-28, Session 7

**Modulation of CdSe fluorescence using palladium nanoparticles**

K. J. Major, M. Jones, The Univ. of North Carolina at Charlotte (United States)

The increasing demands for clean, efficient energy have strongly influenced the direction of nanoscale science. One of the most promising areas of solar energy research lies with cadmium selenide quantum dots (CdSe QDs). Metal nanoparticles have been examined as a means to increase electron - hole charge separation thus providing extended times for electron harvesting. Most of the systems currently explored utilize gold nanoparticles, which is unsurprising due to the vast amount of synthetic methods for these particles and their plasmonic effects on the QDs. We seek to further examine metal nanoparticle - semiconductor quantum dot interactions through the study of CdSe - palladium nanoparticle systems. We employ both steady state and time resolved ensemble fluorescence spectroscopy to observe the effects of increasing palladium nanoparticle concentrations on both the fluorescence intensity and lifetime of various CdSe QDs. We find that decreasing separation distance between the particles, whether through increasing palladium concentration or QD shell thickness, leads to a stronger interaction between the particles. We find expected fluorescence quenching of the QDs at higher concentrations of palladium. At low palladium concentrations however we observe a unique fluorescence enhancement of the QDs. We use this data to explore the relative contributions of energy and electron transfer between the particles and determine the conditions under which the maximum effects of these interactions are observed.

8098-29, Session 7

**Excited state dynamics in carbon nanotubes and graphene nanoribbons for electronics and biological applications**

O. V. Prezhdo, Univ. of Rochester (United States)

No abstract available

8098-31, Session 8

**Environmental effects induced by the oxygen-water redox couple in carbon nanotube and graphene electronics**

R. Martel, Univ. de Montréal (Canada)

Three terminal transport measurements using a back-gated FET geometry are facilitated by using a degenerately doped silicon wafer covered with a thin silicon oxide layer as the substrate. It has been widely assumed that measurements taken in air are dominated by the Schottky barrier at the contacts, which in turn is linked to the intrinsic properties of the material under study. Here we show that the redox active species present on the surface of the oxide substrate induced a drastic suppression of n-type behavior in FETs and provoke large threshold voltage shifts. By using carbon nanotubes and graphene FETs as testbeds, we investigated the impact of the chemical nature of the substrate and of ambient adsorbates on the field effect switching.
behavior of different FETs. Our study revealed that the reduction of n-type conduction occurs when adsorbed water containing solvated oxygen is present on the SiO2 surface. This finding demonstrates that an electrochemical charge transfer reaction is the underlying phenomenon governing the suppression of electron conduction in carbon nanotube and graphene devices.

A variety of Pd-based nanostructured materials including nanoporous Pd networks and PdPt nanodendrites with different compositions have been synthesized using the hydrothermal method. The as-fabricated Pd-based nanostructured materials were characterized by scanning electron microscopy (SEM), energy dispersive X-ray spectroscopy (EDS), X-ray photoelectron spectroscopy (XPS) and X-ray diffraction (XRD). The electrochemical properties of these Pd-based nanomaterials were studied using cyclic voltammetry, chronoamperometry and in-situ electrochemical infrared spectroscopy. Our studies showed that the fabricated Pd-based nanostructures possess a very large surface area and high catalytic activity. The electrocatalytic activity of the different Pd-based nanostructured materials towards the electrochemical oxidation of formic acid will be compared, and the design of high-performance Pd-based electrocatalysts will be addressed in this talk.

8098-32, Session 8

Component identification with Raman spectroscopy colocalized with quantitative nano-mechanical mapping for complex polymer systems

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Most polymer materials are composed of multiple components. It is critical to be able to identify the chemical components and the concurred mechanical properties in the nanoscale. Raman spectroscopy has been historically been used to probe structural characteristic of materials and investigate the chemical states of the bonds in the materials to indentify the different chemical components with limited resolution. On the other hand, Atomic Force Microscope (AFM) has demonstrated nanometer resolution imaging with localized mechanical property measurements with the newly developed peak force tapping mode. The new technology enabled to quantitatively characterize materials at nanoscale with simultaneous topography and mechanical mapping such as modulus, adhesion and energy dissipation. In this paper we report systematic studies of complex polymer systems combining Raman spectroscopy mapping with quantitative nanomechanical mapping, yielding unprecedented capability to both chemically and mechanically characterize components in the complex polymer systems.

Blends based on thermoplastic Polypropylene (PP) and Ethylene-Propylene-Diene Monomer (EPDM) rubber, so called thermoplastic vulcanizes (TPVs) in different component ratios have been investigated. TPV are high-performance materials that combine the best attributes of the vulcanized rubber (flexibility and low compression set) with the processing ease of linear thermoplastics. That makes possible to design details with complex profiles with high precision, which has numerous benefits in appliance, electrical, construction, healthcare and packing applications. Raman spectroscopy microscopy can chemically identify the PP and EPDM domains with 1um resolution and give micro-scale distribution of components. Nano-mechanical mapping, performed in the same area, exhibits fine details of the component distribution concurrently, especially the details at the interface transition regions. Combination of the two technologies not only allows us to identify individual component unambiguously but also provides structural information at the interfaces.

8098-39, Session 8

Interaction between single walled carbon nanotubes and specific optically active molecules

H. Chaturvedi, N. O. Maheshwari, Indian Institute of Science Education and Research, Pune (India); J. C. Poler, The Univ. of North Carolina at Charlotte (United States)

Novel effects like photon enhanced aggregation are observed in solutions of functionalized SWNTs. SWNTs functionalized with optically sensitive molecules like MEH-PPV, ruthenium dyes exhibits enhanced rate of aggregation, due to charge dynamics and consequently its effect on electrical double layer in solutions. Rate of aggregation for functionalized SWNTs depends on the molecular absorption of the optically active molecule and increases linearly with power in the absorption window. We believe charges are transferred onto the nanotubes from the optically excited molecules, initiating rapid aggregation. DLVO theory has been extensively used to understand larger colloidal solutions. However with high specific surface area and enhanced reactivity DLVO theory needs to be well understood in relation to the nanoparticles. Critical coagulation concentration (CCC), the minimum concentration of ionic species to induce coagulation is theoretically based on DLVO theory thus inheriting various approximations. Modified Schulze hardy law is experimentally plotted for SWNT solutions using different inorganic salts. Effect of light, concentration, surface charges and ionic strength on CCC using various optically active coagulants are investigated for both semiconducting and metallic enriched solutions of SWNTs. Binding and molecular interaction between optically active supramolecules with semiconducting and metallic SWNTs are characterized using high resolution microscopic and spectroscopic techniques. Field effect transistor (FET) based on functionalized SWNT is fabricated using optical and e-beam lithography for electro-optical measurements. Optical effect on electronic transport through the functionalized SWNT devices is characterized. Optical doping of SWNTs is observed due to charge transfer onto the nanotubes from the optically active molecules bound to it. Optically controlled variation in electronic current through the FET device is discerned and scheme for realization of prospective optical switches and functional reliable devices will be presented.

8098-33, Session 8

Synthesis and electrochemical FTIR study of Pd-based nanostructured catalysts

A. Chen, R. M. Assumme, S. Chen, C. Asmussen, R. Laurin, Lakehead Univ. (Canada)

Driven by the increasing need for cleaner and more efficient engines in transportation applications, there has been growing interest in the study of the direct electrochemical oxidation of small organic molecules such as formic acid and methanol for the development of fuel cells. Palladium-based nanomaterials with high surface areas have been receiving great attention due to their unique properties, which enable a number of impressive applications in catalysis, fuel cells, hydrogen storage and chemical sensors. Recent studies have shown that the electrocatalytic performance of Pd-based nanomaterials is highly dependent on the composition, morphology and surface conditions of the synthesized materials. In this presentation, we report on the synthesis and electrochemical properties of different Pd-based nanostructured materials.
8099-01, Session 1
Carbon nanotube-mediated siRNA delivery for gene silencing in cancer cells
T. Hong, Vanderbilt Univ. (United States); J. Qiao, Vanderbilt Univ. Medical Ctr. (United States); H. Guo, Vanderbilt Univ. (United States); T. S. Triana, D. H. Chung, Vanderbilt Univ. Medical Ctr. (United States); Y. Xu, Vanderbilt Univ. (United States)

Carbon nanotubes (CNTs) have attracted much attention as a tool for transporting therapeutic molecules into cells; small interfering RNA (siRNA) is among the molecules which can be conjugated to CNTs for drug delivery. siRNA is potentially a promising tool in influencing gene expression with a high degree of target specificity. However, its poor intracellular uptake, instability in vivo, and non-specific immune stimulations have impeded its effect in clinical applications. In order to solve this problem, we have studied two types of CNT-mediated siRNA delivery systems for gene silencing in both neuroblastoma and breast cancer cells. In this study, carbon nanotubes functionalized with two types of phospholipid-polyethylene glycol (PL-PEG) have shown capabilities to stabilize siRNA in cell culture medium during the transfection and efficiently deliver siRNA into cells. Compared to Lipofectamine 2000-mediated siRNA delivery, CNT-mediated siRNA delivery systems yield equal or higher efficiency in silencing target gene expression. Our results have shown that CNT-mediated siRNA can efficiently silence various genes in both neuroblastoma and human breast cancer cells. Although both types of PL-PEGs stabilized siRNA molecules during transfection in cell culture media, PL-PEG 5000-Amine functionalized CNTs showed higher efficiency for gene silencing than CNTs functionalized by DSPE-mPEG 5000, the one without amine group. Based on these fundamental studies, we believe that CNTs hold great potential in mediating siRNA to silence specific genes in various human cancer cells, and will be a novel tool in further clinical applications.

8099-02, Session 1
Ebola virus detection using optofluidic-nanoplasmonic biosensors
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We demonstrate a label-free optofluidic-nanoplasmonic sensor that can directly detect live viruses from biological media at clinically relevant concentrations with little to no sample preparation. This work is the first demonstration of direct detection of intact viruses using extraordinary light transmission phenomena. So far, the questions remain for the possible limitations of this technique, as the penetration depths of the surface plasmon polaritons are comparable to dimensions of the pathogens. In this paper, we addressed this gap and showed that our nanoplasmonic sensors can reliably detect viruses down to 10^5 PFU/ml concentrations and operate over a wide dynamic range. Our sensing platform utilizes specific antibodies for highly divergent strains of rapidly evolving viruses. We demonstrate direction detection and recognition of small enveloped RNA viruses, which make up almost all of the alarming new infectious diseases. Some of these viruses, e.g. the Ebola hemorrhagic fever virus are both emerging infectious and biological threat agent. Patients presenting with RNA virus infections often show symptoms that are not virus specific. Thus, there is great interest in developing sensitive, rapid diagnostics for these viruses to help direct proper treatment. We also tested our platform for the detection of enveloped DNA poxviruses, e.g. the Vaccinia virus, a poxvirus commonly used as a prototype for more pathogenic viruses such as smallpox. This platform, enabling fast and compact sensing of the intact viruses without any mechanical and light isolation, could open up biosensing applications for early and point of care diagnostics.

8099-03, Session 1
Novel, rapid DNA-based on-chip viable bacterial identification system combining dielectrophoresis and amplification-free fluorescent resonance energy transfer assisted in-situ hybridization (FRET-ISH)
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Although real-time PCR (RT-PCR) has become a diagnostic standard for rapid identification of bacterial species in clinical and environmental samples, it remains time-intensive due to sample preparation and amplification cycle times and provides no insight into the viability of detected cells. The assay described in this work incorporates on-chip dielectrophoretic separation and concentration of live cells with fluorescence resonance energy transfer assisted in-situ hybridization (FRET-ISH) species identification. In addition, the assay includes a heating step which provides for simultaneous lysis, permeabilization and DNA denaturation via a Kaptori® KHLV series (Polyimide Film and FEP adhesive) rectangular insulated heaters. Finally, signal amplification in the form of energy transfer from Syto 9, a non-specific DNA stain, to Hexachlorofluorescein (HEX) labeled Escherichia coli specific repetitive sequence probes allows confirmation of Escherichia species via FRET-ISH in real time. Identification of viable, and thus pathogenic, cells is achieved completely on chip in less than thirty minutes from receipt of sample compared to multiple hours required by RT-PCR and its requisite sample preparation. The simplicity, speed, and adaptability for detection of any DNA-based pathogen using this technique makes it an ideal candidate for field use, especially in cases of time-sensitive outbreak.

8099-04, Session 1
Localized drugs delivery hydroxyapatite microspheres for for osteoporosis therapy
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Hydroxyapatite [Ca10(PO4)6(OH)2, HAp] is the main mineral component of bones and hard tissues in mammals and well known for its high biocompatibility and osteoconductivity. In this study, we synthesized hydroxyapatite microspheres for localized drugs delivery, typically osteoporosis related medicines. The formation of calcium phosphate microspheres were initiated by enzymatic decomposition of urea and accomplished by emulsification process (water-in-oil). The microspheres obtained were sintered at 500°C to remove organic compounds remained which potentially causes toxicity. The microspheres with a mean size range of 257 ± 3 were in a spherical shape. Scanning electron microscope (SEM) indicated that the microspheres have various porous with random size, which maximizes the surface area. We performed load of alendronate and BMP-2 into HAp microspheres by adsorption process. The load of drugs was investigated by using FT-IR analysis. Releases of alendronate and BMP-2 were observed at 37°C for 30 days and we found the release of both molecules showed sustained releasing profiles. Finally, animal trial showed the alendronate loaded HAp microspheres enhanced bone density in osteoporosis model rat after inject the drug loaded microspheres. Our study focused on development of non-toxic drug carrier, high drug loading, its sustained releasing and in vivo animal trial to verify the effectiveness. It was reported that oral dose is not adaptable to alendronate administration because oral administration of alendronate causes gastrointestinal disturbances. Hence, we believe that this material is suitable to locally deliver alendronate for osteoporosis therapy.
Highly efficient antibody immobilization with multimer protein G bound magnetic silica nanoparticles

J. H. Lee, H. K. Choi, J. H. Chang, Korea Institute of Ceramic Engineering and Technology (Korea, Republic of)

This work reports the immobilization of monomer, dimer and trimer (multimer) protein G onto silica magnetic nanoparticles for self-oriented antibody immobilization. To achieve this, we initially prepared the silica-coated magnetic nanoparticle having about 50 nm diameters. The surface of the silica coated magnetic nanoparticles was modified with 3-aminopropyl-trimethoxysilane (APTMS) to chemically link to multimer protein G. The conjugation of amino groups on the MNPs to cysteine tagged in multimer protein Gs was performed using a sulfo-SMCC coupling procedure. The binding efficiencies of mono-, di- and trimer were 78%, 62% and 54% respectively. However, the efficiencies of antibody immobilization were 71%, 81% and 90% for mono-, di- and trimer, respectively. To prove the enhancement of accessibility by using multimer protein G, FITC labeled goat anti-mouse IgG was treated to mouse IgG immobilized magnetic silica nanoparticles through multimer protein G. FITC labeled goat anti-mouse IgGs were more easily bound to mouse IgG immobilized by trimer protein G than others. Finally, multimer protein G bound silica magnetic nanoparticles were utilized to develop highly sensitive immunoassay to detect hepatitis B.

Recyclable optical microcavities for label-free sensing

H. K. Hunt, A. M. Armani, The Univ. of Southern California (United States)

Label-free biosensors with high sensitivity and high specificity have shown tremendous potential in medical diagnostics, environmental monitoring, and food safety evaluation. Optical microcavities have very low optical loss, and are therefore uniquely suited to sensing applications that require high sensitivity, particularly when paired with a biochemical recognition element that grants high specificity. The primary limitation of these biosensors, however, is that they are generally single-use systems, unless the recognition element is regenerated. Therefore, the ability to selectively functionalize the optical microcavity for a specific target molecule and then recycle the system, without degrading device performance, is extremely important. Here, we demonstrate a straightforward bioconjugation strategy that not only imparts specificity to optical microcavities, but also allows for biosensor recycling. In this approach, we selectively functionalize the surface of silica microtoroids with a biotin recognition element, using silane coupling agents and N-hydroxysuccinimide (NHS) ester chemistry to graft the biotin onto the surface. We then use a non-destructive O2 plasma treatment to remove the surface chemistry, refresh the recognition element, and recycle the device. The surface chemistry of these devices is demonstrated using XPS, SEM, and fluorescent and optical microscopy. The optical performance of the functionalized and recycled devices is characterized by microcavity analysis. The resulting devices can be recycled several times without performance degradation, and show high density surface coverage of biologically active recognition elements. This work represents one of the first examples of a recyclable, bioconjugation strategy for optical microtoroid resonators, which can be used for label-free detection of biomolecules.

Surface enhanced Raman scattering (SERS)-based sensing schematics for detection and identification of biological samples

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There is a relevant Army need to detect, identify, quantify and differentiate hazardous from benign materials in theatre. These hazardous materials can be energetic, chemical or biological in nature. Raman-based technique are becoming more commonly employed towards this end as they rely on specific vibrations within the molecule from which to produce a fingerprint spectrum, do not suffer from interferences from water, require little to no sample preparation, and can be used with several different excitation sources. Surface-enhanced Raman scattering (SERS) offers all the advantages of Raman, with the added advantage of increased analyte signal. SERS signal enhancements are achieved by irradiating a metalized surface with an analyte in close contact, and then measuring the signal from the chemical and electromagnetic enhancements that occur. In our research, we have characterized several different SERS substrate architectures and determined their applicability to Biological samples. Additionally, we have developed a molecular specific sensor schematic using a dual SERS fluorescence signal.

Bioconjugation strategies for improved optical sensor performance

C. E. Soteropulos, H. K. Hunt, A. M. Armani, The Univ. of Southern California (United States)

The very low optical loss or high quality factors of silica optical microresonator sensors allow them to behave as very sensitive optical transducers. Therefore, they are a potential platform for real-time biosensing and diagnostics applications. However, their use is currently limited by the lack of high specificity and stable surface chemistries for the attachment of probe molecules. The main challenge when developing a method to functionalize optical devices is the need to maintain the optical performance of the device, while at the same time reliably attaching the probe. One extremely stable method of attaching biomolecules to silica surfaces is based on NHS-ester chemistry as the link between the inorganic surface and the biomolecule. This covalent attachment of the probe provides a robust interaction, and the method used is easily translated to a wide range of biomolecules, such as antibodies and antigens. In present work, we have applied this method to the surface of optical microsphere resonant cavities, and demonstrated quality factors above 1 million after probe attachment, thus verifying that the attachment strategy has minimal impact on the optical performance of the device. Through fluorescent imaging, we have confirmed the bioactivity of the binding site, as well as site stability even after long-term device storage (>30 days). Finally, we have performed resonant cavity detection experiments based on resonant frequency shift measurements using the functionalized devices, further confirming the applicability of this approach for imparting specificity while retaining optical performance.

Plasmonic biosensing with nanoimprint binary grating using ellipsometry

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An optical label free and high sensitivity plasmonic biosensor is presented based on the phase information of the ellipsometry signal. Plasmonic binary grating were prepared by using soft nano-imprinting
technique which significantly reduce the fabrication cost and can be realized for a transition from a laboratory-scale method to full-scale technology. The adsorption of bio-molecules on the nanostructure surface were investigated both in dynamic and spectroscopic mode by monitoring the change in polarization state or phase of reflected light as a sensing signal using ellipsometry. As a calibration, the bulk sensitivity obtained from our proposed plasmonic binary grating is about 9600 degrees/RIU by assuming a phase measurement accuracy of about 0.0010 as adopted in the literature. Furthermore, the experimental results were compared with an efficient theoretical simulation based on rigorous coupled wave analysis (RCWA).

8099-10, Session 3

CdSe/ZnS quantum dots with interface states as biosensors
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The paper presents the brief review of published results as well as the original study of photoluminescence (PL) and Raman scattering of core-shell CdSe/ZnS quantum dots (QDs) with radiative interface states. First commercially available CdSe/ZnS QDs with emission at 525 nm (2.36 eV), 565 nm (2.20 eV), 605 nm (2.05 eV) and 640 nm (1.96 eV) covered by PEG polymer have been compared in nonconjugated states. PL spectra of nonconjugated QDs are characterized by a superposition of PL bands related to excitation emission in CdSe cores and to hot electron-hole emission via high energy states (2.00, 2.37, 2.75 and 3.04 eV). The high energy states were studied using QDs of different sizes and at different temperatures. It is shown that these PL bands related to interface states. Then the CdSe/ZnS QDs have been conjugated with bio-molecules - anti IL-10 (Interleukin 10) and PSA (Prostate-Specific Antigen) antibodies. It is revealed that the PL spectrum of bioconjugated QDs has changed dramatically with essential decreasing of hot electron-hole recombination flow via interface states. The variation of PL spectra at the bioconjugation is explained on the base of electrostatic interaction and re-charging of QD interface states [1]. The Raman scattering study of nonconjugated and bioconjugated QDs has shown that mentioned antibodies are characterized by the dipole moment that provokes the surface enhance Raman scattering effect [2] in bioconjugated QD samples.


8099-11, Session 3

Characterization of a silicon photonic biosensor consisting of two cascaded ring resonators employing the Vernier-effect to improve sensitivity and interrogation.

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Many applications require label-free biosensors that consist of a transducer that directly responds to a selective affinity interaction between immobilized receptor molecules and analyte molecules. Silicon-on-insulator ring resonators have already been proven to be excellent transducers that can be incorporated in a dense sensor array capable of multiplexed sensing and moreover can be manufactured with high quality using CMOS-compatible processes. However, ring resonators only have a limited sensitivity, of which an enhancement could not only further improve their detection limit, but it would also enable cheaper interrogation with a broadband light source and integrated wavelength filters.

We propose a sensor that employs the Vernier-effect to enhance the sensitivity of ring resonators with more than an order of magnitude. It consists of two cascaded silicon-on-insulator ring resonators of which only one is allowed to interact with biomolecules.

We designed and fabricated this sensor so that a periodic envelope signal is superposed on the sharp constituent resonance peaks, and experimentally prove that its sensitivity to a changing refractive index (2169nm/RIU) is thirty times larger than that of a single ring resonator. Its detection limit moreover benefits from the sharp transmission peaks that constitute the envelope. Analytical formulas describing the sensors transmission spectrum allow us to accurately track shifts of the envelope signal by data-fitting. Additionally, for the first time on-chip wavelength filtering of the sensor’s signal with an integrated arrayed waveguide grating can be presented, making our sensor compatible with cheap interrogation with a broadband light source. We think that these improvements make silicon-on-insulator ring resonator label-free biosensors even more attractive for many applications.

8099-12, Session 3

Block copolymer modified graphene field effect transistor robust biosensor
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It is essential to control the electronic properties of graphene field effect transistors (GFETs). After spatially controlled CF4 plasma doping, we succeed in controlling the Dirac point of a GFET covered with cylindrical-morphology polycrystalline block co-polymer (BCP) (Poly(styrene-b-4-vinylpyridine)). The BCP microdomain array assembled on graphene provides a new approach to tune both electron and hole conductivity of graphene simultaneously. The BCP-covered GFET could detect 1mM NaF solution under “dry” conditions in 60s. Time studies showed that the sensor lasted for over 3 months. It was also determined that the orientation and periodicity of the resulting BCP array of cylindrical microdomains facilitate the selective sensing property. These findings pave the way for developing more durable and sensitive graphene-based sensors for chemical or biological applications under ambient conditions.

8099-13, Session 3

Nanoplasmon coupled intracellular optical resonance excitation for ultrasensitive 3D fluorescence cell imaging

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With the goal of creating a platform for enhanced 3D fluorescence cell imaging capability, we have fabricated a nanoplasmonic substrate on which three-dimensional confocal fluorescence cell imaging sensitivity is amplified for more than 100 folds especially for cell membrane and cytoplasm. The observed unprecedented three-dimensional fluorescence intensity enhancement on the entire cell microstructure including cell membrane 10 µm above the substrate surface is attributed to a novel field enhancement mechanism, nanoplasmon coupled optical resonance excitation (CORE) mechanism which permits enhanced surface plasmon on the substrate being evanescently coupled to Whispering Gallery mode optical resonance inside the spheroidal cell membrane microcavity. This is distinctly different from metal enhanced fluorescence effects because of the fact that metal enhanced fluorescence is a near field effect and only available up to 100 nm above the metal surface. Evidenced by high-resolution vertical slices of cell fluorescence images, the strong intracellular optical resonance modes provide highly intensified laser excitation inside cells and then lead to the huge amplification of fluorescence imaging sensitivity. Further, we have established the theoretical model for coupling of surface Plasmon evanescent wave with whispering gallery mode using coupled mode theory. In addition, preliminary experiment has also been performed using our device to see the early stage of transfection in a cancer cell.
Kinetic analysis of biomolecular interactions by surface plasmon enhanced ellipsometry

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We present the application of ellipsometry to the phase measurement of surface plasmon resonance (SPR) in biomolecular detection. In this work, the experimental setup for the SPR sensor was based on a custom-built rotating analyzer ellipsometer, which was equipped with a SPR cell and a microfluidic system. We investigate the sensitivity of SPR sensor which is dependent on the thickness and roughness of metal film, alignment of optical system, and stability of microfluidics.

In the drug discovery process, to directly monitor the interaction of small molecule-protein, it is necessary to design a high-sensitivity SPR sensor with a sensitivity of greater than 1 pg/mm2. Our sensor demonstrates a much better sensitivity in comparison to other SPR sensors based on reflectometry or phase measurements. The results of calibration indicate that the phase change, \( \Delta \), had an almost linear response to the concentration of ethanol in the double-distilled water solutions. A quantitative analysis of refractive index variation was possible using the results of the ellipsometric model fits for the multilayered thin film on the gold film. Thus, this method is applicable not only to sensor applications, such as affinity biosensors, but also to highly sensitive kinetics for drug discovery. In this paper, we demonstrate how a custom-built rotating analyzer ellipsometer in the SPR condition can be used to directly obtain the interactions and binding kinetics of low-molecular-weight analytes (biotins, peptides) with immobilized ligand (streptavidin, antibody). We achieved a detection limit of lower than 1.0 x10−7 RIU, which is the equivalent of 0.1 pg/mm2.

Nanobarcoding: a novel method of single nanoparticle detection in cells and tissues for nanomedical biodistribution studies

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Determination of whether nanomedical devices accumulate in diseased (target) or normal (non-target) tissues, known as nanoparticle biodistribution, is absolutely critical in assessing the safety and efficacy of a given nanoparticle formulation for nanomedical purposes. However, current imaging-based methods of evaluating nanoparticle biodistribution are greatly limited. There is an overwhelming need for a more sensitive and more efficient imaging-based method that ideally can (1) detect small numbers of nanoparticles, even single nanoparticles, (2) associate preferential nanoparticle uptake with histological cell type, and (3) allow for relatively quick and accurate nanoparticle detection in the large, complex in vivo environment. One method that has the potential to fulfill the requirements of an improved nanoparticle detection strategy is in situ polymerase chain reaction (PCR). In situ PCR combines the extreme sensitivity of PCR and the cell-localizing ability of in situ hybridization. Since in situ PCR has had success in detecting viral DNA at a low-copy number inside single cells in a tissue section, which is analogous to the small numbers of nanoparticles that can be present, the in situ PCR technique can be adapted to the detection of single nanoparticles. We propose a novel method for nanoparticle detection that utilizes an oligonucleotide “nanobarc ode” conjugated to the nanoparticle surface, which serves to amplify the optical signal from a single nanoparticle via the detection of single nanoparticles. In our experimental setup a spectrometer was coupled to a dark-field microscope by an optical fibre for collecting the emitted light. A small pinhole (150 µm) allows focusing on just one nanoparticle for collecting its optical information. Interparticle distances of larger than 5 µm excludes plasmon coupling effects of adjacent nanoparticles.

Herein, we investigate the sensing potential of different kinds of gold nanoparticles for LSPR-based optical sensing

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The optical properties of noble metal nanoparticles depend on the excitation of localized surface plasmon resonance (LSPR) by electromagnetic irradiation. The position and intensity of the occurring plasmon band is influenced by particle specific features such as size, shape and material/composition. Important for biosensor applications are changes in the local refractive index of the surrounding medium, which can also cause a detectable plasmon band shift. Micro spectroscopy to measure the scattering spectra of chosen particles undergoing biomolecular recognition process on the single particle level has been demonstrated successfully. In our experimental setup a spectrometer was coupled to a dark-field microscope by an optical fibre for collecting the emitted light. A small pinhole (150 µm) allows focusing on just one nanoparticle for collecting its optical information. Interparticle distances of larger than 5 µm excludes plasmon coupling effects of adjacent nanoparticles.

Herein, we investigate the sensing potential of different kinds of gold nanoparticles for LSPR-based optical sensing.
nanoparticles for detecting DNA immobilization and hybridization. After immobilizing the gold nanoparticle on a glass substrate via silane chemistry, the single-stranded capture oligonucleotide was attached to the particle surface by thiol-gold interaction. Afterwards, single-stranded target DNA with a complementary sequence was hybridized to the capture oligonucleotide. Towards each step the scattering spectra of the particle was recorded. An example for 80 nm gold nanospheres is shown in figure 1. An obvious red shift of the plasmon band could be detected for both capture DNA attachment and target DNA hybridization.

8099-20, Session 4

Vertically emitting photonic bandgap cavity arrays for sensing applications

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Highly selective sensing technologies continue to be of considerable interest because of their potential for applications in genetic screening, clinical diagnostics and single-molecule detection, among others. The reduction of the sensing element length scale and the formation of multiple patterned structures on a common substrate is essential for the development of arrayed biosensors. Thus, a patterned nano-structured material is an excellent candidate for such applications.

In this work, we demonstrate a simple and compact gas sensor array based on waveguide-coupled submicron multi-ring photonic bandgap (“bullseye”) structures. The “bullseye” structures were patterned inside the SU-8 waveguide using focussed ion beam etching, which enables precise dimensional control in the submicron range. The center of each “bullseye” - the vertical cavity - was functionalized by incorporating analyte sensitive fluorescent molecules. The “bullseye” structures were designed to confine light at the fluorescence wavelength in the transverse direction by photonic bandgap effect. In this way, when excited by a broadband light source incident through the waveguide, the “bullseye” structure emits light in a cone pointing in the vertical direction. We discuss a methodology for translating this technology to biological sensing. In particular, this unique combination of transverse waveguide-based geometry for excitation and vertical detection will be beneficial for micro-fluidic based biological sensor systems.

8099-33, Session 4

A new glucose biosensor based on ECL technology and self-assembly GC electrode including GOx and silver nanoparticle

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Electrogenerated Chemiluminescence (ECL) involves applying a certain electric potential to a chemical reaction, resulting in the oxidation or reduction of the substance which reacts to produce light. We determine the amount of glucose by its reaction to glucose oxidase (GOx) on the surface of proposed modified electrode which results hydrogen peroxide (H2O2) as side product. After that the reaction between luminol and H2O2 under oxidizing conditions generate dependent light which can be used to analysis. In the current article at first we proposed a convenient method to obtaining a self-assembly modified electrode. A nano based modified glassy carbon electrode (Glucose oxidase, silver nanoparticle, luminol, p-aminobenzene sulfonic acid/ GC electrode) were prepared, and the ECL behavior of luminol in the presence of glucose was examined. Compared to the bare GC electrode, the modified electrode incorporating glucose oxidase significantly enhanced the response of the ECL biosensor to glucose due to the enhanced specificity of the modified surface to enzymatic reaction, and the sensitivity of the luminal ECL reaction. Under optimal conditions, the electrode was found to respond linearly to glucose in the concentration range 5.0×10−7 to 8.0×10−3 mol/L, and the detection limit was established to be a glucose concentration of 4.0×10−8 mol/L.
8099-23, Poster Session

**Nanoparticle-aided surface plasmon resonance: engineered nanoparticles for higher sensitivity with functionalities**

S. Moon, D. Kim, J. Park, B. Kang, S. Haam, Yonsei Univ. (Korea, Republic of)

Simplicity along with relatively high sensitivity has been a great merit that surface plasmon resonance (SPR) based biosensors hold. As more demands towards molecular sensing emerged, abundant researches focused on enhancing the sensitivity even further appeared. Such include employing of surface nano to micro structures to alter the intrinsic surface sensitivity, switching the figure of merit to a more sensitive measure, and applying nanoparticles as signal enhancement agents. This study introduces use of multi-functional nanoparticles (MNPfs) for active selection of labeled biological samples with amplified optical signature. Particles are composed as gold nanoshell surrounding magnetic nanoclustered core and dielectric inner shell. MnFe2O4 has been reported as an outstanding magnetic resonance imaging contrast agent, which also possesses strong sorting capability in flow-based sorting labchips. Gold nanoshells are known for strong absorption characteristics, which implies that enhanced SPR sensor can replace giant magnetic resonance sensor which requires extreme accuracy in fabrication. As an empirical proof-of-concept, DNAs labeled with MNPfs are successfully sorted in a flow chamber and detected with enhanced sensitivity. Also, a range of structural availability is numerically analyzed to provide a guideline for optimized particle synthesis. The results are expected to open a wide application in terms of directed sensing.

8099-24, Poster Session

**Gold @ silica core-shell nanoparticle for enhanced surface plasmon resonance detection of DNA hybridization in combination with gold nanowire gratings**

S. Moon, Y. Oh, D. Kim, H. Lee, H. C. Kim, K. Lee, Yonsei Univ. (Korea, Republic of)

Metallic nanoparticles have drawn much interest due to their distinct plasmonic characteristics especially in imaging and sensing applications. Surface plasmon resonance (SPR) based biosensors have evolved in many ways, among which sensitivity enhancement towards molecular sensing capability came up with strategies to overcome the hard limit of the intrinsic sensitivity of gold thin film. Recently adoption of signal contrast materials has proven successful in biochemical sensing applications. This study employs gold-SiO2 core-shell nanoparticles (CSNPs) as a strong SPR signal contrast agents. To reveal the underlying physics for the contrast mechanism, the particle characteristics were analytically evaluated in terms of light interaction coefficients. We experimentally demonstrate the effect of the CSNPs by applying them to acquire enhanced signal in DNA hybridization sensing scheme. We also applied gold nanowire grating structure on conventional gold thin film to further amplify the intrinsic sensitivity, where localized surface plasmon and locally amplified evanescent fields take parts. The results suggest that CSNPs and the grating structure cooperatively enhance the sensitivity and the role of nanowire gratings was analyzed with numerical methods to allow optimum sensitivity enhancement in terms of fill factor variations. The effects of field localization, amplification and enlarged signature of CSNPs are also discussed.

8099-27, Poster Session

**Silver doped nanomaterials and their possible use for antibacterial photodynamic activity**

K. Wysocka-Król, H. Podbielska, Wroclaw Univ. of Technology (Poland)

Bacteria, viruses and parasites elimination from human environment has been one of the most important problem, extensively studied by many researchers. The growing resistance to commonly used disinfection and/ or sterilization methods and antibiotics, is one of the major problem in the health care sector. Nanomaterials with tailored antimicrobial features may find applications in this field. One of the promising application of nanomaterials is the antimicrobial photodynamic therapy (APDT), which combines a nontoxic photoactive dye - photosensitizer and nanomaterials properties. Titanium dioxide based material known due to it photocatalytic properties, will be examined. The paper focused on the examination of optical and antibacterial properties of silica- and titania-based nanopowders doped with silver and photosensitizer - Photolon. It is known that silver doped biomaterials inhibit microbial growth and have been examined against various bacteria. Silver may interact with cellular wall and disintegrate it. The main target of silver are structural and enzyme proteins. From the other hand, photosensitizers are able to generate singlet oxygen and free radicals after light exposure that kill microbial cells. Various concentration of Photolon and nanomaterials have been examined to check the fluorescence enhancement and increased antibacterial activity. It was proved that the fluorescence intensity of Photolon increased, depending on silver concentration. Antibacterial effectiveness of Photolon and silver nanomaterials revealed antibacterial activity, but in the presence of Photolon, the antibacterial activity of materials is more effective.

8099-28, Poster Session

**Fluorescence enhancement by a dielectric Bragg resonant cavity**

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The strong near-field enhancement of surface plasmon modes can significantly improve fluorescence emission. However, if fluorescent molecules are very close to the metal surface, the fluorescence can be quenched. On the other hand, it is found that purely dielectric structures, such as one-dimensional (1D) periodic gratings or two-dimensional (2D) photonic crystals, can also produce substantial local field enhancement thanks to the resonant photonic modes of the dielectric system. Such a platform based on mere dielectrics normally exhibits much less losses, in contrast to plasmonic structures. Consequently, fluorescence signals can be enhanced without suffering from pronounced quenching. However, so far 1D or 2D periodic dielectric structures have not shown confined fluorescence emission. Under some conditions, we may want to selectively choose a certain area, sometimes a small one, to locally enhance fluorescence emission and use it for subcellular biosensing applications. Here we demonstrate that based on a 2D dielectric annular Bragg resonant cavity, electromagnetic waves can be focused to a diffraction-limited spot and significantly boost the fluorescence emission. Due to the constructive interference of the in-plane guided wave around the resonance wavelength, the electric field can be focused and amplified considerably. This leads to experimentally observed 20-fold fluorescence enhancement averaged over an area of 4 μm2, while theoretically the fluorescence emission can be increased by more than three orders of magnitude at the center of the cavity. Our findings may have broad applications including near-field optical trapping, ultrasensitive chemical and biological sensors and fluorescent microscopy at the single-molecule level.
8099-31, Poster Session

**Nanotechnology in cancer treatment**

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Applications of nanotechnology, which include liposomes, nanoparticles, polymeric micelles, dendrimers, nanocantilever, carbon nanotubes and quantum dots, have significantly revolutionized cancer theragnostics. From a pharmaceutical viewpoint, it is critical that the biodistribution of active agents has to be controlled as much as possible. This aspect is vital in order to assure the proper efficiency and safety of the anticancer agents. These biocompatible nanocomposites show specific biochemical interactions with receptors expressed on the surface of cancer cells. With passive or active targeting strategies, an increased intracellular concentration of drugs can be achieved in cancer cells, while normal cells are being protected from the drug simultaneously. Thus, nanotechnology restricts the extent of the adverse affects of the anticancer therapy. Treatment for metastatic breast cancer, sarcoma in AIDS patients, ovarian and lung cancer is already on market or under final phases of many clinical trials, showing remarkable results. As nanotechnology is perfected, side effects due to normal cell damage will decrease, leading to better results and lengthened patient's survival.

8099-32, Poster Session

**Optical immunosensor for endocrine disruptor nanolayer detection by surface plasmon resonance imaging**

A. Karabchevsky, L. Tsapovsky, R. S. Marks, I. Abdulhalim, Ben-Gurion Univ. of the Negev (Israel)

The presence of chemicals, both natural and synthetic, in the environment with the potential to interfere with the endocrine system in both wildlife and humans has in the last decade become a major international concern. Endocrine disrupting compounds (EDCs) such as estrone are especially prevalent in surface and waste-waters [1] in nano-molar concentrations and therefore, there is a need for sensitive analytical device for its monitoring. We have designed a miniature, low cost and fast surface plasmon resonance (SPR) imaging liquid sensor based on the known Kretschman configuration [2]. Due to its stability to water environment and simple bio-immobilization protocol, gold is usually used as SPR biosensing metal nano-layer. However, poor attachment of gold to the glass substrate needs additional layer of few nm Cr or Ti which deform the SPR reflectivity vs. angle curve. Silver, unlike gold, adheres very well to the glass, has very sharp curve but it is oxidizing when introduced to water or air medium, therefore a thin protective layer (<15nm) is needed to prevent oxidation. We used dense and packed thiol (11-mercaptoundecanoic acid (MUA)) layer which protects the silver from oxidation and enable immobilization of Rabbit Anti-Estrone Polyclonal IgG antibody to the thiol layer through linker. 1-Ethyl-3-(3-dimethylaminopropyl)-carbodiimide and N-hydroxysuccinimide (NHS) were added to make the surface reactive. Shift in the SPR signal indicated the presence of the conjugated material-estrone and a detection limit of 5x10⁻⁶ RIU is demonstrated.


8100-01, Session 1

‘Listening’ to the spin noise of electrons and holes in semiconductor quantum structures
S. A. Crooker, Los Alamos National Lab. (United States)

The coherency and dynamical properties of spins in semiconductors are usually studied with powerful techniques based on optical pump-probe or spin-resonance methods. Such methods are necessarily perturbative, in that one measures the dissipative response of the spins resulting from an external drive or excitation field (eg, free-induction decays). However, in accord with the fluctuation-dissipation theorem, the intrinsic fluctuations of the spin system - if experimentally measurable - can also reveal the same dynamical properties (such as g-factors and decoherence times) without ever perturbing the spin ensemble from thermal equilibrium.

This talk describes how we measure electron and hole spin dynamics in semiconductors by passively “listening” to these small spin noise signals [1]. We employ a spin noise spectrometer based on a sensitive optical Faraday rotation magnetometer that is coupled to a digitizer and field-programmable gate array (FPGA), to acquire noise spectra from 0.1 GHz in real time with picoradian/root-Hz sensitivity. In doped (In,Ga)As/GaAs quantum dots, both electron and hole spin fluctuations generate distinct noise peaks whose shift and broadening with magnetic field directly reveal their g-factors and dephasing rates. A large, energy-dependent anisotropy of in-plane hole g-factors is clearly exposed, reflecting systematic variations in the average confinement potential. In contrast with conventional pump-probe studies, noise signals increase as the probed volume shrinks, suggesting possible routes towards non-perturbative, sourceless magnetic resonance of few-spin systems. [1] PRL 104, 036601 (2010); PRB 79, 035208 (2009).

In collaboration with Yan Li, D. Smith, J. Brandt, C. Sandfort, A. Greilich, D. Reuter, A. Wieck, D. Yakovlev and M. Bayer; supported by LANL-LDRD programs.

8100-02, Session 1

Quantum spin Hall effect in topological insulators
E. B. Sonin, The Hebrew Univ. of Jerusalem (Israel)

The original motivation of great interest to topological insulators was the hope to observe the quantum spin Hall effect. Therefore if a material is in the topological insulator state they frequently call it the quantum spin Hall state. However, despite impressive experimental results confirming the existence of the quantum spin Hall state, the quantum spin Hall EFFECT has not yet been detected. After an introduction addressing topological insulators and the spin Hall effect, I shall discuss whether and how the quantum spin Hall effect could be observed.

8100-03, Session 1

Spin injection into silicon using Al2O3, SiO2 and MgO tunnel barriers

We recently demonstrated injection of spin-polarized electrons from an Fe film into Si[1]. The tunnel barrier is the key component in achieving a large spin accumulation in the semiconductor. Here we will compare three different tunnel barriers, Al2O3, SiO2 and MgO, on highly doped Si using three terminal Hanle measurements. Hanle measurements give insight in the spin-accumulation directly underneath the spin injecting contact. We demonstrate the electrical detection of spin accumulation in Si (doped n-type 3x1018 to 6x1019/cm3) up to 500K via injection from a ferromagnetic contact through a SiO2 tunnel barrier formed by plasma oxidation. Lorentzian fits to Hanle curves yield a spin lifetime of ~100 and 320ps for the 6e19 and 3e18 doped Si, respectively. The direct correlation between spin lifetime and carrier concentration in the Si, and that the magnitude of the Hanle signal agrees well with that expected from theory [2], providing clear evidence that the spin accumulation indeed occurs in the Si and not interface states. A spin lifetime of 120ps was obtained for 3e19 n-doped Silicon for both the Al2O3 and SiO2 tunnel barrier. We will present the bias dependence and the temperature dependence of the spin lifetime for the different tunnel barriers. These results demonstrate that spin accumulation in Si can be a viable basis for spin-based devices. Supported by ONR.


8100-04, Session 2

Lateral spin injection in germanium nanowires
E. Tutuc, E. Liu, J. Nah, K. Varahramyan, The Univ. of Texas at Austin (United States)

Efficient spin injection from ferromagnetic metals (FM) into semiconductors (SC) is typically suppressed by the conductivity mismatch at the FM/SC contact. Spin injection can be achieved however if the contact resistivity at the FM/SC interface is appropriately engineered [1]. Here we examine the spin injection in n-type, phosphorus-doped germanium nanowires using cobalt as FM contacts, and MgO tunnel barriers for contact resistance engineering. The two-point magnetoresistance measurements reveal spin-valve effect, with a low (high) resistance for parallel (antiparallel) polarizations of the FM contacts. Non-local, four-point magnetoresistance measurements, which separate the spin diffusion path from the charge current path, demonstrate that the observed spin-valve effect stems from spin injection in the Ge nanowires. We map out the contact resistance window where lateral spin transport is observed, and manifestly show the conductivity matching required for spin injection. We discuss the implications of these results in the context of the spin diffusion theory.


8100-05, Session 2

Hot-electron spin injection and detection in n-doped silicon
Y. Lu, Univ. Henri Poincaré Nancy (France); I. Appelbaum, J. Li, Univ. of Maryland, College Park (United States); M. Hehn, Univ. Henri Poincaré Nancy (France)

Silicon has been known for decades to have an extraordinarily long spin lifetime. Using unique spin-polarized hot-electron injection and detection techniques [1], we have observed unprecedented spin coherence, and extracted very long spin lifetimes of conduction electrons travelling over macroscopic distances [2]. It is necessary to investigate magnetic and electric field controls of electron spin in doped silicon for integration of spintronics into present-day silicon-based microelectronic technology, where impurity doping often plays a critical role.

By reversing the Schottky barrier-height asymmetry in hot-electron semiconductor-metal-semiconductor ballistic spin filtering detectors [3], we have achieved the following: (1) demonstration of >50% spin polarization in silicon (Fig.1), resulting from elimination of the ferromagnet/silicon interface on the transport channel detector contact and (2) evidence of spin transport at temperatures as high as 260 K, enabled by an increase in detector Schottky barrier height.

Unlike previous studies with undoped Si, the presence of ionized
impurities in the depletion regions of these doped transport layers gives rise to conduction-band bending that (for sufficient biasing conditions) confines injected electrons for long dwell times. Recently, another unexpected source of non-equilibrium spin dephasing in n-type phosphorus-doped silicon is also observed when temperature and voltage conditions provide a confining electrostatic potential conduction band profile between injector and detector Schottky barriers [4]. In addition to Hanle spin precession features for magnetic fields in the kOe range, we also observe substantial (but incomplete) dephasing with much smaller characteristic widths of ~50-100 Oe (Fig.2). The possibility that this phenomenon originates from transit-time delays associated with capture/re-emission in shallow impurity traps is discussed in light of temperature, voltage, and electron density dependence measurements.


8100-06, Session 2
Optical spin orientation in SiGe heterostructures

G. Isella, F. Bottegoni, Politecnico di Milano (Italy); F. Pezzoli, Univ. degli Studi di Milano-Bicocca (Italy); S. Cecchi, Politecnico di Milano (Italy); E. Gatti, E. Grilli, M. Guzzi, Univ. degli Studi di Milano-Bicocca (Italy); F. Ciccacci, Politecnico di Milano (Italy)

Germanium lies between gallium and arsenide in the periodic table, therefore Ge and GaAs features many similarities. In particular, still being and indirect bandgap semiconductor, the absorption properties of Ge are dominated by direct-gap transitions coupling heavy holes (HH) and light holes (LH) states in the valence band with the local minimum of the conduction band (CB) at the Gamma point. As a result, selection rules valid for optical spin orientation in GaAs apply also to Ge. In Ge-based heterostructures strain and quantum confinement effects might be employed to remove the HH-LH degeneracy at Gamma, substantially increasing the polarization of excited carriers. Moreover Ge exhibits centre-of-inversion symmetry, a spin orbit interaction weaker than GaAs and a high compatibility with Si technology, all relevant features for spintronics applications.

We present spin polarized photo emission (SPPE) and photoluminescence (PL) measurements performed on bulk Ge, Ge/ Si(100) epiayers and Ge/SiGe multiple quantum wells heterostructures. SPPE data indicate that compressive bi-axial strain effectively lifts the HH-LH degeneracy raising the polarization of injected electrons above the P=50% limit of bulk material.

PL measurements performed on bulk Ge crystal at different excitation energies give insights on the spin relaxation mechanism related to the thermalization of injected carrier at the Gamma point.

In Ge MQW, direct-gap PL at excitonic resonances indicates that spin injection well above bulk values can be achieved. Part of the polarization is preserved during electron scattering from Gamma to the absolute CB minimum at L, as suggested by the polarization of light associated with indirect-gap transitions.

8100-07, Session 2
Spin injection in metal based lateral nanostructures

P. Laczkowski, L. Vila, J. P. Attané, A. Marty, C. Beigné, L. Notin, Commissariat à l’Energie Atomique (France)

The ability to control and manipulate spin currents, a flow in opposite directions of spin up and spin down without net electrical charge flux, is a key point for the development of new spin based electronic devices in the field of spintronics. Admits the large variety of proposed spin structures [FER08], lateral spin valves (LSV) have recently attracted much attentions, giving the possibility of fabrication of multi-terminal nanostructures. The LSV structure quality can be quantified by its spin signal ΔRs, which is related to the difference of non-local electrochemical potential between the anti-parallel and parallel magnetization states of the electrodes. The spin signal depends mainly on the geometry of the LSV, the quality of the interfaces, and the choice of the used materials.

We will review two basic methods for spin current generation in metal based lateral nanostructures, being current injection with the tunnel or transparent junctions through Ferromagnetic(F)/Nonmagnetic(NM) interfaces, or alternatively at the Ferromagnetic/Paramagnetic interface through the Spin Hall Effect (SHE). Recent experiments using the SHE [VAL09] opened new paths toward the generation and detection of spin current without requirements for magnetic materials neither magnetic fields. In this context, the insertion of materials with large spin-orbit coupling in LSV was demonstrated to be an efficient way to measure the Spin Hall angle [VIL07].

We will also present a technique used to optimize the spin signal of LSV using multi-angle deposition process, avoiding interface contamination and oxidation. Comparison of the spin signals obtained with NM material having either short or long spin diffusion length will be also carried out.


8100-08, Session 3
Spin polarized electroluminescence and spin photocurrent in hybrid Semiconductor/ Ferromagnetic heterostructures : an Asymmetric Problem

T. Amand, P. Renucci, V. G. Truong, Institut National des Sciences Appliquées de Toulouse (France); H. Jaffrès, Unité Mixte de Physique CNRS/Thales (France); L. Lombiez, Institut National des Sciences Appliquées de Toulouse (France); P. H. Binh, Institute of Material Science (Viet Nam); J. George, Unité Mixte de Physique CNRS/Thales (France); X. Marie, Institut National des Sciences Appliquées de Toulouse (France)

The photocurrent obtained under polarized optical excitation and the polarized electroluminescence recorded under forward electric bias have been measured in the same hybrid Semiconductor/Ferromagnetic metal structures (Spin-Light Emitting Diode). The systematic investigations have been performed on devices with different ferromagnetic spin injectors: tunnel barrier of Al2O3 surmounted by a thin Co ferromagnetic layer or MgO tunnel barriers with a CoFeB FM layer. Though a very efficient electrical spin injection is demonstrated with a measured circular polarization of the electroluminescence up to 30% for an external field of 0.8 Tesla, very weak polarizations of the photocurrent are evidenced whatever the nature of the device is [1]. The maximum photocurrent polarization obtained under continuous resonant circularly polarized excitation of the quantum well excitons is about 3%. This demonstrates that the investigated devices do not act as an efficient spin filter for the electrons flowing from the semiconductor part to the ferromagnetic part of these structures though these systems are very efficient spin aligners for electrical spin injection. We interpret the weak measured polarization of the photocurrent as a consequence of the Zeeman splitting of the quantum well excitons which yields different absorption coefficients for the polarized excitation laser with different helicities. This leads to different intensities of photocurrent collected for the two different circularly polarized excitations. This interpretation is confirmed by an experiment exhibiting the same results for photocurrent measured on a device with a non ferromagnetic electrical contact.

Optically oriented electron spin transmission across ferromagnet/semiconductor interfaces

T. Taniyama, Tokyo Institute of Technology (Japan)

An understanding of electron spin transmission across ferromagnet (FM)/semiconductor (SC) interfaces is vital to the successful development of spintronic devices. Both electron transmission processes from the FM into the SC and from the SC into the FM are highly relevant to providing information about the surest route to achieving high efficiency of spin injection into SC. The aim of this work is to examine the electron spin transmission processes from a GaAs quantum well (QW) into a ferromagnetic metal layer using optical spin orientation method. The sample structure we used consists of an Fe layer or an Fe3O4 layer on a GaAs/AlGaAs QW. Once circularly polarized light irradiates the sample from the normal to the layer plane, spin-polarized electrons are excited in the quantum well according to the optical transition selection rules, thereby photocurrent of the spin-polarized electrons flows across the interface. Since the photocurrent varies depending on the excited electron spin orientation, measurement of the circular polarization dependence of the photocurrent, i.e., helicity dependent photocurrent, can provide information about the mechanism of electron spin transmission across the interface. One of the most significant results here we observe is a dip appears in the helicity dependent photocurrent at a particular bias voltage for the Fe/GaAs QW sample and even the sign reversal of the helicity dependent photocurrent occurs. The origin of the bias dependence of the helicity dependent photocurrent is discussed in detail using the Breit-Wigner type resonant tunneling process via interface resonant states.

Spin injection in silicon and germanium

M. Jamet, Commissariat à l’Énergie Atomique (France); A. Jain, L. Grenet, A. Barski, Commissariat à l’Énergie Atomique (France); P. Noé, Commissariat à l’Énergie Atomique (France); S. Auffret, P. Warin, J. Hartmann, A. P. Brenac, E. Augendre, V. Balz, P. Gentile, L. Via, Commissariat à l’Énergie Atomique (France)

Spintronics aims at manipulating both charge and spins in semiconductors. It thus requires a robust scheme for injecting polarized current into these materials. Spin injection into GaAs has already been demonstrated experimentally and theoretically. Recently an increasing number of works are performed on spin injection into silicon and germanium since they are the core materials for potential applications and promising candidates for spin polarized transport due to predicted long spin lifetimes. We present results obtained on spin injection from a ferromagnetic layer into silicon (optical detection) and germanium (electrical detection). SiGe quantum wells embedded in a Si-based pin diode are used to optically detect spin-polarized electrons injected into silicon whereas three-terminal and four-terminal geometries are used for electrical non-local detection of spin accumulation in germanium layers. The electron spins are aligned either in-plane using NiFe and Co electrodes or out-of-plane using a CoPt electrode with perpendicular magnetization. Spin injection through an alumina tunnel barrier is carried out to prevent depolarization due to conductance mismatch with silicon and germanium. For spin injection in silicon, the remanent configuration of the CoPt electrode magnetization allows to study spin injection without applying a magnetic field, avoiding spurious effects such as Faraday rotation in silicon. Light polarization of more than 3 percent has been measured and its temperature dependence will be discussed. Preliminary electrical detection of spin accumulation in germanium will also be presented after overcoming the issue of Fermi level pinning at the interface between germanium and the tunnel barrier.
8100-13, Session 4

Tailoring magnetic relaxation channels at the nanoscale
I. Barsukov, Univ. Duisburg-Essen (Germany)

Controlling spin relaxation is essential for spintronic and spin torque applications. Manipulating spin relaxation allows the adjustment of magnetization reversal speed at microwave frequencies. Moreover, the critical current in spin torque devices can be reduced and tuned. In the experiment it is possible to distinguish between the intrinsic and extrinsic relaxation channels. The latter can be tailored with respect to the intensity and anisotropic behavior. In particular, methods for inducing elementary relaxation channels of uniaxial symmetry and their impact on the magnetization dynamics are discussed in this presentation.

Fe-based thin films have been studied by means of the ferromagnetic resonance technique, by which the intrinsic and extrinsic relaxation processes can be disentangled. While the former are rather isotropic and can be adjusted via spin-orbit interaction, the latter can be modified in an advanced way. It is shown, how crystalline defects, inhomogeneities of chemical composition, and interface modifications can induce the 2-magnon scattering. Control and systematic manipulation of these parameters allow tailoring the overall spin relaxation in a desired manner.

In cooperation with J. Lindner, R. Meckenstock, H. Wende, P. Landeros, K. Lenz, and M. Farle.

Financial support by the DFG, SFB 491 is acknowledged.

8100-14, Session 4

Emergent magnetic monopoles and associated Dirac strings in artificial kagome spin ice
L. J. Heyderman, Paul Scherrer Institut (Switzerland)

Artificial spin ice systems, consisting of two-dimensional arrangements of single-domain nanomagnets, have recently been in the focus of scientific interest since they provide an opportunity to directly study the effects of frustration [1, 2]. Our work has focused on artificial kagome spin ice, with elongated nanomagnets arranged on the kagome lattice forming an array of hexagonal rings. Synchrotron x-ray photoemission microscopy allows direct imaging of the magnetic state of each nanomagnet, having moments pointing in one of two orientations parallel to their long axis. Our recent observations demonstrate the existence of emergent magnetic monopoles and their associated Dirac strings at room temperature in a quasi-infinite nanomagnet array [3]. In an applied magnetic field, monopole-antimonopole pairs nucleate and then separate in an avalanche-type manner along one-dimensional Dirac strings, consisting of overturned dipoles. This behaviour is distinct from conventional domain growth in two-dimensional systems and results in the formation of a "stripe phase" towards the end of magnetization reversal. The observed hysteresis, monopole densities and 1D Dirac-string avalanches are quantitatively explained by Monte Carlo simulations and the results open the way to a controlled manipulation of magnetic charges that may lead to new spintronic devices.

8100-17, Session 5

Single-electron spin ratchet
S. O. Valenzuela, Institució Catalana de Recerca i Estudis Avançats (Spain) and Catalan Institute of Nanotechnology (Spain) and Univ. Autonoma de Barcelona (Spain)

We describe a spin ratchet at the single-electron level that produces spin currents with no net bias or charge transport. Our device [1] is based on the ground-state energetics of a single-electron transistor (SET). The SET comprises a superconducting island connected to normal leads via tunnel barriers with different resistances that break spatial symmetry. We demonstrate spin transport and quantify the spin ratchet efficiency by using ferromagnetic leads with known spin polarization.


8100-18, Session 5

Single spins in quantum dots and impurities
C. E. Pryor, The Univ. of Iowa (United States)

There are a variety of methods available for confining and manipulating single spins in solid state systems. While heterostructures can be engineered to the requirements of the problem, their variability is a disadvantage compared to identical impurities. I will discuss theoretical calculations of single spins both in quantum dot heterostructures and bound to impurities. These include calculations of the spin state itself, the effective coupling to a magnetic field, the response to an electric field, and include both electrons and holes.

8100-19, Session 5

Nuclear spin dynamics in semiconductor nanostructures
I. Tifrea, California State Univ., Fullerton (United States)

I will discuss recent advances in understanding the nuclear spin dynamics in low dimensional systems. The focus will be on the hyperfine interaction between nuclear and electronic spins and the role this interaction plays on the dynamical nuclear polarization of semiconductor nanostructures. The natural confinement provided by low dimensional semiconductor nanostructures such as quantum wells and quantum dots is responsible for a position dependent nuclear spin dynamics in these physical systems. Consequently, the nuclear spin relaxation time and implicitly the nuclear spin polarization will be position dependent leading to important implications for optical NMR and Faraday rotation experiments. Additionally, numerical simulations prove that nuclear spin diffusion may be reduced in the same conditions. As an example I will discuss the case of a GaAs quantum well. I will present results for Overhauser shifts, measurable in Faraday rotation experiments, and Knight shifts, measurable in optical NMR experiments. In connection with these results I will present results for nuclear spin diffusion and prove its relatively small effect on the overall polarization of As nuclei. This work was supported by Research Corporation.

8100-20, Session 6

Spin relaxation and spin transport in graphene and the interface of multiferroic oxides
M. Wu, Univ. of Science and Technology of China (China)

Invited talk for SPINTRONICS IV

8100-21, Session 6

Dopants and charge carriers in colloidal semiconductor quantum dots
D. R. Gamelin, Univ. of Washington (United States)

The generation, manipulation, and detection of electron spins in semiconductor nanostructures are all central themes in spintronics and spin-photonics. This talk will describe recent advances in the introduction, study, and manipulation of spins in colloidal semiconductor nanocrystals, focusing on properties of doped nanocrystals such as transition-metal-doped CdsSe, ZnO, and ZnSe quantum dots. Topics will include unusual photoclinorescence phenomena, magneto-optical spectroscopies, magnetic resonance spectroscopies, photoluminescence decay, spin relaxation dynamics, carrier-dopant magnetic exchange interactions, and photon-controlled magnetization. The properties to be discussed underlie many important spin-electronic and spin-photon phenomena including carrier-mediated ferromagnetism, excitonic magnetic polaron nucleation, and proposed spin-based quantum information processing. Basic aspects of doped quantum dot electronic structures will be discussed in this context.

Related references:

8100-22, Session 6

Inelastic light scattering of hole spin excitations in p-modulation-doped GaAs-AlGaAs single quantum wells
M. Hirmer, M. Hirmer, T. Korn, D. Schuh, Univ. Regensburg (Germany); W. Wegscheider, ETH Zürich (Switzerland); R. Winkler, Northern Illinois Univ. (United States); C. Schüller, Univ. Regensburg (Germany)

We have investigated spin-density excitations of holes in one-sided p-modulation-doped GaAs-AlGaAs single quantum wells by means of resonant inelastic light scattering. The experiments yield a direct measure of the Rashba spin splitting of holes in quantum wells with an asymmetric potential profile. The samples are highly-doped GaAs-AlGaAs single quantum wells with well widths of 15, 20 and 25 nm, and different doping densities. The experiments were performed at temperatures of about 4 K, using a tunable Ti:Sapphire laser and a triple Raman spectrometer with liquid-nitrogen cooled CCD detector. In the low-energy range of the inelastic light scattering spectra, we observe in all samples well-defined excitations with excitation energies between about 1 meV and 4 meV, which can be attributed to spin-density excitations of the two-dimensional hole systems due to polarization selection rules. We interpret the excitations as spin-density excitations, where holes are excited between the Rashba spin-split ground states, performing a spinflip. The strong resonance behavior of the inelastic light scattering process allows us to scan the k dependence of the hole spin splitting. Comparison to k*p bandstructure calculations, performed with the NextNano3 program package, shows good agreement of the measured and calculated k-dependent spin splittings. Details of the spectra show a distinct dependence on the directions of light polarizations with respect to crystallographic axes. In particular, we have detected a doubling structure of the hole spin excitations, which may be attributed to the anisotropic hole spin splitting within the quantum-well plane.

Related references:
New insights into nanomagnetism by spin-polarized scanning tunneling microscopy and spectroscopy

H. Oka, P. Ignatiev, S. Wedekind, G. Rodary, L. Niebergall, V. Stepnyuk, D. Sander, J. Kirschner, Max-Planck-Institut für Mikrostrukturphysik (Germany)

Spin-polarized scanning tunneling microscopy (SP-STM) allows imaging and spectroscopic characterization of nanostructures with unsurpassed spatial resolution. Its working principle exploits the dependence of the tunnel current on the relative magnetization orientation of a sample and the magnetic STM tip. We present results by SP-STM, where we investigate the correlation between structural, electronic, and magnetic properties of individual nm small Co islands with several hundred to thousands of atoms. We use external magnetic fields of up to 4 T to tune the magnetic state of both tip and sample, and we extract the corresponding change of the differential conductance of the tunnel junction.

A recent example is our measurement of magnetic hysteresis loops of individual nm small Co islands on Cu(111) at 8 K by SP-STM in external magnetic fields. We find switching fields of up to 2.5 T for islands with roughly 8,000 atoms. The quantitative analysis of these results provides novel insights into the magnetization reversal on the nanoscale, and deviations from the venerable Stoner-Wohlfarth model are discussed.

We also exploit the high spatial resolution of SP-STM in magnetic fields to measure maps of the differential conductance within a single nm small Co island. In connection with density functional theory calculations we demonstrate for the first time that the spin polarization is not homogeneous but spatially modulated within the Co island. We ascribe the spatial modulation of the spin polarization to spin-dependent electron confinement effect within the Co island [1].

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Oxide interfaces: spin transport at the nanoscale

T. Banerjee, Univ. of Groningen (Netherlands)

Oxide spintronics is an emerging research direction where the fundamental thrust is on understanding the physics of electron charge/spin/orbital interactions in perovskite oxide interfaces at the nanoscale. Epitaxial interfaces of half-metallic ferromagnets on oxide semiconductors are the building blocks of spintronic devices. Very little is known about spin transport across such interfaces, at the nanoscale, where intriguing phenomena are likely to emerge. In this talk, I will discuss our recent experiments on nanoscale (spin) electron transport across epitaxial interface of La0.67Sr0.33MnO3(LSMO) on Nb:Si(001) using the technique of Ballistic Electron Emission Microscopy (BEEM) and illustrate its importance in oxide electronics.

An antiferromagnetic insulator with voltage controlled surface polarization

P. A. Dowben, N. Wu, X. He, C. Binek, K. Belashchenko, T. Komesu, Univ. of Nebraska-Lincoln (United States)

For the prototypical magneto-electric Cr2O3(0001), we have observed a finite remanent polarization at the surface in spin-polarized photoemission [1], spin polarized inverse photoemission, and X-ray magnetic circular dichroism. This occurs when the antiferromagnetic single domain state is selected in a magneto-electric annealing process. In a magneto-electric material, an applied electric field induces a net magnetic moment. This becomes important to surface magnetism because there is also a finite remanent magnetization at the surface or boundary of magneto-electric antiferromagnets, predicted using symmetry arguments, and recently demonstrated [1]. In the single domain antiferromagnetic state of Cr2O3, the magnetic Cr2O3(0001) surface moment evolves and is robust against surface roughness, which may be useful for device fabrication. The surface polarization has now been measured to be as high as 70 to 80%, at binding energies corresponding to a strongly weighted surface density of states.

This surface magnetic order, combined with the magneto-electric behavior of Cr2O3(0001), enables the investigator to have electric control
of a net magnetic moment at the Cr2O3(0001) surface. The surface magnetic domain structure has also been imaged in X-ray circular dichroism combined with photoemission electron microscopy (PEEM) at the surface of Cr2O3(0001), under conditions of no electric field cooling and with electric field cooling. Consistent with the other measurements, profound differences are observed.

8100-61, Session 7
Spin injection and relaxation in graphene
W. Han, R. K. Kawakami, Univ. of California, Riverside (United States)

Graphene is a unique and promising candidate for spintronics due to its high mobility, gate tunable transport properties, and low intrinsic spin-orbit and hyperfine coupling. However, the spin injection efficiency has been low (< 10%) and spin lifetime is still much shorter (50-200 ps) than predicted theoretically (~ micro seconds). To fulfill the potential of graphene for spintronics, two major advances need to be accomplished; enhance the spin injection efficiency and extend the spin lifetime. In this talk I will focus on the following two results in graphene spintronics. First, tunneling spin injection into graphene is achieved using MgO tunnel barrier. The non-local spin signal is found to be as high as 130 ohms at 300 K, with a spin injection efficiency of 30%. Second, using tunneling contacts to suppress the contact-induced spin relaxation, we observed the spin lifetimes as long as 771 ps at 300 K, 1.0 ns at 4 K in SLG, and 6.2 ns at 20 K in Bilayer graphene. These advances are important for the development graphene for spintronic applications in logic and storage.

8100-28, Session 8
Chemically-driven nanoscopic magnetic phase separation at the SrTiO3(001)/La1-xSrxCoO3 interface
C. Leighton, M. Sharma, M. Torija, Univ. of Minnesota, Twin Cities (United States); J. Gazquez, M. Varela, Oak Ridge National Lab. (United States) and Univ. Complutense de Madrid (Spain); J. Schmitt, C. He, Univ. of Minnesota, Twin Cities (United States); J. Borchers, M. Varela, National Institute of Standards and Technology (United States); S. El-Khatib, Univ. of Minnesota, Twin Cities (United States)

The remarkable functionality of complex oxides provides many opportunities for new physics and applications. The perovskite cobaltites are an excellent example, being of interest in gas sensing, catalysis, ferroelectric memory, and solid oxide fuel cells. From the magnetism perspective they have high conduction electron spin polarization, and a variety of functional ground states. However, the same delicate balance between phases that provides such impressive functionality also leads to a serious problem; it can be difficult to maintain desired properties close to the interface with a dissimilar oxide. In this work, using SrTiO3(001)/La1-xSrxCoO3 as a model system, we have combined epitaxial growth with detailed structural characterization (including STEM/EELS imaging), conventional magnetometry, electronic transport, and small-angle neutron scattering (SANS). In the SrTiO3(001)/La1-xSrxCoO3 case we observe the usual degredation in magnetization and conductivity in the very thin film limit. We demonstrate that this is due to nanoscopic magneto-electronic phase separation in the interface region. Essentially, nanoscopic ferromagnetic (FM) clusters form in an insulating non-FM matrix near the interface, resulting in reduced magnetization and conductivity, even at compositions that display no such phase separation in the bulk. Depth profiling of the chemical composition reveals that this effect has a chemical origin, being due to subtle depth-wise variations in Sr and O content, resulting in reduced hole doping near the interface. Simple thermodynamic and structural arguments for the origin of these variations are provided.

Work at UMN supported by NSF and DoE, at ORNL by DoE, and at UCM by the European Research Council.

8100-29, Session 8
Structural and magnetic properties of the Mn-based antiperovskites from first principles
P. Lukashev, Univ. of Nebraska-Lincoln (United States)

Magnetomechanical coupling in crystals has many practical applications, such as in sensors, magnetic recording devices, etc. Recent experimental and theoretical studies of the magnetoelectric (ME) effect in the nanocomposite structures and in laminates show an enhanced ME coefficient. These materials combine piezoelectric properties of the paramagnetic phase and magnetoelectric properties of the magnetic phase. In my talk I will present density functional theory (DFT) based results of the structural and magnetic properties of antiperovskite compounds, such as Mn3GaN - a potential candidate for practical applications in ME devices. Due to interplay of magnetic and elastic properties these compounds exhibit variety of interesting features, such as invar effect (or even negative thermal expansion) and a near zero temperature coefficient of resistance. I will show that the magnetic structure of antiperovskite compounds (Mn3GaN) can be controlled by a small applied biaxial strain. The lowering of symmetry with the strain causes the local magnetic moments of Mn atoms to rotate from the trigonal I$\bar{3}$ space group with nonuniform of spin density in the (111) plane to a monoclinic symmetry structure. As a result, an appreciable net magnetization appears in the strained system. I will also discuss the appearance of the net magnetization in Mn-based antiperovskite compounds as a result of the external strain gradient (flexomagnetic effect). In particular, I will describe the mechanism of the magnetization induction in the Mn3GaN at the atomic level in terms of the behavior of the local magnetic moments of Mn atoms. I will show that the flexomagnetic effect is linear and results from the nonuniformity of the strain, i.e., it is absent not only in the ground state but also when the applied external strain is uniform. At the moderate values of the strain gradient (0.1%) the flexomagnetic contribution to the net induced magnetization is comparable with the nonlinear contribution, thus making it attractive for practical applications. Finally, I will discuss the possibility of combining Mn3GaN with typical ferroelectric, such as PbTiO3 to form a prototypical magnetoelectric device.

8100-30, Session 8
Spintronic nanoelectronics using graphene based magneto-logic gates
H. Dery, Univ. of Rochester (United States)

We present a novel design concept for a seamless integration of spin-based logic and memory circuits. The building blocks are universal and reconfigurable magneto-logic gates based on a hybrid graphene/oxide/magnet material system. These nano-gates consist of five ferromagnetic electrodes using nonlocal spin-valve geometries. The logic operations rely on the generation of non-equilibrium spin accumulation when spin polarized electrons tunnel from a ferromagnetic contact into the graphene via a tunnel barrier. Readout of logic operations is triggered by perturbing the magnetization direction of one of the ferromagnetic terminals. This leads to a binary transient current response whose speed and amplitude depend on the RC of the system and on the spin accumulation profile in the graphene layer.

In our simulations we use extracted parameters from recent nonlocal spin-valve measurements in Co/MgO/graphene at room temperature. In addition, we employ spin-transfer torque magnetization writing techniques using all-metallic paths. These path allow significant energy savings compared to the standard spin-transfer torque pillar technique (i.e., if the writing current flows through the tunnel barriers and graphene).
Finally, we present circuit prototypes in which over 100 spin-based logic operations are carried out before any need for a spin-charge conversion. Consequently, supporting CMOS electronics requires little power consumption. Specifically, network search engines are used as a technology demonstration vehicle. We present a spin-based circuit design with smaller area, faster speed, and lower energy consumption than the state-of-the-art CMOS counterparts. This design can also be applied in applications such as data compression, coding, image recognition, and business analytic.

8100-31, Session 8  
**Spintronics using the graphene, fullereene and other group IV materials**  
E. Shikoh, M. Shiraishi, Osaka Univ. (Japan)

In the research field of spintronics, studies using group IV elements have recently attracted much attention. Our group has been focusing not only the graphene spintronics, but also the spintronics using other carbon materials and Si. The gigantic MR effect (1.4 million % at 2K) in C60(fullerene)-Co nanocomposites was observed. That MR effect was well explained with our original theory including the Coulomb Blockade regime. The spin transport properties in Si, such as the bias-current dependence of spin polarization in Si, were observed at room temperature. Those researches are also introduced in addition to our topics in graphene spintronics.

8100-32, Session 9  
**Direct growth of graphene on MgO for spin and charge device applications**  
J. Kelber, Univ. of North Texas (United States)

We have demonstrated the growth of single and few layer graphene on MgO(111). Graphene/MgO interactions induce a graphene band gap of ~ 0.5-1eV. The importance of graphene/MgO heterojunctions for both conventional transistor and spin transport applications will be discussed.

8100-33, Session 9  
**The influence of lattice relaxation on the electron-spin motion in ferromagnetic films: Experiment and theory**  
W. Weber, A. Hallal, T. Berdot, P. Dey, L. Tati-Bismaths, L. Joly, Institut de Physique et Chimie des Matériaux de Strasbourg (France); A. Bourzami, Univ. Ferhat Abbass de Sétif (Algeria); F. Scheurer, Institut de Physique et Chimie des Matériaux de Strasbourg (France); J. Henk, Max-Planck-Institut für Mikrostrukturphysik (Germany); M. Alouani, Institut de Physique et Chimie des Matériaux de Strasbourg (France)

By taking the example of Fe films on Ag(001), we report, first, the discovery of a 180 degrees electron-spin precession in spin-polarized electron reflection experiments, which marks the ultimate limit of spin manipulation in reflection. In fact, this is the largest possible precession angle which can be measured in a single electron reflection. Both experiments as a function of Fe film thickness and ab initio calculations show that the appearance of this giant spin precession depends with utmost sensitivity on the relaxation of the Fe lattice during growth.

Second, the effect of submonolayer MgO coverage on the Fe films is studied. We note that the interface system MgO/Fe(001) has attracted great interest in recent years for its large room temperature TMR, which has been predicted and observed in epitaxial Fe/MgO/Fe(001) tunnel junctions. Although many results have been published concerning the interfacial structure of MgO/Fe, little effort was devoted to elucidate the spin-dependent electron reflection properties of MgO/Fe interfaces. It is thus an open question how MgO is modifying the spin-dependent electron reflection properties of the Fe(001) surface. It is shown in this contribution that the spin polarization direction of the reflected electrons on Fe(001) strongly changes with minute amounts of MgO. Our calculations reveal that the MgO-induced out-of-plane relaxation of the Fe surface layer is responsible for this behavior. Our study points towards the subtle feature that the major change of the spin-dependent electron reflection properties of the Fe(001) surface is already caused by the very first MgO coverage.

8100-34, Session 9  
**Development of low-RA perpendicular-MTJs for spin-RAM application**  

MgO-based magnetic tunnel junctions with perpendicularly magnetized electrodes (p-MgO-MTJs) have been attracting a great deal of attention as memory cells in ultra-high-density spin-transfer-torque random access memory (Spin-RAM or STT-RAM) because nanometer-sized perpendicular magnetic cells can have a thermal stability high enough for data retention over 10 years. A p-MgO-MTJ is required to have not only a magnetoresistance (MR) ratio higher than 100% at RT but also a low resistance-area (RA) product. A low RA product is required for matching the MTJ resistance to the resistance of pass transistors. Assuming a Spin-RAM over 1 gigabit (F = 65 nm), it requires the MTJ cells to have an RA product of about 30 Ωµm2. In this study, we have aimed to achieve high MR ratios of more than 100% in p-MgO-MTJs with ultra-low resistance-area (RA) products less than 5 Ωµm2. [1, 2]

We fabricated p-MgO-MTJs with a [Co/Pt]n/CoFeB/CoFe bottom electrode (free layer) and a CoFeB/CoFeB/TbFeCo top electrode (reference layer) using C-7100 (Canon Anelva), and successfully attained high MR ratios of 100% at room temperature and a low RA product of 2 Ωµm2, simultaneously. We have also fabricated various p-MgO-MTJs by changing the composition of the CoFeB insertion layers. The results suggested that the use of an Fe-rich CoFeB layer gave rise to a high MR ratio. Such a high MR ratio in low-RA p-MgO-MTJs is the key to developing ultra-high-density spin-transfer-torque MRAMs. This work was supported by New Energy and Industrial Technology Development Organization (NEDO).


8100-35, Session 10  
**Utilization of Rashba spin orbit coupling in a semiconductor channel**  
J. Chang, Y. H. Park, H. C. Koo, H. C. Jang, S. H. Han, Korea Institute of Science & Technology (Korea, Republic of)

Spin orbit coupling (SOC) in semiconductors couples the spin of electron to its momentum and provides a new way for electrically initializing and manipulating electron spins for future spintronics devices and spin-based quantum information processing. The effective magnetic field induced by Rashba SOC, which is controllable by electric field, in a quantum channel produces spin splitting and population imbalance between spin-up and spin-down electrons even in the absence of applied magnetic field. It is widely used in the applications in spintronics such as spin field effect transistor and spin Hall effect. In this paper, we present a detection of Rashba SOC using rotational applied field in addition to the Shubnikov-de Haas oscillation, the channel resistance of InAs based quantum channel depending on the alignment between the applied field and the Rashba field and finally oscillatory channel conductance as a function of gate voltage.
Spin currents in solids: definition and application to semiconductors

F. Bottegoni, H. Drouhin, Ecole Polytechnique (France); G. Fishman, Institut d’Électronique Fondamentale (France); J. Wegrowe, Ecole Polytechnique (France)

Spin transport in semiconductors can be dramatically modified by spin-orbit interactions, producing such effects as coherent precession of the spin current. A proper and physically meaningful definition of the transport of spin currents in 3D systems (2DESs) is usually dominated by the D'yakonov-Perel spin dephasing mechanism resulting from the underlying spin-orbit (SO) fields. The observed anisotropic dispersion relations of electrons in the two fields, is due to general features of the energy contour surface of the electrons. Furthermore, the electron-beam formation can be traced, using a stationary phase analysis of the real-space Green’s function, to coalescing stationary points. Such beams should appear in two-contact transconductance as well as other transport and scattering phenomena.

Anisotropic spin dephasing in an (110)-grown high-mobility AlGaAs/GaAs quantum well measured by resonant spin amplification technique

M. Griesbeck, Univ. Regensburg (Germany); M. Glazov, Ioffe Physico-Technical Institute (Russian Federation); E. Sherman, Univ. del Pais Vasco (Spain); T. Korn, D. Schuh, Univ. Regensburg (Germany); W. Wegscheider, ETH Zurich (Switzerland); C. Schüller, Univ. Regensburg (Germany)

The spin dynamics in zincblende-based two-dimensional electron systems (2DEGs) is usually dominated by the D’yakonov-Perel spin dephasing mechanism resulting from the underlying spin-orbit (SO) fields. The observed anisotropic dispersion relations of electrons in the two fields, is due to general features of the energy contour surface of the electrons. Furthermore, the electron-beam formation can be traced, using a stationary phase analysis of the real-space Green’s function, to coalescing stationary points. Such beams should appear in two-contact transconductance as well as other transport and scattering phenomena.

Synchronization of high power vortex oscillators at multiple of the fundamental frequency.

C. Baraduc, S. Martin, Commissariat à l’Énergie Atomique (France); C. Thirion, Institut NÉEL (France); Y. Liu, M. Dovek, Headway Technologies, Inc. (United States); B. Diény, Commissariat à l’Énergie Atomique (France)

RF vortex spin-transfer oscillators based on low RA magnetic tunnel junctions were investigated. A very high power of excitations has been obtained characterized by a power spectral density containing a very sharp peak at the fundamental frequency and a series of harmonics. The observed behaviour is attributed to the combined effect of Oersted-Ampere field generated by the large applied dc-current and of the spin transfer torque. We furthermore show the synchronization of a vortex oscillation by applying a RF bias current which frequency is twice the oscillator fundamental frequency.
8100-41, Session 11

Coupling of two vortices in spin-valve nanopillars for spin-transfer oscillators

N. Locatelli, Unité Mixte de Physique CNRS/Thales (France)

Spin transfer induced vortex dynamics and the radio-frequency signal thereof have recently focused many interest, in particular to address the issues of coherence and power for spin transfer oscillators. However, the signal linewidth obtained for a single vortex gyration is still too large (about 1 MHz). In this work, we will focus on using coupled vortices oscillators. Besides the drastic improvement of the signal coherence, fundamental interests of this system lie in the identification of the excited coupled modes and their selection rules.

The samples are Py(15nm)/Cu(10nm)/Py(4nm) spin-valve nanopillars having a vortex nucleated in each of the magnetic layer. In such systems with interacting vortices, the influence of the various interactions on the dynamical properties is central. Besides the observation of highly coherent vortex oscillations, we demonstrate that the dynamic behaviour is highly dependent on the vortices parameters, notably relative chiralities and polarities. We will compare the results to analytical predictions and simulations, studying the importance of different sources of coupling between the vortices. This work will be extended further to conditions to synchronize arrays of interacting vortex oscillators.

References:

8100-42, Session 11

Spin-torque vortex oscillators in nanopillar geometry

D. E. Buerger, V. Sluka, A. Kakay, R. Hertel, C. M. Schneider, Forschungszentrum Jülich GmbH (Germany)

We present experiments on current-induced vortex dynamics in nanopillars fabricated by optical and e-beam lithography from epitaxially grown Fe/Ag/Fe(001) multilayers. The pillar diameters range from 150 to 230 nm, and the Fe layers with thicknesses between 2 and 30 nm are separated by a 6 nm Ag spacer. Both layer magnetizations and the external field are in-plane. We measure current-driven high-frequency (HF) excitations of spin-torque oscillators (STO) with the free layer in the vortex or uniform state. Our ability to switch between them in a given STO enables a direct comparison of STO properties yielding for the vortex state larger emitted HF power and a wider frequency tuning range. Injection locking of the gyrotropic mode to external HF signals reveals for our GMR-based nanopillars a gap of three orders of magnitude between the HF power emitted by one oscillator and the power needed for phase-locking. Finally we modify the sample geometry such that magnetic vortices can be formed in both Fe disks. We study the dynamics of the single and double vortex state and find for the latter a dependence of the excitation frequency on the current polarity that we relate to exchanged dipolar interaction. Here, we present collective vortex gyration modes of nano-elliptic-ring (NER) shaped magnetic tunnel junctions (MTJs) with the major axis of around 120 nm and minor axis of around 60 nm, and ring width of around 25 nm was fabricated successfully. Magnetic field and current-driven magnetization switching were observed in such NER-MTJs with key stack layers of both spin-valve-type antiferromagnetic (AFM)/ferromagnetic (FM)/insulator (I)/ferromagnetic (FM) and sandwich-type hard-FM/1/soft-FM structures. When the electric current density exceeds a critical value of the order of 7.8x10^6 A/cm^2 (critical driven current is 0.40 mA), the magnetization of the soft(FM) and reference (hard-FM) layer nano-elliptic-rings can be switched back and forth between parallel and antiparallel onion states. Tunneling magneto-resistance (TMR) ratio between 10% and 40% with different thickness of thin Al-O barrier were measured at room temperature as we apply a magnetic field or a pulsed current. The experiments and micromagnetic analysis show that the spin transfer torque (STT) plays a main switching role in the magnetization reversal and the pulse-current-induced elliptic magnetic field play an assisted-switching role in such NER-MTJs. Compared with our previous studies of nano-ring-shaped (NR) MTJs and Nanoring MRAM, the NER-MTJ has a relative symmetric current driven critical behavior, which is due to the shape anisotropy of elliptic-ring architecture. The NER-MTJs also show the comparative lower switching field or critical current value (or density) and can be as the memory bit cells. Therefore, the manipulation of anisotropy in NER-shaped MTJs open a new way to develop more reliable and easier operational NER-MRAM devices.

8100-43, Session 12

3-dimensional spintronics for ultrahigh density data storage

R. P. Cowburn, Univ. of Cambridge (United Kingdom)

Spintronics could have a revolutionary impact on microelectronics and data storage if it provides the enabling step for transforming today’s planar 2-dimensional devices into volume-filling 3-dimensional devices, where the data storage and processing capacity are related to the minimum feature size of the fabrication process, F, by F^2 instead of F^3. Although magnetic domain wall devices have been discussed as a possible approach to 3-dimensional architectures (e.g. ‘racetrack’), no convincing demonstration has yet been realised. In this talk I describe a new approach to 3-dimensional spintronics. I show that the domain wall is not the only possible topological object in nanostructured magnetic materials; topological kink solitons can also exist in multilayered magnetic materials if anisotropy and interlayer exchange coupling are carefully chosen in the correct proportion. Such solitons can be extremely stable at room temperature, highly compact, and easily injected, detected and synchronously propagated. They are therefore an ideal candidate for the manipulation and storage of digital information. Most importantly, their natural environment is a 3-dimensionally structured one, making them ideal for 3-dimensional architectures. I illustrate one of many potential applications of topological solitons by showing an outline design for an MRAM-like device that could store data at an equivalent areal density in excess of 10 Tbits/inch^2 using only 100nm lithography and common magnetic materials.

8100-44, Session 12

Nanoring or nano-elliptic-ring shaped magnetic tunneling junctions and their applications in developing MRAM devices

X. Han, Institute of Physics (China)

A series of nano-elliptic-ring (NER)-shaped magnetic tunnel junctions (MTJs) with the major axis of around 120 nm and minor axis of around 60 nm, and ring width of around 25 nm was fabricated successfully. Magnetic field and current-driven magnetization switching were observed in such NER-MTJs with key stack layers of both spin-valve-type antiferromagnetic (AFM)/ferromagnetic (FM)/insulator (I)/ferromagnetic (FM) and sandwich-type hard-FM/1/soft-FM structures. When the electric current density exceeds a critical value of the order of 7.8x10^14 A/cm^2 (critical driven current is 0.40 mA), the magnetization of the free (soft-FM) and reference (hard-FM) layer nano-elliptic-rings can be switched back and forth between parallel and antiparallel onion states. Tunneling magneto-resistance (TMR) ratio between 10% and 40% with different thickness of thin Al-O barrier were measured at room temperature as we apply a magnetic field or a pulsed current. The experiments and micromagnetic analysis show that the spin transfer torque (STT) plays a main switching role in the magnetization reversal and the pulse-current-induced elliptic magnetic field play an assisted-switching role in such NER-MTJs. Compared with our previous studies of nano-ring-shaped (NR) MTJs and Nanoring MRAM, the NER-MTJ has a relative symmetric current driven critical behavior, which is due to the shape anisotropy of elliptic-ring architecture. The NER-MTJs also show the comparative lower switching field or critical current value (or density) and can be as the memory bit cells. Therefore, the manipulation of anisotropy in NER-shaped MTJs open a new way to develop more reliable and easier operational NER-MRAM devices.

8100-45, Session 12

Vortex-gyration-mediated information-signal transfer in one-dimensional arrays of soft magnetic nanodisks

S. Kim, D. Han, Seoul National Univ. (Korea, Republic of)

Low-energy input signals and their transport with low-energy dissipation are the key technological factors in the design of information processing devices. Coupling between different oscillators allows for the possibility of mutual energy transfer between them and the information-signal propagation. Recently, it was found that stimulated vortex gyration is a robust new mechanism for energy transfer between spatially separated dipolar-coupled magnetic disks based on the concept of coupled vortex-core oscillators. The rate of energy transfer from one disk to the other is determined by the two normal modes’ frequency splitting caused by dipolar interaction. Here, we present collective vortex gyration modes in one-dimensional arrays of dipolar coupled vortex-state nanodisks, as studied from micromagnetic simulations and analytical derivations of their characteristic band structures that vary with the relative polarization...
states. The quantized mode can be referred to as “vortex gyrator”. This mechanism provides the advantages of tunable energy transfer rate, low-power input signal, and low-energy dissipation for magnetic elements with negligible damping. Coupled vortex-state disks might be implemented in applications for information-signal processing.

8100-46, Session 12

**Different geometries for spin-transfer oscillators**

A. M. Deac, Ecole Polytechnique Fédérale de Lausanne (Switzerland)

Several geometries have recently been proposed for spin-transfer oscillators, with the purpose of optimizing the output power and frequency dependence on the applied current, as well as minimizing the external magnetic field required to stabilize the dynamics. The two structures most compatible with applications involve hybrid multilayers, including magnetic films magnetized in the plane, as well as perpendicular to the plane of the layers - acting either as polarizing layer for the current, or as excited/free layer, respectively. The feasibility of both types of devices has been experimentally demonstrated. Here, we present a quantitative numerical comparison between the two.

8100-47, Session 13

**Organic spintronics: playing with spins and molecules**

S. Sanvito, Trinity College Dublin (Ireland)

Weak spin-orbit and hyperfine interaction make the spin-lifetime in organic molecules and molecular solids reaching up to the second mark. However organic materials have also poor mobilities, so that their spin-diffusion lengths are rather short. These peculiar characteristics position organic molecules in a unique space within Spintronics and one should envision applications where the spins are manipulated close to where they are injected [1]. This is the realm of single molecule spintronics. In this contribution I will review the current state of the art of the theory of spin-transfer and manipulation in organic materials. In particular I will discuss how to manipulate and how to read the spin configuration of a magnetic molecule. I will start by discussing a range of mechanisms for manipulating the spin state of a molecule by means of a static electric field. These are based either on the Stark effect in super-exchanged coupled molecules with two magnetic centers [2] or on electric-field induced tautomeric interconversion [3]. Then I will move to discuss the consequences of such effects on the transport properties of the molecules, addressing both the temperature dependence of the electron transport and the description of the low-bias spin-flip inelastic spectra. Finally I will present results for spin-transfer in Mn12 and demonstrate that the magnetic state of the molecule can be read electrically with a single I-V read-out obtained by using non-magnetic electrodes [4].


8100-48, Session 13

**Electrical spin injection in a hybrid organic/inorganic spin-polarized light emitting diode (spin-LED)**

E. Johnston-Halperin, The Ohio State Univ. (United States)

The field of semiconductor spintronics promises the extension of spin-based electronics beyond memory and magnetic sensing into active electronic components with implications for next-generation computing and quantum information. The development of organic-based magnets with room temperature magnetic ordering and semiconducting functionality promises to further broaden this impact by providing a route to all-organic spintronic devices and hybrid organic/inorganic structures capable of exploiting both the multifunctionality of organic systems and the well established spintronic functionality of inorganic materials. Here we report the successful extraction of spin polarized current from a thin film of the organic-based room-temperature ferrimagnetic semiconductor V[TCNE]x (x~2; TCNE: tetracyanoethylene) and its subsequent injection into a GaAs/AlGaAs light-emitting diode (LED). The orientation of this spin current is determined by polarization analysis of the electroluminescence from the LED and is found to be parallel to the magnetization of the V[TCNE]x~2 layer, in agreement with theoretical predictions. Detailed analysis of the optical selection rules in the LED, coupled with control measurements of magnetic circular dichroism in the V[TCNE]x~2 layer, reveals the magnitude of the electron spin polarization to be largely insensitive to both electrical bias and temperature. This successful demonstration of spin injection in a hybrid organic/inorganic structure opens the door to a new class of active, hybrid spintronic devices with the potential for multifunctional behaviour defined by the optical, electronic and chemical sensitivity of the organic layer.

8100-49, Session 14

**Semiconductor spin-lasers**

I. Zutic, J. Lee, R. Oszwaldowski, C. D. Gothen, Univ. at Buffalo (United States)

Practical paths to spin-controlled devices are typically limited to magnetoresistive effects, successfully employed for magnetically storing and sensing information. However, spin-polarized carriers generated in semiconductors by circularly polarized light or electrical injection, can also enhance the performance of lasers, for communications and signal processing. While such spin-lasers already demonstrate a lower threshold current for the lasing operation [1-3] as compared to their conventional (spin-unpolarized) counterparts, many theoretical challenges remain. Even in the steady-state regime, several surprises have only recently been revealed. For example, we show that a very short spin relaxation time of holes can be advantageous [4], with the maximum threshold reduction larger than what was theoretically thought possible. We also analyze dynamical operation of spin-lasers and reveal that the spin modulation can improve their performance. Spin-polarized injection can lead to an enhanced bandwidth and desirable switching properties of spin-lasers [5]. Future advances in spin-lasers may depend on progress in magnetic memories and data storage related to the ultrafast magnetization dynamics and timescales for magnetization reversal. Experimental efforts to increase the temperature of electrically-injected spin-lasers have also used quantum dots as the active region [6] and we compare their operation to the lasers based on quantum wells[7]. Supported by NSF-CAREER, ONR, AFOSR-DCT, and DOE-BES.

8100-50, Session 14

**Ferromagnet/semiconductor spin-LEDs for optical communication of spin information**

R. Farshchi, M. Ramsteiner, J. Herfort, A. Tahraoui, H. T. Grahm, Paul-Drude-Institut für Festkörperelektronik (Germany)

Exciting advances are being made in the field of semiconductor spintronics toward the realization of spin-based transistors and logic architectures [1, 2]. However, for the full implementation of circuits that exploit the spin degree of freedom of electrons, it is necessary to transport the spin information from one device to another. In semiconductors, spin transport can be achieved, but they often suffer from high spin relaxation rates that significantly limit the spin diffusion lengths [3], making electrical transport of spin information highly inefficient. It is well-known that injection of spin-polarized electrons from a ferromagnetic layer into an underlying semiconductor quantum well structure in so-called spin light emitting diodes (spin-LEDs) leads to the emission of circularly polarized light [4-7]. According to the selection rules in the quantum well, injection of opposite spin polarizations (up or down spin) leads to the emission of opposite light helicities (right- or left-handed). Therefore, the spin information of electrons can be optically transported in the form of light helicity.

In this presentation, we will demonstrate that the spin information associated with electrons injected into the quantum well of a spin-LED structure can be transported optically and retrieved by a second spin-LED. Different ferromagnetic layers, namely Fe and Co2FeSi, are used to inject opposite spins into the emitter LED structure and generate light with opposite helicity. The spin information can be remotely deciphered based on the magnetic field dependence of the photocurrent in the detector spin-LED. This work opens the door for employing light as a functional component in spintronic circuits.

References:

8100-52, Session 14

**Spin-orbit interactions in optics**

K. Y. Bliokh, National Univ. of Ireland, Galway (Ireland)

We re-examine the problem of the identification of the spin and orbital parts of the angular momentum (AM) of an electromagnetic wave, which has a long history and has posed fundamental difficulties both in quantum electrodynamics and classical optics. We give an exact self-consistent solution in terms of the fundamental photon operators and unify previously disjointed results:

(i) non-canonical orbital AM and spin AM operators obtained for the second-quantized fields;
(ii) non-commutative photon position operator and Berry monopole field in momentum space;
(iii) separation of the spin and orbital parts of Poynting energy flows.

We show that the polarization-dependent non-paraxial part of the orbital AM arises from Berry-phase terms describing the spin-orbit interaction (SOI) of light. A similar effect occurs dynamically upon spin-to-orbital AM conversion in focusing and scattering of polarized light. Other manifestations of the SOI are the spin and orbital Hall effects of light (i.e., transverse shifts of the field centre of gravity) which are described by our position operator and take place even in free space. We apply the general theory to Bessel-beam solutions where the fundamental operators manifest themselves in immediately observable orbital- and spin-dependent intensity distributions.

8100-62, Session 14

**Electron and hole spin coherence in semiconductor quantum wells**

D. R. Yakovlev, Technische Univ. Dortmund (Germany)

An overview of the effects related to generation, control, and relaxation of the electron and hole spin coherence in III-V and II-VI semiconductor quantum wells will be presented. Spin dynamics has been measured by pump-probe Faraday- and Kerr rotation techniques also with the use of the Resonant Spin Amplification regime. Structures based on GaAs, InGaAs, CdTe, and ZnSe containing resident carriers of low density have been investigated. For all of them a long-living spin coherence (up to 20-40 ns for electrons and few ns for holes) has been found under conditions providing carrier localization. We discuss spin relaxation and spin dephasing mechanisms and dependence of their efficiency on temperature and magnetic field. The role of the charged exciton states for the generation of the carrier spin coherence under resonant excitation is highlighted. The generated spin coherence can be controlled optically and additive and nonadditive contributions of the control pulses are discussed.

8100-53, Poster Session

**Simulation and optimization of magnetoresistance in Schottky barrier spin MOSFETs**

A. M. Roy, Stanford Univ. (United States); D. E. Nikonov, Intel Corp. (United States); K. C. Saraswat, Stanford Univ. (United States)

Schottky barrier spin MOSFETs have emerged as a strong contender for future logic and memory promising low power consumption and reconfigurable circuits. However the development of these devices has been stymied by low values of magnetoresistance (MR) measured in experiments. Simulation studies have largely focused on diffusion driven or ballistic transport in the semiconductor and a simplistic treatment of spin injecting contacts. Here we demonstrate a novel framework to simulate spin injection and spin transport in semiconductors in the drift-diffusion regime and a tunneling based model for spin injecting contacts thereby enabling simulation and optimization of experimental devices. The main contributions of this work are

[a] the development of an efficient transfer matrix formalism for spin transport in semiconductors including electric field effects

[b] the prediction of spin saturation effects leading to high magnetoresistance at high electric fields in spite of large resistance area product of the contacts

[c] the development of a Tsu-Esaki tunneling based model for spin injecting contacts accounting for spin accumulation in the semiconductor

[d] the simulation of Schottky barrier spin MOSFETs through a self consistent solution of spin injecting contacts and spin transport in the semiconductor channel

[e] the optimization of material and structure properties (tunnel barrier materials, tunnel barrier thickness, semiconductor doping density etc.) for magnetoresistance of Schottky barrier spin MOSFETs

Our approach and implementation are general and provide a useful tool for experimental research on spin injection and detection in semiconductors.
8100-54, Poster Session

**Thickness and substrate dependence of ferromagnetism in Mn doped ZnO thin films**

G. Nammalvar, B. Ananthan, B. Lakshmi Narayanan, J. Gurusamy, T. Balasubramanian, National Institute of Technology, Tiruchirappalli (India)

We report the effect of thickness and substrate on ferromagnetism in Mn doped ZnO thin films grown by RF magnetron sputtering. The films of various thicknesses (15, 35 & 105 nm) have been grown on Si (100) and Si (111) substrates. The films have been grown from the 5 mol% Mn doped ZnO target which is prepared by conventional solid state reaction route. The grown films have been characterized by X-ray diffraction (XRD), Photoluminescence (PL), Hall measurement and Vibrating sample magnetometer to study its structural, optical, electrical and magnetic properties, respectively. The XRD result shows that all the films are preferentially oriented along (002) plane and free from the formation of secondary phases. The PL spectroscopy shows that the concentration of defects varies with the film thickness comparatively in both the substrates. This has been well acknowledged by our Hall measurements. It has been found that the observed ferromagnetism is strongly influenced by film thickness as well substrate surfaces. The presence of dopants in the films has been confirmed by Energy dispersive spectroscopy. The important features have been discussed in detail.

8100-55, Poster Session

**Defect induced Raman active modes in Mn doped ZnO thin films**

A. Aravind, K. Hasna, M. K. Jayaraj, Cochin Univ. of Science & Technology (India)

Zinc oxide is a II-VI semiconductor with a wide direct band gap of about 3.37 eV at room temperature. Among the various growth techniques of ‘Mn’ doped ZnO thin films, pulsed laser deposition (PLD) offers the advantages such as deposition at relatively high oxygen pressure, high deposition rate and growth of highly oriented crystalline films at low substrate temperature. The substitution of ‘Mn’ in ZnO host lattice affects the lattice dynamical properties. Raman scattering provides a great deal of information in the optical modes of vibrations at the center of Brillouin zone. The parameters of Raman mode such as frequency, line width and lifetime provide the basic information of lattice dynamics. The PLD grown films were analysed using x-ray diffraction (XRD), scanning electron microscopy (SEM), UV-Vis-NIR spectroscopy and Raman spectroscopy. Good optical quality of the films was confirmed from the transmittance of the film greater than 80% in the visible region. The presence of non-polar E2high and E2low Raman modes in thin films indicates that ‘Mn’ doping didn’t change the wurzite structure of ZnO. The intensity of E2high mode and the peak position shifted towards the lower frequency with increase of ‘Mn’ concentration. Apart from the normal modes of ZnO the Zn1-xMnxO ceramic targets shows two additional modes at 332 cm-1 (I2) and 524 cm-1 (I4). The modes I2 and I4 are assigned as multi-phonon scattering considering the two phonon process in the disorder lattice due to Mn doping.

8100-60, Poster Session

**Numerical study of spin diffusion effects on the spin transfer torque effect and the dynamics of domain walls**

D. Claudio-González, Univ. de Guanajuato (Mexico); A. Thiaville, J. E. Mittat, Univ. Paris-Sud 11 (France)

We report the observation of an increase of DW velocity at steady-state that can be as high as 21.5% due to spin diffusion when implementing a method that couples micromagnetics with the semiclassical transport model proposed by Zhang and Li [S. Zhang and Z. Li, Phys. Rev. Lett. 93, (2004) 127204 ]. Experimental measurements of two of the quantities that can be associated with the non adiabatic component, the so-called beta term [T. Taniguchi et al., IEEE Trans. Magn. 44, (2008) 2636 ][J. Bass and W. P. P. Jr, Journal of Physics: Condensed Matter 19, 183201 (41pp) ] used to model spin transfer torque (STT) effects in Ni80Fe20 nanowires [A. Thiaville et al., Europhys. Lett. 69, (2005) 990] makes relevant the use of spin diffusive models to analyze and study the dynamics of domain walls (DWs). The geometry considered in this study corresponds to a semi infinite Ni80Fe20 nanowire featuring a single domain wall. Unlike previous approaches, we explicitly take spin diffusion into account along with experimentally measured values to show that these parameters can truly define the non adiabatic spin torque and that spin diffusion causes an effective beta value which is responsible for velocity increase observed.

8100-63, Poster Session

**Revealing the long spin lifetimes of holes in self-assembled (In,Ga)As quantum dots via spin noise spectroscopy**

Y. Li, S. A. Crooker, D. L. Smith, N. A. Sinitsyn, Los Alamos National Lab. (United States); D. Reuter, A. D. Wieck, Ruhr-Univ. Bochum (Germany); D. R. Yakovlev, M. Bayer, Technische Univ. Dortmund (Germany)

“Spin noise spectroscopy” is a recently-developed technique that uses optical Faraday rotation to passively measure the intrinsic spin fluctuations of electrons and holes in semiconductor systems. As guaranteed by Fluctuation-Dissipation Theorem, the frequency spectra of the spin noise alone reveals dynamic spin properties such as spin lifetimes and Lande g-factors. Here we use spin noise spectroscopy to measure the spin relaxation of holes that are confined in self-assembled (In,Ga)As/GaAs quantum dots (QDs) grown by molecular beam epitaxy. Owing to their p-type wavefunctions, holes experience much less hyperfine interaction with nuclei as compared with confined electrons, leading (in principle) to long spin decoherence times which are favorable for potential qubit applications. In zero applied magnetic field, we observe a narrow spin noise peak centered at 0 Hz, indicating long hole spin relaxation times of a few hundred nanoseconds. In transverse magnetic fields, we observe that a portion of the 0 Hz peak still remains (in addition to the expected noise peak at the hole Larmor precession frequency), which we attribute to the presence of an effective hyperfine field arising from dipole-dipole interactions between the hole spin and the nuclear spins. We suppress these hyperfine fields using applied longitudinal magnetic fields, and observe hole spin lifetimes further enhanced by over one order of magnitude at low temperatures. Systematic studies as a function of temperature and applied field allow us to identify different regimes of spin relaxation.
Recent progresses in carbene functionalization of SWCNTs and graphene
Q. Zhang, C. Liu, Nanyang Technological Univ. (Singapore)

In this talk, we will focus on our recent progresses in carbene functionalization of single walled carbon nanotubes (SWCNTs). The influences of carbene-based covalent functionalization on the electrical properties of an isolated m-SWCNT, a semiconducting (s)-SWCNT, and a mixture network of both m- and s-SWCNTs are studied. We find that the functionalization does not reduce the conductance of m-SWCNTs significantly. It does deactivate the semiconducting feature of s-SWCNTs. Interestingly, the influences of the functionalization are reversible upon thermal annealing under ambient conditions.1


structure reactivity of single-walled carbon nanotubes for various diazonium reagents and its application for separation by electronic types
W. Kim, Kyungwon Univ. (Korea, Republic of)

Diazonium salts are reported to selectively react with metallic Single-Walled Carbon Nanotube (SWNT) over semiconducting SWNT and we showed that covalently attached chemical groups can alter the densities of individual SWNT in a predictable and highly controllable manner, enabling SWNT separation by electronic types. In this study, we investigated the structure reactivity of SWNT with diazonium salts having different electron donating or withdrawing functional groups, analyzed their influence on the reaction selectivity using UV-Vis-nIR absorption spectroscopy, and developed structure-reactivity relations to understand and correlate the reactivity of a number of electron acceptors. Metallic SWNT react preferentially with diazonium salts over semiconducting SWNT in all diazonium studied, however the reactivity as well as the selectivity for metallic SWNT of this reaction strongly depends on the functional groups attached to the diazonium salts. Diazonium salts having electron withdrawing groups (Cl) have higher reactivity metallic for SWNT than those having electron donating groups (OH or COOH), thus lower selectivity for metallic SWNT, which would lower the separation efficiency in the following separation process. We also show that covalently attached functional groups can alter the densities of individual SWNT in a predictable and highly controllable manner, and the density increase of SWNT due to the attached functional groups varies. These results together with the structure reactivity of SWNT with different diazonium reagent are utilized for SWNT separation by electronic types and diameters.

Pillared graphene nanostructure: a new 3D carbon hybrid architectures
M. Ghazinejad, S. Guo, R. K. Paul, M. Ozkan, C. S. Ozkan, Univ. of California, Riverside (United States)

Using chemical vapor deposition technique a novel 3D carbon nano-architecture called a pillared graphene nanostructure (PGN) is synthesized in situ. The fabricated novel carbon nanostructure consists of CNT pillars of variable length grown vertically from large-area graphene planes. A one-step CVD process for large-area PGN fabrication through combination of surface catalysis and in situ vapor-liquid-solid mechanisms is described. The dependence of the morphology of the large-area PGN on the synthesis process conditions was investigated by optical microscopy, SEM, TEM, HRTEM, and Raman Spectroscopy techniques. The highly crystalline interface between the CNT pillar and graphene floor confirmed the seamless contact between the two carbon allotropes. Moreover, to tune the PGN architecture, arrays of catalyst particles with controlled size and separation distance are fabricated using block copolymer films as template. This strategy yields tunable diameter and separation distance of pillar carbon nanotubes, and provides control over the amount of final carbon structure surface area. The successful transfer of the large area PGN onto arbitrary substrates, while keeping the 3D architecture intact, was also accomplished. The new synthesis methodology offers a promising pathway for fabricating novel 3D nanostructures with huge potential in hydrogen storage and supercapacitors, and provides a powerful means to fulfill Department of Energy’s targets for energy storage.

Hierarchical large-area graphene materials and functionalization
C. S. Ozkan, Univ. of California, Riverside (United States)

I will first describe the patterning of biomolecules on graphene layers to modulate their electronic properties. Single stranded Deoxyribonucleic Acids (ssDNA) are found to act as negative potential gating agents
that increase the hole density in single layer graphene. Current-voltage measurement of the hybrid ssDNA/graphene system indicates a shift in the Dirac point and intrinsic conductance after ssDNA was patterned. The effect of ssDNA was to increase the hole density in the graphene layer. Next I will describe block co-polymer patterning of large-area graphene layers grown by chemical vapor deposition which enables spatially controlled fluorine plasma doping to provide a tuning mechanism for the Dirac point. Poly(styrene-b-4-vinylpyridine) with cylindrical-morphology polycrystalline block co-polymer was employed in the patterning process. X-ray photoelectron spectroscopy (XPS) characterization revealed the existence of fluorine after doping; high doping levels could be achieved just in 10s. The BCP-Graphene composite FET has been used for the detection of chemical agents including NaF. Finally, I will describe a new class of graphene material in the form of a three dimensional architecture called pillared graphene nanostructure (PGN), which is a combination of the two allotropes of carbon including graphene floors and carbon nanotube pillars. We developed a one step chemical vapor deposition process for large-area PGN fabrication via a combination of surface-catalysis and in-situ vapor-liquid-solid mechanism. We also developed a process by which PGN layers can be transferred onto arbitrary substrates. Single and multilayer stacked PGN are envisioned for future ultra-large and tunable surface area applications in hydrogen storage and super-capacitors.

8101-06, Session 2
Unique thermal properties of graphene: prospects of thermal management applications

A. A. Balandin, Univ. of California, Riverside (United States)

As the electronic industry moves towards few-nanometer-scale CMOS and 3D IC designs thermal management becomes crucially important for achieving high performance and reliability of advanced electronic chips [1]. One approach for mitigating the self-heating problems is finding materials with very high thermal conductivity, which can be integrated with Si ICs or used as fillers in the next generation of the thermal interface materials (TIMs). In 2008, we discovered that graphene reveals extremely high intrinsic thermal conductivity, which can exceed that of bulk graphite [2-3]. We explained this fact by the fundamental difference in the low-energy phonon transport in 2D graphene and 3D graphite [4-6]. Thermal conductivity of graphene layers depends strongly on their geometrical size, coupling to the adjacent substrate or capping layers, edges roughness and defect concentration. I will overview the experimental and theoretical results for the thermal conductivity evolution of the few-layer graphene (FLG) considering two limiting cases of the phonon transport limited by the intrinsic and extrinsic effects. The use of graphene as interconnects and heat spreaders in advanced 2D and 3D computer chips will also be discussed. The last section of the talk will have a description of the data for graphene TIM materials.

The work was supported by SRC-DARPA Functional Engineered Nano Architectonics (FENA) center and ONR project on Graphene Quilts for Thermal Management.


8101-07, Session 2
Investigating the nanoscale surface chemistry of graphene

K. F. Kelly, Rice Univ. (United States)

In this talk, I will review our recent success in applying probe microscopy to understanding the chemistry of graphene and graphitic nanoparticles. We have used STM to compare the morphology and defect density in graphene grown on copper foils by liquid-phase epitaxy to that produced by other methods such as mechanical exfoliation and pyrolysis of silicon carbide. In addition, we have applied a similar analysis to the characterization of chemically suspended graphitic nanoparticles. Lastly we obtained an atomic-scale view of the fluorination and defluorination. Coupled with these studies, we performed chemical characterization of these systems using Raman microscopy.

8101-08, Session 2
Scanning Raman spectroscopy of nanostructured graphene: Doping due to presence of edges

S. Heydrich, M. Hirmer, T. Korn, J. Eroms, D. K. Weiss, C. Schüller, Univ. Regensburg (Germany)

We have investigated nanostructured graphene layers, which were prepared on exfoliated graphene single layers via electron-beam lithography and oxygen-based reactive ion etching, by means of scanning Raman spectroscopy. The peak positions, peak widths and intensities of the characteristic phonon modes of the carbon lattice have been studied systematically in a series of samples. In nanopatterned samples, where periodic arrays of holes (a so called antidot lattice) with typical hole diameters on the order of a few tens of nanometers and periods of a few hundreds of nanometers were prepared, we found a systematic stiffening of the G band mode, accompanied with a line narrowing, while the 2D mode energies are found to be linearly correlated with the G mode energies. We interpret this as evidence for p-type doping of the graphene antidot lattices [S. Heydrich et al., Appl. Phys. Lett. 97, 043113 (2010)]. Moreover, we have detected and analyzed a two-phonon mode at about 2450 wavenumbers in single layer plain graphene. Wavelength-dependent measurements show that it can be interpreted as a LO-2LA mode from the K point of the Brillouin zone. A detailed analysis of the electron-phonon coupling strength of this mode shows that it is of the same order of magnitude as that of the G mode. This would have significant implications for the upper limit of carrier mobilities in intrinsic graphene layers.

8101-10, Session 3
Highly selective CNTFET based sensors using metal diversification methods

P. Bondavalli, L. Gorintin, G. Feugnet, Thales Research & Technology (France)

This contribution deals with Carbon Nanotubes Field Effect transistors (CNTFETs) based gas sensors fabricated using a completely new dynamic air-brush technique (patented) for SWCNTs deposition. The extreme novelty is that our technique is compatible with large surfaces, flexible substrates and allows to fabricate high performances transistors exploiting the percolation effect of the SWCNTs networks achieved with extremely reproducible characteristics. This technique is extremely interesting considering that it is suitable for industrial transfer. More precisely, we have developed a machine which allows us the dynamic deposition on heated substrates of SWCNT solutions, improving dramatically the uniformity of the SWCNTs mats. The CNTFETs have been developed for gas sensing applications. Indeed we have fabricated arrays of CNTFETs achieved using different metal electrodes (patented approach) to exploit the change of metal/SWCNTs junction characteristics as a function of the gas detected in order to identify a sort of electronic fingerprinting. This phenomenon is related to the change of the metal work function and so of the Schottky barrier and seems to be extremely selective. Results concerning exposure to NH3, NO2, DMM, that will be extensively shown at the conference, at different concentration (from 100ppb to 10ppm) demonstrate that each gas interacts in a specific way with each CNTFET. For example, for the same concentration, CNTFET fabricated using Pt are more sensitive than those fabricated using gold electrodes for DMM. Inversely, CNTFET fabricated
using gold electrodes are more sensitive than those fabricated using Pt electrodes for NH3.

8101-11, Session 3

Printed CNT transistors with high on-off ratio and linearity

G. Gu, R. Liu, Y. Ling, X. Lu, Univ. of Massachusetts Lowell (United States)

We report an all-printed flexible carbon nanotube (CNT) thin-film transistor (TFT). All the CNT TFT components, including the source and drain electrodes, the TFT transport channel, and the gate electrode, are printed on a flexible substrate at room temperature. A high ON/OFF ratio of over 1000 was achieved. The all printed CNT-TFT also exhibits bias-independent transconductance over a certain gate bias range. This all-printed process avoids the conventional procedures in lithography, vacuum, and metallization, and offers a promising technology for low-cost, high-throughput fabrication of large-area flexible electronics on a variety of substrates, including glass, Si, indium tin oxide and plastics.

8101-12, Session 3

Light-triggered conducting properties of a random Carbon Nanotubes network in a photochromic polymer matrix

R. Castagna, Istituto Italiano di Tecnologia (Italy) and Politecnico di Milano (Italy); C. Sciascia, Istituto Italiano di Tecnologia (Italy); A. R. S. Kandada, Politecnico di Milano (Italy); M. Meneghetti, Univ. degli Studi di Padova (Italy); G. Lanzani, Istituto Italiano di Tecnologia (Italy); C. Bertarelli, Politecnico di Milano (Italy) and Istituto Italiano di Tecnologia (Italy)

It is well known that photochromic materials reversibly change their colours due to a photochemical reaction that takes place when the material is irradiated with photons of suitable energy. This peculiar feature has been exploited to develop smart sunglasses, filters and inks. With a proper molecular design it is possible to enable modulation not only of colour but also of other properties such as refractive index, dipole moment, nonlinearity or conductivity by a photoswitching of the molecular structure. The approach herein followed consists in modifying, upon irradiation, the properties of another component the photochromic molecule is coupled to. In particular, the switching features of photochromic systems are matched with the intriguing peculiar properties of carbon nanotubes (CNTs). A photochromic polyester has been properly synthesised to be used as switching polymer matrix coupled with a network of CNTs. Irradiation of the polymer/CNTs blend results into a light-triggered conductance switching. Supported by electrical and spectroscopic evidences, we argue that the reversible electrocyclization, experienced by the polymer under UV-vis illumination, affects the inter-tube charge mobility resulting in a dramatic overall resistance variation. Differently from previous literature, based on single molecule approach, we obtain blended films by simple solution techniques, with sheet-resistance modulation larger than 50%, FET characteristic, good thermal stability and remarkable fatigue resistance at room conditions.

1. X. Guo et al. Science 311, 356 (2006);

8101-13, Session 3

CdSe/ZnS coated single layer graphene photovoltaic devices

S. Guo, J. Reiber Kyle, W. Wang, M. Ozkan, C. S. Ozkan, Univ. of California, Riverside (United States)

Large-area flexible and transparent optoelectronic devices were fabricated through non-covalent interaction between CdSe/ZnS quantum dots and single layer graphene. Single layer graphene was synthesized via CVD method. Pyridine was utilized for capping the quantum dots and the pi-pi interaction between pyridine and graphene enable QD immobilized on the surface of graphene. The photo induced charge transfer was confirmed by photoconductivity measurements. Quantum dots decorated graphene device display good photo-switching property which could be utilized for long wavelength sensitive sensor. Further construction of layered solar cell was accomplished with graphene and QDs layer by layer assembly technique.

8101-14, Session 3

Optical and structural modifications and characterization of ion- irradiated glassy polymer carbon

M. A. Abunaemeh, Alabama A&M Univ. (United States) and Ctr. for Irradiation of Materials (United States); M. Seif, Alabama A&M Univ. (United States); A. Elsamadicy, The Univ. of Alabama in Huntsville (United States); D. Ila, Alabama A&M Univ. (United States) and Ctr. for Irradiation of Materials (United States)

The TRISO fuel that is planned to be used in the GenerationIV nuclear reactor consists of a fuel kernel of UOx coated in several layers of materials with different functions. We are looking at the ion irradiation induced optical structural modifications of the glassy polymeric carbon (GPC) microstructure and their effect on the mechanical and physical properties. GPC is considered as a potential replacement for the pyrolytic carbon coatings, with a function of diffusion barrier for the fission products. We irradiated GPC samples with 1 MeV protons, 5 MeV Ag and Au ions. We chose protons to simulate the effects of neutrons. During the nuclear fission of 235U, the fission fragment mass distribution has two maxima around 98 and 137 that would best fit Rb and Cs However, both ions are hard to produce from our SNICS source therefore we chose Ag (107 amu) and Au (197 amu) as best replacements.

8101-15, Session 4

Radio-frequency transmission of graphene layer

H. S. Yoon, J. Y. Oh, W. Kim, J. Y. Kang, J. Lim, J. Kim, S. C. Jun, Yonsei Univ. (Korea, Republic of)

Graphene has shown high potential to be used as interconnects in the field of high frequency electrical devices. In this study, we demonstrate the effect of graphene geometry on the microwave properties using the measurements of S-parameter in range of 500 MHz - 40 GHz. Graphene used in this study was fabricated by mechanical cleavage of highly oriented pyrolytic graphite and CVD method. High frequency properties of graphene, such as impedance, insertion loss, R, L and C were measured at room temperature condition. We confirm that impedance and resistance decrease with increasing the number of graphene layer and w/l ratio. This result shows proper geometry of graphene to be used as high frequency interconnects.
Carbon nanotube terahertz spectroscopy: study of absorption and dispersion properties of SWNT and MWNT

H. Lamela, E. Radrasnia, Univ. Carlos Il de Madrid (Spain); J. Lampin, Institut d’Electronique, de Microélectronique et de Nanotechnologies (France); M. B. Kuppam, F. Garet, J. Coutaz, Univ. de Savoie (France)

Carbon nanotubes (CNT) have been widely investigated because of their unique properties in view of applications in electronics and mechanics (Dresselhaus, et al., Springer, 2000). Their structures and properties have been studied by several means such as photonic emission, scanning, microscopy and tuning fields. It appears that several physical parameters of CNT’s are within the terahertz (THz) frequency range (Ugawa, et al., Phys. Rev. B 60, 1999, Hilt, et al., Phys. Rev. B 61, 2000) like the plasma frequency and the phonon frequency. In addition, GHz CNT transistors have been demonstrated and THz CNT transistors are predicted (Burke, Nanosensing: Materials and Devices, SPIE, 2004). Therefore, THz spectroscopy of CNT samples is nowadays subject to intense researches. THz time-domain spectroscopy (TDS) is certainly the best tool to perform these studies, as it leads to the simultaneous determination of both the refractive index and absorption coefficients of the material over a very large frequency band, extending from typically 0.1 THz up to several THz (Mittleman, Springer Series in Optical Sciences, 2003. D死uellet et al., Topics in Quant, Electron., 739, 1996). First reports on THz spectra of CNT obtained by THz-TDS have been published in the late 90’s (Ugawa, et al., Phys. Rev. B 60, 1999), and more recent papers have permit to define precise physical models to describe the THz properties of CNT films (T-I. Jeon, et al., J. Appl. Phys. 98, 2005, C. Kang et al., Phys. Rev. B 75, 2007, Kim, et al., J. Korean Phys. Soc. 50, 2007, E. P. J. Parrott, et al., Adv. Mat. 21, 2009).

In this paper, we report on the optical and electrical properties of single-walled CNT films (SWNT), pure or F-doped, investigated by THz-TDS. The SWNT electromagnetic properties are modeled with a Drude model to describe the free carrier contribution associated to a Maxwell-Garnett model that accounts for the composite tubular structure of the films. The calculated spectra of the absorption coefficient and index of refraction for pure SWNT and F-doped SWNT are demonstrated. At the conference, we will present corresponding experimental results as well as the effect of various ranges of filling factor and geometrical factor in these two SWNT samples and multi-walled carbon nanotubes (MWNT). This work is supported by MITEPHO project (www.uc3m.es/portal/page/ portal/grupos_investigacion/optoelectronicseuropean_projects/mitephoph/ which is coordinated by GOL research group in Carlos Il de Madrid University with foundation grant agreement number 238393 (EU-FP7) in order to develop compact tunable dual-mode diode lasers and terahertz spectroscopy in sensing and biomedical applications.

Low-frequency 1/f noise in graphene field-effect transistors

A. A. Balandin, Univ. of California, Riverside (United States)

Unique properties of graphene, such as its extremely high electron mobility, saturation velocity and breakdown current density make this material promising for future high-frequency and mixed-signal electronics. We have recently discovered that graphene has superior intrinsic thermal conductivity [1], which improves its prospects for practical applications in nanometer scale devices. Most of the proposed applications require low levels of the electronic 1/f noise, which dominates the noise spectrum at low frequencies. The up-conversion of noise, unavoidable in electronic systems, results in increased phase noise of the systems. Thus, it is important to investigate the noise level in graphene field-effect transistors and identify its sources. In this talk, I will overview the results of our experimental study of graphene devices [2]. A special attention will be given to the noise sources in these devices and the effects of aging and environmental exposure on their characteristics. I will present an experimental proof that the measured noise originates in the graphene channel itself rather than in contacts. The obtained results can be used for graphene device optimization for electronic and communication applications.

Electronic cooling in a single flake of bi-layer graphene studied by ultrafast spectroscopy

E. Da Como, T. Limmer, J. Feldmann, Ludwig-Maximilians-Univ. München (Germany)

Graphene and few-layer graphene have demonstrated unique electrical properties such as ballistic transport and gigahertz switching frequencies in field effect transistors. Recently, the applications of graphene have entered the optoelectronics arena, with devices such as ultrafast photodetectors. Here, not only the transport properties are of interest, but also the optical response in terms of light absorption, electron-hole generation and carrier relaxation. In order to understand the operation of such devices and expand the application of graphene in optoelectronics, it becomes crucial to understand photocarrier relaxation with very high time resolutions.

In this communication, we report the first experiments probing the carrier relaxation on a single flake of bi-layer graphene with femtosecond resolution. Bi-layer graphene flakes have been obtained by mechanical exfoliation of natural graphite and do not show signatures of extrinsic carrier doping. We have probed carrier relaxation by ultrafast pump-probe spectroscopy in the femtosecond time scale, with a unique range of probe energies spanning between 1.2 to 0.25 eV. This allows us for obtaining snapshots of the carrier population distribution after the initial photoexcitation pulse at 1.55 eV. By modeling the carrier distributions as two separated Fermi-Dirac distributions for electrons and holes we extract carrier temperatures and cooling rates. Our analysis shows that carriers loose half of their energy within the first 500 femtoseconds by carrier-phonon scattering. The results are relevant for graphene optoelectronic devices and give valuable information for the understanding and modeling of hot carrier transport in ultrafast graphene devices.

8101-22, Session 5
Digital data transmission performance of CVD grown few-layer graphene ribbons
A. B. Guvenc, J. Lin, M. V. Penchev, C. S. Ozkan, M. Ozkan, Univ. of California, Riverside (United States)

We investigated the electrical characteristics and digital data transmission performance of few-layer graphene ribbons grown by chemical vapor deposition. Data transmission measurements were accomplished on graphene field effect transistors (FETs) fabricated on Si/SiO2 substrates. The mobility values were calculated from the transconductance, g = dIds/dVgs, in which Ids and Vgs values are acquired from back gate measurements. Data stream is randomly generated and uploaded to a waveform generator which generates the stream and transmits it repeatedly with the desired frequency. The signal was applied on the sources of the FETs and collected from the drains of the same devices. During the data transmission measurements no back gate voltage was applied. Collected data was first filtered with a low pass filter, to clear the noise and the high frequency parasitic effects then the output of the filter was used to create the eye diagrams of the devices and by using these eye diagrams, the bit error rates, attenuation values, quality factor values and maximum data transmission values are calculated. Graphene ribbons having a mobility of 2,180 cm2V-1s-1 can sustain data rates up to 90 megabits per second at 100 nm length and behave as RLC lines, thus the bandwidth is inversely proportional to resistance caused by defects in the graphene layers and the inductance and capacitance of the ribbons. Improving the graphene mobility to highest measured values (~200,000 cm2V-1s-1) and using structures with multiple coplanar transmission lines in parallel could carry the bandwidth beyond the terabits per second level.

8101-23, Session 5
Ultra thin films of carbon nanotubes for sustainability monitoring in civil engineering: New insight on promising nanosensors
B. Lebental, E. Norman, Ecole Polytechnique (France); A. Ghis, Commissariat à l’Energie Atomique (France); C. Cojocaru, Ecole Polytechnique (France)

In recent years, requirements in terms of service-life of civil engineering structures have become more and more stringent, so that the focus of designers and owners is now set on structural durability. Foreseeing structural failures and repairing damaged structures at an early stage has become a major stake. This is the incentive for the world-wide development of various in-situ monitoring techniques for structural materials.

However, to this day, no existing sensor features the resolution required to investigate in-situ structural materials at the micro- and nanoscale. This is a major lack, as micro and nanoscale features play a significant role in the durability of cementitious materials. From this perspective, IFSTTAR, CEA-LETI and LPICM have set themselves the long-term goal to devise together innovative nanoscale structural health monitoring solutions using single-walled carbon nanotubes based nanosensors.

We will present two promising devices, ultrasonic nanotransducers for microporosity assessment and field-effect transistors for humidity monitoring, which both rely on ultra-thin SWNT films for sensing, either by electromechanical or adsorption effect. Processing of ultra-thin films by techniques such as dielectrophoresis, spray or CVD growth, as well as thickness assessment by AFM or MEB will be the focus of our contribution. We will emphasize the relationship between high quality of the films and final sensing features of the devices.

8101-24, Session 5
A review of carbon based supercapacitor
P. Bondavalli, Thales Research & Technology (France)

The contribution deals with the state of the art and the critical analysis of studies concerning the fabrication of electric double layer capacitor (EDLC) also called super or ultracapacitors fabricated using carbon nanotubes (CNTs). From the first work in 1997, it was clear that supercapacitors achieved using carbon nanotube as electrodes showed very interesting results and that they could outperform traditional technologies based on activated carbon. Different methods to fabricated CNT based EDLC have been proposed in order to improve the performances (meyn energy densities and power), for examples CNT mats achieved by filtration, direct growth on metal collector or deposition using air-brush technique. The advantages and drawbacks of all these techniques will be analyzed. Recently, after a pause of some years, there has been a peak in the scientific community interest surely connected with the new challenges related to the research of new systems for the smart management of energy and to very hot topics such as the electric vehicles. This has been translated in a lot of new studies in the domain. We will focus our attention on the more interesting ones. We can also point out, for example, an increasing interest for supercapacitors achieved on flexible substrates for new kind of applications. Finally, we will try to find the coherence for the different research works and their related potential to strike the market : specific capacitance, energy and power densities, cost, versatility.

8101-33, Session 5
Graphene-based broadband optical modulator
M. Liu, X. Yin, Univ. of California, Berkeley (United States); F. Wang, X. Zhang, Univ. of California, Berkeley (United States) and Lawrence Berkeley National Lab. (United States)

Data communications have been growing at a speed even faster than Moore’s Law, with a 44-fold increase expected within the next 10 years. Data Transfer on such scale would have to recruit optical communication technology and inspire new designs of light sources, modulators, and photodetectors. An ideal optical modulator will require high modulation speed, small device footprint and large operating bandwidth. Silicon modulators based on free carrier plasma dispersion effect and compound semiconductors utilizing direct bandgap transition have seen rapid improvement over the past decade. One of the key limitations for using silicon as modulator material is its weak refractive index change, which limits the footprint of silicon Mach-Zehnder interferometer modulators to millimeters. Other approaches such as silicon microring modulators reduce the operation wavelength range to around 100 pm and are highly sensitive to typical fabrication tolerances and temperature fluctuations. Growing large, high quality wafers of compound semiconductors, and integrating them on silicon or other substrates is expensive, which also restricts their commercialization. In this work, we demonstrate that graphene can be used as the active media for electroabsorption modulators. By tuning the Fermi energy level of the graphene layer, we induced changes in the absorption coefficient of graphene at communication wavelength and achieve a modulation depth above 3 dB. This integrated device also has the potential of working at high speed.
Fabrication of transparent and conductive chemically converted graphene films by dip-coating technique

F. Ait medjane, R. Wendelbo, Abalonyx AS (Norway); S. Karazhanov, Institutt for Energiteknikk (Norway)

Transparent conductive films (TCFs) are crucial components in modern electronics. They are generally produced from indium thin oxide (ITO) and due to globally diminishing stocks of indium, are becoming more expensive. In addition, for many future applications, electrodes will need to be flexible, a development that can not be accomplished by ITO. Graphene is widely considered to be an ideal material for the use as TCFs because of its unique two-dimensional structure, remarkable electrical conductivity, and optical transparency to visible and near-infrared light as well as excellent mechanical properties. Graphene based TCFs are cheaper, far more flexible than traditional ITO films. Currently, mechanical cleavage of graphite is able to make high quality graphene reaching a millimeter size but with a very low yield. Alternatively, chemical exfoliation starting from the oxidation of graphite is an efficient process to produce graphene on a large scale and at low cost, combined with post-reduction processes.

Here we have developed, a simple and low cost approach for preparing TCFs using CCG dispersions and polycations. Graphene films were deposited onto glass and silicon substrates at ambient temperature by the dip-coating technique. An automated high-throughput set-up was developed for the purpose, by using a commercial robotic arm to dip 24 substrates in parallel. The set up include in house made instrumentation for on-line measurement of conductivity and transmittance. The properties of the obtained films were characterized by SEM, TEM, XPS and Raman spectroscopy. The resulting CCG films show promising electrical and optical properties.

The enhanced mechanism of the CNTs/TiO2 core-shell nanotubes

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After pre-patterned electrodes, we connected the nanotubes by e-beam lithography followed by Ti/Au (70 nm/30 nm) E-gun system. We connected the nanotubes which one side was carbon nanotubes (CNTs) and the other side was TiO2. The IV characteristic is asymmetric due to asymmetric connection. The thickness of TiO2 film is about 4 nm from transmission electron microscopy. Compared to the TiO2 nanotubes from others’ research, the gain was at the same order of magnitude with ours under illuminated but our response time and reset time were faster than the TiO2 nanotubes. Our multi-walled carbon nanotubes (MWCNT) are metallic and make no response for the light. Upon illumination, the e-h pairs are generated and the electrons reach to the conduction band of TiO2 and transfer to the CNTs. And the unpaired holes were left behind in the TiO2. Since MWCNT behave as conducting wire, there is no possibility of accumulation of the electrons on CNT side. That will prevent the electrodes and holes from recombination so they can increase the density of the carriers. This enhances the electron-hole separation and helps in the faster growth of the photocurrent. When illumination is turned off, the photo-generated e-h pairs will stop. And the excess electrons in the CNT side transfer to the TiO2 side for recombination with the holes which is a very fast process.

Hydrogen storage in single-walled carbon nanotubes purified by microwave digestion method

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Hydrogen is considered to be a clean energy carrier. However, the most serious barrier to potential uses is the development of feasible hydrogen storage systems. The discovery of high hydrogen storage capacity of carbon nanotubes (CNTs) makes up alternatives for hydrogen storage systems. To reach the full potential of the CNTs, many problems still need to be solved, including the development of an easy and effective purification procedure, since synthesized CNTs contain impurities, such as amorphous carbon, carbon nanoparticles and metal particles. These impurities impede utilization of the unique properties of CNTs. Also, as-synthesized CNTs usually have both ends closed, which may hinder their adsorption and capillarity properties. Therefore, a purification procedure should involve both opening the tubes ends and the elimination of the impurities to increase hydrogen storage capacity of CNTs.

In this study, the hydrogen adsorption on single-walled carbon nanotubes (SWCNTs) was investigated. SWCNTs were firstly synthesized by chemical vapor deposition (CVD) of acetylene (C2H2) on a magnesium oxide (MgO) powder impregnated with an iron nitrate (Fe(NO3)3·9H2O) solution. The synthesis parameters were selected as: the synthesis temperature of 800°C, the iron content in the precursor of 5% and the synthesis time of 30 min. The microwave digestion method was applied for the purification of the synthesized SWCNT materials. Nitric acid (HNO3) was used in the removal of the metal catalysts. Purification experiments were carried out at three different temperatures (120, 150 and 200 °C), three different acid concentrations (0.5, 1 and 1.5 M) and for three different time intervals (15, 30 and 60 min). The hydrogen storage capacities of the purified materials were measured using volumetric method at the liquid nitrogen temperature and gas pressure up to 100 bar and the effects of the purification conditions such as temperature, time and acid concentration on hydrogen adsorption were investigated.

Computational study of negative differential resistance in graphene bilayer nanostructures

K. M. M. Habib, S. Ahsan, R. K. Lake, Univ. of California,
Leaky-mode resonance photonics: an applications platform

R. Magnusson, The Univ. of Texas at Arlington (United States)

Incident light induces resonant leaky modes on dielectric and semiconductor layers patterned in one or two dimensions. Properly designed resonance structures may support a collection of complex, interacting waveguide modes providing interesting, novel spectral expressions. Here we present applications that include bandpass and bandstop filters, laser mirrors, polarizers, wave plates, ultrasensitive biosensors, absorption-enhanced solar cells, security devices, tunable filters, nanoelectromechanical display pixels, and dispersion/slow-light elements. We summarize the physical basis for this technology and provide numerous designed and fabricated device examples. Key issues in design and fabrication will be discussed. In particular, we invented and implemented highly accurate, label-free, guided-mode resonance (GMR) biosensors that operate in narrow-line reflection or transmission. The sensor is based on the high parametric sensitivity inherent in the fundamental resonance effect. As this sensor technology has high-value applications in medical diagnostics, drug discovery and development, industrial process control, and environmental monitoring, it is being commercialized. Moreover, the arsenal of optical components can be extended by use of the resonance concept. We have designed and fabricated a variety of bandstop and bandpass filters at differing spectral bands. Similarly, wideband polarizers fashioned in a single resonant layer have been fabricated and characterized showing high-quality response. We have designed ultra-wideband reflectors as well as new types of wave plates using a multilevel architecture. In general, these devices exhibit a minimal layer count relative to their classical multilayer thin-film counterparts. Another interesting pursuit relates to wideband tuning of these filters that is achievable by perturbing the structural symmetry using nano/microelectromechanical (MEMS) methods. Mixed metallic/dielectric resonance elements exhibit simultaneous plasmonic and leaky-mode resonance effects. Thus, leaky-mode resonance photonics technology is an enabling applications platform with interesting prospects.

Ultraslow photon diffusion in aperiodic nanostructure arrays

T. Rich, N. Lawrence, Boston Univ. (United States); J. Zhang, S. Cabrini, Lawrence Berkeley National Lab. (United States); L. Dal Negro, Boston Univ. (United States)

Stochastic models of the transport of photons through disordered media suggest that it is possible to create photonic materials that support ultra-slow diffusion of light, known as Sinai sub-diffusion. In disordered lattices, these stochastic processes are non-Markovian due to the effect of long-range correlations, and photon diffusion is significantly slowed down, according to a mean squared displacement that varies as $t^{\beta}$, where $\beta<1$. In this work, based on multiple scattering Monte Carlo calculations and electrodynamics computations (Finite Difference Time Domain), we present our design and demonstration of complex photonic materials with ultraslow photonic sub-diffusion over broad frequency spectra. Nanofabrication and optical characterization results of anomalous photon diffusion in aperiodic waveguide structures and two-dimensional nano-pillar arrays will also be presented. Characterizing the relationship between disorder and anomalous transport will allow for the engineering of novel materials whose transport properties can be actively tuned. Such precise control of the photon transport characteristics has not yet been demonstrated and will offer profound advancements in the ability to develop novel optical devices such as optical buffers for solar and on-chip energy harvesting applications.

Experimental confirmation of fluorescence enhancement using one-dimensional GaP/ SiO2 photonic band gap structure

J. Gao, A. M. Sarangan, Q. Zhan, Univ. of Dayton (United States)

In this paper we report the experimental confirmation of the fluorescence enhancement effect using one-dimensional photonic band gap (1D PBG) structure. The 1D PBG structure consists of periodic multi layer thin films with gallium phosphide (GaP) and silicon dioxide (SiO2) as the alternating high and low index materials. Strongly enhanced evanescent field can be generated at the last interface due to the combination of total internal reflection and photonic crystal resonance for the excitation wavelength. Meanwhile, the 1D PBG structure is designed as an omni-directional reflector for the red-shifted fluorescent signal emitted from the surface bounded molecules. Such an omni-directional reflection helps to improve the collection efficiency of the objective lens and further increase the detected fluorescent signal. Compared with the commonly used bare glass substrate, an average enhancement factor of 62 times has been confirmed experimentally with quantum dots as fluorescent markers. This fluorescence enhancer may find broad applications in single molecular optical sensing and imaging.

Aperiodic arrays of Er3+-SiNx pillars for light emission enhancement at 1.55um

N. Lawrence, L. Dal Negro, Boston Univ. (United States); S. Cabrini, J. Zhang, Lawrence Berkeley National Lab. (United States)

The engineering of optical devices in silicon (Si) has the potential to revolutionize the optoelectronics industry by providing a solution to interconnect bottleneck problems and enabling low-cost, high-performance applications ranging from inter and intra-chip interconnects and communication to integrated optical bio-sensing. The development of fully Si-based lasers can result in the mass production of high-performance optoelectronic components and systems through integration with CMOS technology, however, the progress limited by the lack of efficient light emission from Si. To overcome this, variation in the local density of photon states (LDOS) can be created by altering the surrounding environment to enhance material light emission. Unlike periodic photonic structures, Deterministic Aperiodic Structures (DAS) possess unique light localization and anomalous transport properties related to far richer spectral features, however, unlike random media, DAS are defined by the iteration of simple mathematical rules yielding repeatability. To exploit the unique light localization properties of these structures we have fabricated pillar arrays of Erbium (Er) doped Silicon-Rich Nitride (SRN) based on DAS using electron beam lithography and inductively coupled plasma (ICP) varied geometry to optimize the emission enhancement around 1.55 m. An over 30 fold increase in the volume normalized PL is measured along with angularly resolved emission profiles and emission time dynamics (TRPL). The experimental results have been interpreted using the null-field theory formulation (T-matrix) for systems of particles of arbitrary shape. These results suggest that light localization effects in engineered pillar arrays can lead to strong radiative enhancement for CMOS compatible on-chip integration.
Scattering optics resolves nanostructure (Keynote Presentation)
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Scattering of light is usually seen as a nuisance in microscopy. It limits the penetration depth and strongly deteriorates the achievable resolution. However, by gaining active spatial control over the optical wave front it is possible to manipulate the propagation of scattered light far in the multiple scattering regime. These wave front shaping techniques have given rise to new high-resolution microscopy methods based on strong light scattering. This is based on the realization that scattering by stationary particles performs a linear transformation on the incident light modes. By inverting this linear transformation, one can focus light through an opaque material and even inside it. An extremely high resolution focus can be obtained using scatterers embedded in a high-index medium, where the diffraction limit for focusing is reduced by a factor n. We have constructed a scattering lens made of the high-index material Gallium Phosphide (GaP) which is transparent over most of the visible spectrum and has the highest index of all nonabsorbing materials in the visible range. This yields a focal spot resolution of less than 100 nm, and it seems theoretically possible to create a focus of order 70 nm. We will discuss how the system resolution of a fluorescence microscope using this lens could be pushed even higher.

A photonic DNA processor: concept and implementation
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To deal with molecular information at a molecular level based on external signaling, a photonic DNA processor is a primal processing core of a nanoscale information system that works in molecular environment, for example, in situ. Use of photonic signals enables remote and spatio-temporal control of the processor. As an implementation example, we report a photonically-controlled DNA nanomachine which identifies and processes molecular information and implements physical processing as reporting the result using fluorescence signal. The nanomachine has two hairpin DNAs incorporating azobenzene and forms a tweezers-like structure. The hairpin structures are opened by ultraviolet-light irradiation, and a single-strand region is exposed to activate functionality in recognizing a target molecule. In contrast, visible-light irrigation makes the hairpin DNA close to inactivate the sensing function, and it releases the captured molecule. During activated term, the nanomachine changes its tweezers-like structure depending on existence or absence of the target molecule: the nanomachine transmutes into the closed state from the open state (initial state) by binding to the target molecule. Depending on the state, the nanomachine generates a fluorescence signal owing to fluorescence resonance energy transfer. In experiments, we demonstrated that the fluorescence intensities changed depending on existence and absence of the target molecule under photonic activation and inactivation. The result indicates that the nanomachine obtained information on the target molecule, changed the state, and reported the information to the outside world. In addition, we confirmed experimentally the functionality in measuring the concentration of the target molecule.

Threshold current calculations and optical cavity optimization for PbSe/PbSrSe MQW structures
M. Khodr, Hariri Canadian Univ. (Lebanon)

Threshold current is a key parameter in the design and proper operation of quantum well lasers. In this publication, threshold current analysis and calculations are done on four PbSe/Pb0.93Sr0.066 Se quantum well laser structures: SQW, SCH-SQW, MQW, and MMQW. The current work is a continuation to previous publications where energy levels, modal gain, optical confinement, and total losses were published for these four structures assuming the energy bands are non-parabolic. The threshold current as a function of total losses, cavity length, and cavity end mirror reflectivity was obtained for these structures. It is shown that the threshold current decreases with a decrease in the cavity length and then increases at a critical cavity length. The effects of non-parabolicity on the threshold current values are more obvious for short cavities and decreases with an increase in cavity. Whether the SQW or the MQW is the better structure depends on the loss level. At low loss, the SQW laser is always better because of its lower current density where only one QW has to be inverted. At high loss, the MQW is always better because the phenomena of gain saturation can be avoided by increasing the number of QW’s although the injected current to achieve this maximum gain also increases. Owing to this gain saturation effect, there exists an optimum number of QW's for minimizing the threshold current for a given total loss. At this typical value, the effects of non-parabolicity on the threshold current values can be neglected without loss of accuracy. However, there is a 20% shift in the output lasing energy that cannot be neglected.
Nano-imprint of photonic-plasmonic nanostructures on bio-polymers

D. Lin, Boston Univ. (United States); H. Tao, Tufts Univ. (United States); S. Y. Lee, Boston Univ. (United States); F. Omenetto, Tufts Univ. (United States); L. Dal Negro, Boston Univ. (United States)

Nanostructures have been extensively exploited to construct photonics and plasmonics for light emission (lasers, LEDs) and optical biosensing. Current optical platforms are based on widely used substrates such as quartz, silicon, and other semi-conductor materials. Novel polymers, such as silk biopolymer, which are biocompatible and biodegradable, have emerged to expand the functionality of current photonics devices for biomedical applications. However, the nanofabrication of photonic-plasmonic nanostructures on top of these solvent-sensitive bio-polymers poses unique challenges. Here, we demonstrate a rapid nanoimprint method capable to fabricate at room temperature both nano-hole patterns and gold nanoparticle arrays on protein-based biopolymer (silk) substrates. Nano-hole structures are imprinted with mold of Si pillars, while gold nanoparticle patterns are predefined on a donor mold, and then transfer-imprinted onto the surface of a silk film. By this approach, various patterns with feature sizes down to 15nm scale can be reliably fabricated and scaled over cm2 areas. The SEM images of imprinted nanostructures on silk and actively doped (luminescent) polymer layers demonstrate that a mold can be completely replicated onto a silk substrate with high fidelity. This technique provides an attractive approach to fabricate large-area nanostructures on the surface of solvent sensitive polymers with nanoscale resolution and at low cost. Since the imprint procedure relies on mechanical deformation, it preserves the biological, chemical and physical properties of biopolymers, and therefore it is applicable for implantable devices and environmental monitors.

Optimization of the spray parameters for ZnO based hybrid solar cells

A. Vasudevan, S. Jung, T. Ji, Univ. of Arkansas (United States)

Global energy demand has been increasing drastically and major share of this demand is met from fossil fuels. Fossil fuels being non-renewable, efforts are being made to tap energy efficiently from renewable energy sources. Among renewable energy sources, solar energy is a major energy source and solar cells are used to convert it into electrical energy. Solar cells currently used are silicon based because they have higher efficiency than cells from other materials but the manufacturing cost is high. Though cheaper cells can be fabricated using organic materials because it solution processable, the efficiency is very low. The low efficiency of organic solar cells is due to the low mobility of the carriers, the efficiency can be improved if inorganic materials are incorporated. The incorporated inorganic material provides better transport to the carriers generated by organic material. Hybrid solar cells with ZnO nanorods as the inorganic and P3HT and PCBM as the active layer reported in literature is usually prepared by spin coating. The major drawback of using spin coating technique is that large area fabrication is not possible. Large scale production is feasible if these cells can be prepared by spray coating. We will discuss the fabrication of these cells by spray coating technique. The dependence of efficiency of the cell on the active layer thickness, substrate temperature and spray parameters like pressure of the carrier gas will be studied. By comparing the efficiency of the cells prepared under different conditions the optimum condition for preparing efficient hybrid solar cells will be determined.

8102-10, Session 3

Nanotechnologies for efficient solar energy conversion and storage

L. A. Eldada, SunEdison (United States)

The immense gap between solar energy’s tremendous potential and our utilization of it to produce electricity can be overcome over time by increasing the efficiency of the conversion and storage processes, which are today well below their theoretical limits. We present nanotechnologies that improve the conversion efficiency of solar energy into electricity, and enhance the round-trip efficiency of energy storage systems. We describe nanostructures that enhance light concentration, light trapping, photon absorption, charge generation, carrier multiplication, hot electron extraction, charge transport, and current collection in photovoltaic systems, as well as nanomaterials that enhance the efficiency of electrochemical processes, boost gravimetric and volumetric energy densities, reduce the rate of self-discharge, increase the peak power rating, and extend the cycle life of secondary batteries and ultracapacitors.

8102-11, Session 3

Analytical approach to 3D device modeling of nanoarchitectures for solar energy conversion

A. Wangperawong, S. F. Bent, Stanford Univ. (United States)

Recently there have been many new experimental device architectures utilizing vertical nanojunctions to decouple light absorption from charge carrier collection. Despite great experimental work in the field, theoretical studies have been limited. We have developed models that for the first time describe the device performance of nanostructured solar cells in three dimensions, distinguishing between isolated and interdigitated nanojunctions. Our analytical approach is a powerful tool for designing nanostructured solar cells of various architectures and materials that can be both efficient and cheap. Beyond photovoltaics, other applications include photoelectrochemical cells and photocatalytic devices.

8102-14, Session 4

An active matrix arrayed microphone with acoustic bandwidth response

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We have demonstrated a monolithically integrated two dimensional (8X8) active matrix microphone fabricated on a flexible polymer piezoelectric sheet (polyvinylidene difluoride) which uses thin film organic field effect transistors to both locally amplify the piezoelectric charge signal and switch individual elements, allowing for sensing site localization. The integrated design of the sensor and amplifier eliminates a previously dominant parasitic capacitance, allowing an acoustic bandwidth response, and the flexible, thin film form factor allows maximum versatility in applications. Each sensor element is controlled by an organic thin film transistor. The switch transistor is sized significantly smaller than the amplifying/sensing transistor to optimize the cell isolation, on/off characteristic, and parasitic load. The sensor element converts the charge response of the polyvinylidene difluoride (PVDF) sheet into a current signal, overcoming downstream parasitic charge sharing from both switch transistors and interconnects. The device is tested using both turbulent air current and far field acoustic excitation in this work. Our design extends the bandwidth of a locally amplified piezoelectric sheet sensor to the acoustic range, and demonstrates a monolithically integrated active matrix sensing architecture capable of sensing in the acoustic range and mapping both boundary layer and far field acoustic excitation for a variety of applications.
Low temperature zinc oxide nanorod synthesis for gas detection applications

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Devices fabricated on silicon substrates can have limited applications due to material costs and non-biocompatibility. Glass and flexible polymer substrates are inexpensive and biocompatible making them an excellent choice of substrate for sensor design due to their broad range of potential applications; however require low processing temperatures unlike conventional silicon based devices. To address this low temperature processing requirement of substrates, Zinc Oxide (ZnO) nanorods have been grown on glass and polymer substrates using a low temperature wet chemical synthesis process. Substrates were seeded with ZnO nanoparticles synthesized in methanol and then annealed at 125°C. The substrates were then inverted and placed in a sealed container of nanorod growth solution in a sealed container for 6 - 8 hours at 90°C. The resulting nanorods ranged from 1 - 2 μm in length and 50 - 150 nm in diameter. Samples were characterized with Scanning Electron Microscopy and X-ray Diffraction. The synthesis of ZnO nanorod was optimized to create vertically aligned single crystal nanorods suitable for gas detection with a proprietary interdigitated electrode design. The mechanism for gas detection is an upward shift in the conduction band structure of ZnO nanorods as gas is absorbed on its surface which results in a measurable increase in conductance. A gas sensor was fabricated with the optimized ZnO synthesis process and its response characterized using CO in N2 at standard temperature and pressure at concentrations from 150 ppm to 10,000 ppm.

UV detector from ZnO nanorods with electrodes resembling a wheatstone bridge pattern

A. Vasudevan, S. Jung, T. Ji, Univ. of Arkansas (United States)

Detectors currently used for UV detection are Si based and photomultiplier tubes. These detectors being bulky and less sensitive, we need to find an alternative material that could improve the sensitivity and to build portable detector. Past work by different authors show that ZnO based photo detectors have better sensitivity even at room temperature, also have characteristics like radiation hardness, chemical stability and high temperature stability. The structure of the ZnO detectors can be of the following types (1) p-n junction diode (2)schottky barrier type (3) Metal-semiconductor-metal type, of these metal-semiconductor-metal type detector is simple and cheaper for fabricating. Usually metal-semiconductor-metal structure detectors use simple interdigitated electrode but the sensitivity of these detector can be improved if better electrode design is chosen. We will use electrodes that are designed in square pattern which almost resembles a wheatstone bridge and this new improved design enhances the collection of carriers and also miniaturization of the detector. The nanorods for the detector will be grown by solution growth technique and rods of different length will be grown to know how it affects the response of the detector. To study how the response of the detector depends on the length of the interdigitated fingers and spacing between the interdigitated fingers, electrodes of different dimension will be fabricated. The response of the detector will be determined from I-V measurements made with and without UV light of wavelength 365nm for different bias voltage.

Polyaniline nanoﬁlms as a base for novel optical sensor structures

V. Va?inek, J. Bocheza, S. Hejduk, K. Witas, J. Vitasek, Technical Univ. of Ostrava (Czech Republic)

Polyaniline hydrochloride was prepared by the oxidation of aniline hydrochloride with ammonium peroxodisulfate in dilute hydrochloric acid. The polyaniline films were produced during the polymerization on the microscope glass surfaces immersed in the reaction mixture. The thin film was created and its thickness has been about 100 nm. We have measured the spectral transmittance together with temperature changes. The polyaniline thin film is conductive and we observed changes in optical transmittance spectra and reflective spectra with electric current. Optical spectra have been measured in range from 380 nm to 1010 nm. The electric conductivity has been changed with silicate substrate. This substrate influenced the free electrons distribution and therefore the optical properties of polyaniline. Due to electric current going through the nanofilm its sensitivity to temperature has been increased. We also observed two specific spectral windows. The first one was characterized by its insensitivity to temperature; the second one has been temperature sensitive. The central wavelength of insensitive window is about 500nm. This property can be the base for novel sensors structures. We used Ocean Optics USB spectrometer for evaluation of spectral changes. Wideband white light halogen source from the same manufacturer has been applied as a light source. Small polarizing dependence of reflected light has been observed too.
Periodical microstructures induced by IR femtosecond laser pulses on silicon surface for color marking
S. Makarov, National Research Nuclear Univ. MEPhI (Russian Federation)

We investigate basic regimes for ripples formation by IR (λ ≈ 744 nm) femtosecond laser pulses on silicon surfaces and topological evolution of quasi-periodic surface nanostructures with increasing laser irradiation dose (the product of the number of pulses and laser fluence). We demonstrate possibility of controllable and theoretically predictable surface color-marking, which is developing of the new method of surface colorizing by writing laser-induced periodical structures.

Fabry-Perot scanning probe for aperture-based near-field optical microscopy
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In present paper we present a new type of interferometric aperture-based probe for near-field optical microscopy based on a fiber optic Fabry-Perot microresonator with a nanosized aperture milled in one of its mirrors. The dependence of resonant modes spectral shift δλ on the Fabri-Perot microresonator on the distance between the output aperture and the test object was obtained by using finite-difference time-domain (FDTD) method. It was shown theoretically that minimal longitudinal resolution of the method is defined by the Q-factor of the resonator. In accordance with numerical data obtained, proposed method allow one to achieve the value of longitudinal and lateral resolutions more then δλ/15 and δλ/40 correspondently.

The spatial resolution not worse than 120 nm, which corresponds to –λ/14 at wavelength λ = 1550 nm was experimentally demonstrated using proposed probe based on the fiber optic Fabry-Perot interferometer (Q-factor=5^10^4) with the 100-nm-sized circular aperture milled in its output mirror with the focused ion beam. A further increase in spatial resolution of the proposed method can be achieved by using resonators with higher Q factor.

Nanoscale organic light-emitting transistors: NanoOLETs
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Light-emitting organic crystalline nanofibers made from small molecules exhibit a wide range of extraordinary optical properties [1] such as intense, anisotropic luminescence, waveguiding, electroluminescence and lasing. For lighting and display purposes, the defect free morphology of the nanofibers, the high quantum yield and the easy tunability of the color by changing the molecular building blocks are especially important.

The application of such nanostructures as electrically driven light-emitters requires integration with suitable metal electrodes for efficient carrier injection. Here, we implement two different methods for achieving such nanofiber integration. The first method is based on initially preparing the nanofibers by epitaxial growth on a special growth substrate (muscovite mica) and subsequently transferring them to a suitable device substrate by a recently developed roll-on transfer technique [2]. The second method relies on growing the nanofibers directly between the metal electrodes on a substrate that has been specially designed to guide the nanofiber growth [3]. We present results of both techniques in terms of morphological, optical and electrical characterization and demonstrate how appropriate biasing with an AC gate voltage enables electroluminescence from organic nanofibers. The electroluminescence occurs in the close vicinity of the electrodes (space charge region) and thus the characteristic dimension of the lighting transistor is on the nanoscale.

Deposition of sol-gel sensor spots by nanoimprint lithography and hemi-wicking
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We present a method for homogeneous deposition of sol-gel sensor materials, which enables fabrication of sensor spots for optical pH and oxygen measurements inside plastic containers. Using the principle of hemiwickiing [Quéré, Physica A (2002)], a deposited droplet is guided by posts imprinted in the surface and fills the imprinted structure automatically, not being sensitive to alignment as long as it is deposited inside the patterned area. A periodic pattern of posts is imprinted into a polycarbonate substrate, and a droplet of the sol-gel sensor material is deposited on the structured surface, where after it spreads, guided by the imprinted posts. The layer thickness of the deposited film is determined by the geometry of the posts and surface energy.

Hemwicking is an effective method to immobilize a low viscosity liquid material in well-defined spots on a surface, when conventional methods such as screen- or stamp-printing do not work. On length scales of the order of the microstructure period, surface tension will govern the shape of the liquid-air interface, and the liquid will climb up the pillars to keep a fixed contact angle with the sidewalls. The surface to volume ratio is therefore constant all over the surface of the liquid spread by hemiwickiing, when considering length scales larger than the microstructure period. Material redistribution caused by solvent evaporation, i.e., the “coffee ring effect” [Deegan et al., Nature (1997)], can therefore be avoided because the evaporation rate does not vary on length scales larger than the period of the pattern.
They offer the possibility of beating the ideal thermal limit to the inverse subthreshold slope of 60 mV/dec and thus promise reduced power operation.

However, whether the tunneling can provide sufficient ON-current for high-speed operation is an open question.

In this work, for a p-i-n device, we investigate the source doping level necessary to achieve a target ON-current (1 micro A) while maintaining a high I(ON)/I(OFF) ratio (1E6) for a range of NW diameters (2-8 nm). Our approach uses a fully-discretized 8 band k.p model combined with the non-equilibrium Green’s function (NEGF) formalism.

The electrostatics is calculated using a finite difference solution of Poisson’s equation. With a fixed drain bias voltage and a maximum gate overdrive, we compare the performance of the inverse subthreshold slope (SS) and I(ON)/I(OFF) ratio as a function of NW-diameter and source doping. Increasing the source doping level increases the current as a result of the reduced screening length and increased electric field at source which narrows the tunnel barrier.

However, since the degeneracy is also increasing, it reduces the effective energy window for tunneling which, in turn, tends to decrease the current for a given voltage.

This leads to an optimum choice of source doping considering the inverse SS and I(ON)/I(OFF) ratio for these TFETs.

8102-25, Session 5

Carrier leakage in Ge/Si core-shell nanocrystals for lasers: core size and strain effects

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Ge/Si core-shell nanocrystal lasers have been proposed because of their compatibility with existing Si based technology. They exhibit size dependent stimulated emission and reduced threshold current density. In such structures, lasing is obtained at lower current density because of large carrier confinement and a favorable density of states for population inversion. A recent experimental report suggested an increase in the light emission probability because of increased radiative lifetimes, however the performance is exponentially dependent on the temperature due to the current leakage mechanism. This hole current leakage mechanism is governed by the thermionic lifetime of the confined carrier which is determined by the height of the barrier over which the hole must be emitted. Higher thermionic lifetime indicates a minimal escape rate of the carriers from the core to the confining shell barrier. In this paper, we calculate the thermionic lifetimes as a function of the Ge-core size and strain. Our method also provides a novel and accurate barrier calculation that is required for the leakage current formulation by capturing the bound and extended eigenstates, well below the band edges, and corresponding eigenvalues using the atomistic tight binding method as implemented in NEMO3D. In addition, the effect of both core size variation and strain on the leakage current, and on other fundamental but important electronic and optical parameters will be presented.

8102-26, Session 6

3D tectons as functional nanostuctures for self-assembled functional thin films towards nanophotonics

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In order to achieve the nanometer-scale control over the positioning and organization of functional molecules into monolayers at surfaces, we developed an original approach allowing the exact positioning of (photo)active organic molecules on the substrate (graphite) leading to the formation of nanostructured functional thin films. 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. We will present a series of such building-block exhibiting tunable wavelength emission. This strategy results in the precise organization of chromophores arrays (subwavelength-sized photon sources) a few Å above the conducting surface, as determined by scanning tunneling microscopy (STM), opening interesting perspectives for applications in nanophotonics.

8102-28, Session 6

Boost nonlinearity by monolayer graphene

T. Gu, Columbia Univ. (United States)

Graphene exhibit interesting optical properties such as high Kerr nonlinearity, absorption saturation, Faraday rotation, but in all those experiments light has TM polarized component and thus hard distinguish the graphene effects from the substrate. Here we conformally place the CVD grown graphene on suspended silicon membrane, and send TE polarized light into the pattern defined on the suspended semiconductor membrane. It is observed that the refractive index of the media is sensitive to the light intensity, indicating the silicon’s nonlinear effect is enhanced by the graphene cladding since the TE mode like does not direct interact with the one atom thick graphene sheet. Further discussions on the mechanism and fabrication are performed.

8102-29, Session 6

Exciton polariton coupling and enhanced emission in SiC nanocrystals

G. Polupan, T. V. Torchynska, Instituto Politécnico Nacional (Mexico)

The essential interest in last decade appears to different applications of SiC nanocrystals (NCs) such as porous SiC (PSC) or SiC NC composite layers. The large band gap of SiC NCs makes them the good candidates for blue and ultraviolet (UV) light emitter diodes and full-color displays. SiC-based homoepitaxial structures, new types of PSiC-based photodiodes and UV gallium nitride photodetectors grown on SiC substrates have been reported recently [1].

The paper presents the results of SiC nanocrystal characterization using photoluminescence, its temperature dependence, scanning electronic microscopy (SEM) and X-ray diffraction techniques. Photoluminescence study of porous SiC layers with different SiC NC sizes reveals the intensity stimulation for high energy PL bands. The investigation of temperature dependences of high energy PL bands has shown that these PL bands related to different excitons in SiC NCs. The intensity enhancement of exciton-related PL bands in big size (50-250nm) SiC NCs is attributed to exciton recombination rate increasing due to the realization of exciton weak confinement and exciton-polariton coupling. The numerical simulation permits to estimate the optimal SiC NC size for exciton-polariton coupling. The comparison of experimental and numerically calculated results will be presented as well.

8102-30, Session 6

Advanced patterning for patterned magnetic media

Patterned media is a solution to provide data bit thermal stability for future generation disk drives. Patterned bit media is not expected in the disk drive manufacturing until densities of 1 Tb/in² or greater. If the bits were to be placed on a square lattice, 1 Tb/in² would correspond to a dot period of 25 nm. The specifications for the patterned media geometry and accuracy are determined by the required magnetic switching field distribution of the magnetic bits and the recording head. One of the major contributors to a wider switching field distribution is a variation in island size. From configurations of today’s write heads, the shape of the future bits may be rectangular rather than square or round. A bit aspect ratio of 2:1, corresponds to a track pitch of 36 nm and a downtrack bit pitch of 18 nm at 1 Tb/in².

Because of the tighter distribution of island sizes, e-beam lithographically guided self assembly of PS-b-PMMA is shown to narrow the island size distribution and the magnetic switching fields of patterned magnetic bits over bits patterned by e-beam lithography alone. Self assembly allows the multiplication of the density of the patterns to 1 Tb/in² or greater. In addition, we show e-beam writing strategies to minimize e-beam write time and exploit the pattern correction of directed self assembly. We also show techniques to address different shape bits. The application of e-beam directed self assembly to fabricating imprint templates and imprinted patterned media is demonstrated at densities up to 1 Tb/in².

8102-31, Session 6

Advanced holographic methods in EUV interference lithography
B. Terhalle, A. Langner, B. Päiväranta, C. David, Y. Ekinci, Paul Scherrer Institut (Switzerland)

Extreme ultraviolet interference lithography (EUV-IL) has recently been attracting growing interest as a fabrication tool for high-resolution periodic nanostructures due to its various fundamental features, e.g. high throughput, large depth of focus etc [1]. Consequently, the technique has been successfully applied to a variety of nanofabrication problems until now [2].

The most common experimental scheme in EUV-IL involves the illumination of a mask containing several diffraction gratings with a spatially coherent beam in order to overlap first-order diffracted beams at a certain distance from the mask and record the resulting interference pattern in a suitable photosist. This way, the fabrication of high resolution one- and two-dimensional periodic nanostructures becomes possible. So far however, the existing experimental realizations are mostly limited to rather simple symmetries such as one dimensional line patterns or two-dimensional dot arrays [3].

In this contribution, we extend the above concept and study the generation of more complex pattern geometries using EUV-IL. In particular, we demonstrate the use of five or more interfering beams for the fabrication of sub-100nm quasiperiodic nanostructures. Furthermore, we investigate the generation of complex beam shapes such as EUV-vortices and Bessel beams and discuss potential applications for future use in EUV-IL.


8102-32, Session 6

Fabrication of complex structures with an array of nanopinhole cameras
H. S. Leipner, Martin-Luther-Univ. Halle-Wittenberg (Germany); N. Geyer, Max-Planck-Institut für Mikrostrukturphysik (Germany); F. Syrowatka, H. Cheng, B. Fuhrmann, Martin-Luther-Univ. Halle-Wittenberg (Germany)

There is a big demand of reliable lithographic techniques to produce a wide array of different nanostructures. Colloidal lithography has been proven to produce precise arrays of particles on a broad range of substrates. More complicated nanostructures are required for applications in real-time chemical and biological sensors, based e.g. on the effect of localised surface plasmon resonance. This powerful technique is sensitive to shape, size, interparticle distance, and composition of metallic nanoparticles and the dielectric surrounding. Metallic nanostructures are required for negative refractive index metamaterials as well. In this work, we present a method for the fabrication of ordered arrays of complex structures, which combines colloidal lithography with the principle of a pinhole camera well known in optics. By using atomic beams in high vacuum instead of light, it is possible to overcome the problem of the diffraction limit for small apertures with nanometer dimensions. There are no geometrical or chromatic aberrations, since no refracting elements exist. Limitations exist due to the finite size of the nanopinholes, which lead to a certain blurring of the replica deposited on the substrate. However, compared to focused ion beam technique or electron beam lithography, the method is rather simple and has a broad applicability.

8102-33, Session 6

Synthesis of surface patterned YAG:Ce/TiO2 nanocomposite films as converter layer for white LEDs.
A. Revaux, G. Dantelle, Ecole Polytechnique (France); D. Decanini, A. Haghiri-Gosnet, Ctr. National de la Recherche Scientifique (France); C. Weisbuch, J. Boliot, T. Gacoin, Ecole Polytechnique (France)

Rare-earth doped oxides are well-known for their applications in light emitting devices. In the case of white LEDs, micron-sized YAG:Ce particles are commonly deposited on blue LED chips to produce an additional yellow component. To avoid losses due to backscattering effects, we propose to control separately the down-conversion and the extraction of light instead of using micron size luminescent particles acting simultaneously as both converters and scatterers. Very stable suspensions of luminescent YAG:Ce nanoparticles, with a crystallite size of 25 nm, were synthesized by a glycothermal method at relatively low temperature (300°C). A protected annealing process in a silica matrix, allowed further treatment of these nanoparticles at high temperature without any aggregation and growth and a significant improvement of their optical properties. The obtained colloidal nanoparticles were finally incorporated into a sol-gel matrix of TiO2. Thanks to the relative matching of refractive indexes between TiO2 and YAG, and to the sub-wavelength size of YAG particles, the resulting films are nearly transparent (i.e non scattering). When used as light converters for white LEDs, these films could offer the opportunity to diminish the backscattered light absorption losses. We showed that the surface of these sol-gel TiO2 films can be periodically patterned by soft nano-imprint lithography. The diffraction due to the obtained photonic crystal at the surface offers the opportunity to control the extraction the converted light. We investigate how the angular distribution of the emitted light depends on the chosen geometry.
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8102-34, Session 7

Types, characterization, and applications of carbon nanotube grades

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Carbon Nanotubes are a quite complex class of materials. As such, there is no easy way to characterize the many grades available for purchase from scores of companies and distributors. The simplest classification that has found widespread use is single wall or multiwall, SWNT or MWNT. An alternate classification is either fullerene polymer molecules or nanoscale carbon fibers. This paper is concerned with the fullerene polymer sub-class of carbon nanotubes. Fullerene science and technology began in 1985 with the discovery of C60, the molecule officially called buckminsterfullerene by the American Chemical Society, and “buckyballs” by the discoverers.

Fullerene nanotubes are a new class of electrically and thermally conducting polymers that are also useful for structural applications since they are strong, stiff, tough, resilient and durable. Similar to other polymers, they are polydisperse. We use a three level description of structure: primary, secondary and tertiary to describe this polydispersity. At the primary structure level, fullerene nanotubes have diameter, length and number of wall distributions. These three components contribute to the molecular weight distribution of the grade. These primary structural elements influence the character of the secondary structure called ropes or bundles. Similar to traditional semi-crystalline polymers, the fullerene polymers attract each other through van der Waal forces and bundle together. These bundles or ropes can be crystalline or non-crystalline. The arrangement of these bundles in macro dimensions creates the tertiary structure. This paper will illustrate this hierarchical characterization approach for a grade of fullerene nanotubes targeting high electrical conductivity applications.

8102-35, Session 7

The low-threshold nonlinear optical effects in suspensions of dielectric alpha Al2O3 nanoparticles, dispersed in dielectric organic immersion oil.

V. Dzyuba, V. Milichko, Y. N. Kulchin, Institute for Automation and Control Processes (Russian Federation)

This report presents the results of the study the low-threshold nonlinear optical effects in suspensions of dielectric alpha Al2O3 nanoparticles, which are dispersed in dielectric immersion oil. It was found that the refractive index of nanoparticles suspension changes in the weak laser radiation field of visible range (intensity did not exceed 0.2kW/cm2) and it is a function of intensity and frequency of the incident radiation. Nonmonotonic nonlinear additive to the refractive index (nonlinear refraction) was substantiated theoretically and confirmed experimentally as well as additive numerical values were calculated. Maximum absolute value of this nonlinear additive to refractive index was 10-4. The proposed theory of nonlinear optical properties formation in these suspensions of wide-dielectrics nanoparticles presented the results which consistent with experimental results.

We also investigated the transmission spectra of suspensions of nanoparticles in liquid matrices of different chemical composition and the theoretical assumption about the causes of the difference spectra and optical properties of nanoparticles in various matrices was given. The results of these studies could form the basis for a deeper investigation of suspensions of dielectric nanoparticles, both in liquid and in solid dielectric matrices as well as allow for creation of new types of nanostructured materials for electronics and laser optics.

8102-36, Session 7

Enhancement of optical nonlinearity in β-AgVO3 nanobelts by incorporation of Ag nanoparticles

M. R. Parida, C. Vijayan, Indian Institute of Technology Madras (India)

The synthesis of Silver vanadium oxides (SVO) with well-controlled size, morphology, and chemical composition can offer great opportunities for exploring their novel optical properties and for the fabrication of nanodevices. These nanostructures of SVO are synthesized by a simple hydrothermal reaction and characterized by standard techniques. The XRD pattern of the as-prepared β-AgVO3 can be indexed to the phase of β-AgVO3 monoclinic structure. The HRSEM image shows the diameter of the nanobelts to be in the 100-300 nm range with length up to several micron which is also conformed from TEM. The optical nonlinearity is measured by the Z-scan technique using 5 ns pulse of Nd-Yag laser. The results indicate strong nonlinear absorption which is fitted theoretically two photon absorption process followed by saturable absorption process. The values of two photon absorption coefficient and saturation intensity are calculated. Ag nanoparticles are supported on β-AgVO3 synthesis by the same hydrothermal technique by increasing the concentration of silver nitrate in synthesis reaction. The HRSEM and TEM images confirm that there is no definitive interface relations between the particles, the branches and the stem. They are separated by grain boundaries. There is an enhancement of optically nonlinearity observed in this system compared to undoped SVO. The values of two photon absorption coefficient and saturation intensity are found to be enhanced that because of surface plasmon effect.

8102-37, Session 7

Effect of nano-particles on the dynamic and thermal characteristics of composite materials

M. Seif, M. A. Abunaemeh, Alabama A&M Univ. (United States)

The effect of the nano-silica fillers and dispersion parameters on the mechanical and thermal properties of graphite/epoxy composite materials have been investigated. The dispersion of nano-particles in epoxy resin is carried out using sonication method. The study summarizes the effect of different nano-silica concentrations on the tensile strength of the Epoxy. Modal analysis has been used to determine the vibration properties and damping parameters. The vibration characteristics of nano-composites have been compared with neat epoxy resin. Moreover, the effects of nano-silica fillers on the thermal conductivity and the glass transition temperature of the epoxy resin have been studied. The results show that nano particles have a direct effect on the thermal conductivity and glass transition temperature of the new composite materials. This will allow the possibility of developing new composite materials that will have certain thermal and dynamic properties for wide applications.

8102-38, Session 7

Fabrication of quartz nanoneedles by using Cr thin films as wet etching masks

M. Hung, J. Liou, C. Chang, National Central Univ. (Taiwan)

Quartz crystals are widely used in many engineering fields due to their exceptional piezoelectric, optical, and many other properties. Micro/nano-structured quartz is crucial for miniaturization of quartz devices and many potential MEMS/NEMS applications. The manufacturability for quartz crystals, however, is very limited. Unlike the silicon wet etching that generally has simple etching patterns, the wet etching of quartz crystals results in complex and poor symmetric patterns. Thus,
to fabricate elaborate micro/nanoscale quartz structures is usually not straightforward and requires expensive dry etching processes.

In this manuscript, we present a study of the fabrication of quartz nanoneedles by wet etching. Chromium is evaporated on the Z-cut quartz surface and serves as the etching mask. The deposition process is tuned to certain conditions for Cr atoms to accumulate and form nanosized individual Cr islands. Ammonium bifluoride solutions are used as the etchant. Due to the particular etching anisotropy of quartz crystal orientation, nanoneedles can be formed. By controlling the Cr nanoparticle distributions and etching time, quartz nanoneedles of different sizes are produced. The lengths and shapes of the nanoneedles are observed using scanning electron microscope (SEM) to study the anisotropy of the quartz etching and the mechanism of the needle formation. We have successfully produced very sharp and high aspect ratio nanoneedles with lengths of few micrometers. The growth rate of nanoneedles is found to be increased with the etching time but have a maximum value. The experimental results fit well with our simulated predictions. This study may have potential impacts in quartz MEMS/NEMS.

8102-39, Session 7

An alternative approach to fabricate metal nanoring structures based on nanosphere lithography

Z. A. Lewicka, V. L. Colvin, Rice Univ. (United States)

In this work we present an improved, cost-effective fabrication method for metal ring-shaped nanostructure arrays based on nanosphere lithography. Periodic arrays of symmetric nanorings, non-symmetric nanorings, and nanocrescents with different sizes were fabricated using a simple method that includes self-assembled monolayer formation, plasma treatment and sputter deposition of metal. Lower cost and higher throughput were achieved due to the replacement of focused ion beam milling with reactive ion etching usually used in other methods. The dimensions of ring-like structures could be controlled by the size of the polystyrene spheres, the amount of deposited metal and the argon plasma etching time. These nanostructures may be made of essentially any metal and be used as elements in optoelectronic nanodevices.

8102-40, Session 7

fabrication and optical characterization of nanopore Si

H. Jin, G. L. Liu, Univ. of Illinois at Urbana-Champaign (United States)

Nanopore Si has been applied to demonstrate advantages in various fields such as photovoltaic, biosensing, DNA sequencing, and also particle sorting. The optical and mechanical properties provide enhanced solar conversion efficiency, surface enhanced Raman effects, elongation of DNA, and also blocking of vapor phase molecules. Typical fabrication of nanopores would utilize e-beam lithography followed by DRIE. Focused ion beam may also be utilized. The use of such methods are time consuming in formation of nanopores on a relatively larger area. Another approach would be the use of anodized aluminum oxide (AAO), by applying a voltage to high purity aluminum foil (99.999%) in oxalic acid. The non-lithographic fabrication method would enable a cost effective approach of nanopore fabrication. However, the use of aluminum foil based AAO results in a film that is too thick to transfer the nanopore features to another substrate.

In this paper, the fabrication and the optical properties of nanopore Si is presented. Aluminum is evaporated on the surface of N-type Si by e-beam evaporation. Nanopore structure is formed by a two-step AAO formation in oxalic acid. Diameter size from 30 to 80 nm is achieved, depending on the condition of anodization and etch. Deep reactive ionic etch (DRIE) is done, with AAO as the mask layer. The nanopore AAO template allows etching depth of up to 700 nm. Parameters that affects the fabrication are evaluated. Optical properties of various pore depth is discussed.

8102-41, Poster Session

Efficient approach for the calculation of transmission and reflection spectra of photonic crystal waveguide devices

R. Chen, Y. Lin, Lunghwa Univ. of Science and Technology (Taiwan)

Photonic crystal (PC) waveguide devices have inspired great interest because of their potential in realizing compact photonic integrated circuits. To design a PC waveguide device, it is important to know its transmission and reflection spectra. Among the various simulation techniques, the finite-difference time-domain (FDTD) method is popularly employed due to its versatility in dealing different structures. However, the traditional approach to calculate the transmission and reflection spectra by the FDTD method is a task of both time and memory demanding. A sizable computational cell must be used and several pulses covering different ranges of frequencies must be sent down the waveguide and the field amplitudes are monitored at two proper locations. The monitored field profiles are then Fourier transformed to obtain the transmission and reflection spectra. In this work, we propose a more efficient approach to obtain these spectra. First, the PC-based absorbing boundary condition proposed by Koshiba is employed instead of the popularly used perfectly matched layer boundary condition. Second, the reflected pulse is obtained by subtracting from a reference input waveform. To demonstrate the effectiveness of this approach, a T-junction in square lattice PC is simulated. A computational cell of only 40 x 36 lattice constants can be used for the proposed approach, compared to 150 x 80 lattice constants for the traditional approach. Accordingly, the simulation time is reduced to only one tenth of that using the traditional approach.

8102-42, Poster Session

Design of sharp waveguide bends with a wide high-transmission bandwidth in triangular photonic crystal slab

R. Chen, Y. Lin, Lunghwa Univ. of Science and Technology (Taiwan)

Photonic crystal slabs (PCSs) have received considerable attention due to their potential in high-density photonic integrated circuits. Optical confinement is provided via the photonic bandgap in the plane of periodicity and via refractive index in the vertical direction. By removing one row of air holes, a single-line-defect waveguide can be obtained. Some sharp waveguide bends in PCSs have been proposed but their high-transmission bandwidths were limited. In this work, we design a 60-degree waveguide bend with a wide high-transmission bandwidth (~ 9.8% of the center frequency, or 150 nm at the wavelength of 1550 nm) in a triangular PCS. Within the high-transmission bandwidth, power reflection at the bend is found to be lower than 2% of the input power. Based on this 60-degree bend, a sharp 120-degree bend with a compact device area is proposed. A similar transmission efficiency is also found for this 120-degree bend.

The principle of the proposed sharp bends is as follows. First, the adjacent air holes along the two sides of the single-line-defect waveguide is enlarged such that the waveguide becomes single-mode. Second, a mirror plane is introduced at the bend region to improve the power transmission. This is done by further enlarging three air holes at the bend region and by moving inward one of them such that a photonic crystal mirror plane is formed. Numerical simulation is performed by employing the finite-difference time-domain method and power transmission and reflection spectra are calculated by launching pulses and by Fourier transformation.
8102-43, Poster Session

Nano and micro structures imaging based on asymmetric Bragg diffraction
A. V. Kuyumchyan, American NanoScience and Advanced Medical Equipment, Inc. (United States); D. A. Kuyumchyan, Riverside Community Colleges (United States); A. Snigirev, I. Snigireva, European Synchrotron Radiation Facility (France); M. V. Grigorev, E. V. Shulakova, Institute of Microelectronics Technology and High Purity Materials (Russian Federation)

We present results of focusing and imaging properties of lens-crystal system for hard x-ray radiation; consisting of such elements as parabolic refractive lens made from beryllium and asymmetric mono crystal from silicon. The beryllium refractive lens has advantages like small absorption, high efficiency and high spatial resolution. This work demonstrates for the first time a phenomenon of image transmission using the Bragg diffraction of focused x-ray beam from asymmetric mono crystal. For recording the magnification X-ray phase contrast was used asymmetric mono crystal Si (220) with factor asymmetry b=9 at the x-ray energy 17 keV. The experimental investigations have been conducted on the station BM-5, ESRF, France. The peculiarities of redistribution of intensity are investigated both experimentally and theoretically when the focus of refractive lens is moved across the optical axis. The intensity distribution along the optical axis is also investigated. We elaborate a computer program for theoretical study of image transmission based on lens - crystal system with asymmetric Bragg diffraction. The calculation is based on the use of Kirchhoff propagator in a paraxial approximation and fast Fourier procedure. The intensity map on the plane perpendicular across the optical axis is calculated for any parameters, including the phase shift of the test object.

8102-44, Poster Session

Fabrication of Multiple Si Nanohole Thin Films from Bulk Wafer by Controlling Metal-Assisted Etching Direction
S. Shiu, T. Lin, K. Pun, H. Syu, S. Hung, C. Lin, National Taiwan Univ. (Taiwan)

Crystalline Si photovoltaic modules still have high production cost due to significant consumption of the Si wafer. Reducing the large amount of Si material consumption is thus a critical issue. Here we develop a two-step metal-assisted etching technique for forming vertically-aligned Si nanohole thin films from bulk Si wafers. The formation of Si nanohole thin films includes a series of solution processes: deposition of Ag nanoparticles in an AgNO3/HF aqueous solution, formation of Si nanohole arrays at the first-step metal-assisted etching and side etching of the roots of the nanohole structure at the second-step metal-assisted etching. All the processes can proceed at around room temperature. A Si nanohole thin film with an average hole size of 100 nm and a thickness of 5um-20 um was hence formed at the top of the wafer. Afterwards, the Si nanohole thin film was transferred onto alien substrates. The Si nanohole thin film has the crystal quality similar to the bulk Si wafer. The above bulk Si substrate can be reused. With similar processes, other Si nanohole thin films can be formed from the above recycled Si wafer. The hole size and thickness are similar. The Si wafers recycled will significantly reduce the material consumption of Si. Thus, such technique is promising for lowering the cost of Si solar cells.

8102-45, Poster Session

Design and fabrication of 3D dielectrophoretic chip on separating 2-type of bacteria
C. W. Su, Tatung Univ. (Taiwan)

With the improvement of quality of life, people want to have better medical treatment. MEMS technology is applied by biotechnology such as PCR chip, detection chip, separated chip and etc. Biological, chemical, or medical processes involving complex fluids with embedded particles often require preparative separation of particles, cells, or even molecules that are needed for the subsequent procedures. In this research, the MEMS technologies which is applied to make the 3D electrodes with the 3D electric field. The structure of biochip is consisted of PDMS flow channel, copper electrode and glass. In order to achieve DEP performance, we utilize CFD-ACE+(Computational Fluid Dynamics) to simulate the effect of the sharp electrodes, wide electrodes and narrow electrodes. We deposited 50um of copper as electrodes on glass and 50um of PDMS as flow channel. We use the 3D DEP chip to separate yeast cells and aspergillus niger. We succeeded in trapping yeast cells at 5MHz, 10Vpp, and separating the different cells. Compared with typical planar DEP devices, the proposed 3D DEP chip, presents an increased DEP force in the vertical direction. The electric field will become wider than before. Fabrication 3D electrodes on glass can result in lower costs and less time-consuming. The chip we fabricated is demonstrated that the electrodes which is fabricated by MEMS technologies can manipulate the bioparticle. As the result, the trapping or levitation effect can be achieved at a lower voltage and with a reduced heating of the solution.

8102-46, Poster Session

A model of photoconductivity of porous silicon
L. S. Monastyrsky, B. Sokolovskii, Ivan Franko National Univ. of L'viv (Ukraine)

It is presented a model of the photoconductivity of porous silicon in the conditions of homogeneous generation of photocarriers. By the finite element method it is calculated the stationary photoconductivity and the time evolution of photoconductivity after instantaneous shutdown of light. Dependences of the stationary photoconductivity and relaxation time of photoconductivity on the velocity of surface recombination of nonequilibrium carriers at the surfaces of pores, radius of pores and average distance between them are analyzed. It is shown that increase of the surface recombination velocity leads to decreasing both the value of stationary photoconductivity and the time of photoconductivity relaxation, with at lower values of the distance between the pores these changes being more significant. Decrease of the relaxation time at the expense of changing the surface recombination velocity can reach almost one order of magnitude. The latter occurs in the materials with high level of porosity when the area of pore's surface per unit volume is large. The results of modeling show that peculiarities of the photoconductivity of porous silicon is of interest for manufacturing gas sensors.
8102-47, Poster Session

**Investigation of 0-3 composites for novel capacitors and energy storage**

A. Buchsteiner, H. S. Leipner, J. Glenneberg, C. Ehrhardt, M. Zenkner, T. Grossmann, S. Ebbinghaus, H. Beige, Martin-Luther-Univ. Halle-Wittenberg (Germany)

Up to now, rechargeable batteries are mostly used for energy storage purposes. However, their electrochemical working principle limits the field of application. Capacitors with very high energy densities are an alternative approach for energy storage. They can be very quickly charged/discharged and have long lifetimes.

We develop novel capacitors on the basis of 0-3 composites, where nanoparticles of perovskites are embedded in a matrix material. Specific organic surfactants of the nanoparticles force their uniform distribution in the matrix.

These new materials combine the electrical advantages of ceramics and glasses/polymers (high permittivities and breakdown voltages) and can easily be processed as thin films.

8102-49, Poster Session

**Engineering of Photonic Crystal Waveguide Defects for Slow Light Applications**

V. Janyani, Malaviya National Institute of Technology (India)

In recent years photonic crystal waveguides (PCWs) made of silica and air holes have provided a new approach for dispersion compensation and slow light generation, due to the design flexibility obtained by variation in the geometric parameters of the holes and corresponding tailoring of the effective refractive index. For slow light generation, a large value of group index is desirable to slow down the light. At the same time, however, the bandwidth of the range over which the slow light is achieved and the dispersion produced in the signal as a result of slow-down of the pulses of become much significant.

The signal propagates through the ‘defect’ in the PCW which is obtained by removing one linear row of air holes in the hexagonal-lattice photonic crystal. The effect of the rows nearest to this line defect have been found to have much influence on the propagation characteristics of the signal and on the slow light generation process. This paper proposes a new geometry of PCWs, which uses carefully designed elliptical holes in the two rows adjacent to the defect through which the signal propagation takes place. These elliptical holes are shifted along the longitudinal direction in such a way that the arrangement provides a delay-bandwidth product which is significantly higher than that previously reported in literature. The paper discusses the theory behind the design process and the principle of operation, and necessary numerical results are presented to verify the behavior claimed.
8103-01, Session 1

Developments of high-sensitive DNA sensors (Keynote Presentation)
N. Ogata, Chitose Institute of Science and Technology (Japan)

Pure DNA which is isolated from Salmon roe has a huge high molecular weight of over billion and can form a strong and uniform film and the double helical structure of DNA has a characteristic feature of intercalation of various optical dyes among stacked layers of nucleic acid bases to enhance optical properties of dyes, so that applications of DNA as materials are now possible in such areas as photonics, separation process or biomedical materials. Recent research results on DNA-lipid complexes have shown various attractive applications such as E/O or O/E devices, optical memories, switches and sensors1-4. It was reported2 to study on possibility of basic optical characteristics, such as refractive indices, absorbance and fluorescence intensity, and photochromic properties, of spiropyran-doped DNA-cetyltrimethylammonium (CTMA) complex films, which were derived from DNA from Salmon, which showed potential applications to optical switches5, 6. Although DNA-lipid complexes showed promising potentials for optical functional devices such as switching or signal processing devices, their response speeds were relatively slow to apply them to practical uses. It was shown5, 6 that much faster response speed (switching times) could be attained by increasing the excitation light intensity. Thus, applications of DNA photonic devices have been widely studied in the world7-10

The large enhancements of optical properties of the dye-intercalated DNA lead us to apply the dye-intercalated DNA as various sensors with a high sensitivity to detect environmentally toxic gases such as dioxine, NOx or carbon monoxide. This paper retorts on DNA sensors for the further applications of DNA as materials. Also, bio-medical applications of DNA sensors such as alcohol or glucose sensors will be reported.

References

8103-02, Session 1

BiOTFT memory with DNA complex
N. Kobayashi, T. Yikimoto, K. Nakamura, Chiba Univ. (Japan); S. Uemura, H. Kamata, National Institute of Advanced Industrial Science and Technology (Japan)

No abstract available

8103-03, Session 1

Novel DNA-cationic lipid complexes and their application as gate dielectrics
L. Cui, Univ. of Connecticut (United States); X. Wei, Case Western Reserve Univ. (United States); L. Zhu, Univ. of Connecticut (United States)

In this study, we report molecular shape and size effects of lipid tails on the mesophase self-assembly of various cationic lipids complexed with double-stranded DNA. The molecular shape of the cationic lipids changes from rod-like (a cyanobiphenyl imidazolium salt) to discotic (a triphenylene imidazolium salt), and finally to cubic [a polyhedral oligomeric silsesquioxane (POSS) imidazolium salt]. An increase in the cross-sectional area of the hydrophobic tails with respect to the hydrophilic imidazolium head induces a negative spontaneous curvature of the cationic lipids. As a result, a morphological change from lamello-columnar phase for the DNA-cyanobiphenyl imidazolium salt (DNA-rod) and DNA-triphenylene imidazolium salt (DNA-disk) complexes to an inverted hexagonal phase for the DNA-POSS imidazolium salt (DNA-cube) complex is observed. The DNA-rod complex has a typical smectic A (SmA) lamellar morphology, while the DNA-disk complex has a double lamello-columnar phase. However, when the lipid tail changes to POSS, an inverted hexagonal morphology is achieved. Their application as the gate dielectrics in transistors will be briefly introduced.

8103-04, Session 1

Biopolymers-based gate insulators for BioFETs
F. Ouchen, Air Force Research Lab. (United States); P. P. Yaney, Univ. of Dayton (United States); C. M. Bartsch, E. M. Heckman, M. B. Dickerson, J. G. Grote, Air Force Research Lab. (United States)

No abstract available

8103-05, Session 2

Photophysical properties of lanthanide(III) chelates-doped DNA-CTMA complex
K. Nakamura, A. Sagara, N. Kobayashi, Chiba Univ. (Japan)

No abstract available
Metal incorporated M-DNA: structure, magnetism, optical absorption
K. Mizoguchi, Tokyo Metropolitan Univ. (Japan)
No abstract available

Optical and electrical properties of DNA-CTMA biopolymers in Metal-Biopolymer-Metal photodetectors
B. Zhou, Univ. at Buffalo (United States); S. J. Kim, Univ. of Miami (United States); C. M. Bartsch, E. M. Heckman, F. Ouchen, Air Force Research Lab. (United States); A. N. Cartwright, Univ. at Buffalo (United States)
The application of a DNA biopolymer into an electro-optic device is investigated. Specifically, a complex of DNA with cationic surfactant hexadecyltrimethylammonium chloride (CTMA) is used to obtain organosoluble DNA material. In order to increase the electrical conductivity of the DNA biopolymer, PEDOT:PSS is added to DNA-CTMA. Optical and electrical conductivity properties of the DNA-CTMA and DNA-CTMA-PEDOT are investigated. CW absorbance and time-resolved photoluminescence of the resulting DNA samples were studied experimentally. Both DNA samples demonstrated absorbance peaks at ~260 nm and photoluminescence at ~470 nm. The PEDOT doped DNA polymer shows shorter lifetime (260 ps) than the undoped DNA biopolymer, which may be indicative of charge transfer from the DNA-CTMA to the PEDOT in the composite biopolymer. Interestingly, the PL lifetime was observed to decrease in both cases with increasing excitation in an air ambient. Specifically, after excitation with a high power ultrafast (~150 fs) UV (266 nm) pulse in air, the lifetime decreases dramatically after a few minutes of exposure. This is most likely due to photo-oxidation that results in trap creation on the polymer surface and an increase in the non-radiative recombination. In order to investigate the photocurrentivity, metal-biopolymer-metal (MBM) ultraviolet photodetectors with interdigitated electrodes were fabricated. The optical responsibility of these MBM UV photodetectors increased as the electron transport length (the space between the MBM fingers) were decreased to the nano-scale. Prospects for the use of these materials in optical devices will be discussed.

Modeling of stochastic kinetics for process of photochromic dye semi-intercalation into DNA-based polymeric matrix
A. C. Mitus, G. Pawlik, J. Mysliwiec, A. Miniewicz, Wrocław Univ. of Technology (Poland); J. G. Grote, Air Force Research Lab. (United States)

DNA architectures for templated material growth
A. S. Finch, J. Sumner, U.S. Army Research Lab. (United States)
We will present a methodology that allows for the coupling of biology and electronic materials, where double stranded DNA serves as a template for electronic material growth. Self-assembled DNA structures allow for a variety of patterns to be achieved on the nanometer size scale that are difficult to achieve using conventional patterning techniques. Herein, we describe the procedures for the creation of self-assembled DNA nanostructures in aqueous and non-aqueous media, and their subsequent deposition onto substrates of interest. DNA self assembly under non-aqueous conditions has yet to be presented in literature, and is necessary if unwanted oxidation of certain electronic substrates is to be avoided. Solubilization of the DNA in non-aqueous solvents is achieved by replacing charge stabilizing salts with surfactants. Retention of DNA hierarchical structure under both conditions will be presented by observing the structures using AFM imaging, gel electrophoresis, and circular dichroism spectroscopic studies.

Morphological and physical properties of graphene/DNA layered bio-nanocomposites
Z. Bai, Univ. of Dayton Research Institute (United States); T. D. Dang, S. N. Kim, R. R. Naik, Air Force Research Lab. (United States)
No abstract available

Evanescent field excitation of Cy5-conjugated lipid bilayers using optical microcavities
L. M. Freeman, The Univ. of Southern California (United States) and Univ. of California, San Diego (United States); Y. Dayani, S. Li, H. Choi, N. Malmstadt, A. M. Armani, The Univ. of Southern California (United States)
Whispering gallery mode optical microresonators are devices used for performing ultra-sensitive optical detection. Although the majority of the sensor research has been focused on label-free detection strategies for diagnostics, a whispering gallery mode device is ideally suited to perform fluorescent label-based biodetection as well. However, previous research using optical microcavities to excite fluorescent molecules has focused
on cavity quantum electrodynamics applications and fundamental studies of the interactions of large fluorescent nanoparticles with the resonant cavity.

In the present work, a method for forming self-assembled lipid bilayers, a mimic for cell membranes, on a spherical microresonator is developed. Solid-supported lipid bilayers, which are approximately 5nm thick, have been shown to accurately model cell membranes, and researchers use lipid bilayers in combination with fluorescent microscopy when developing theoretical models for the transport of molecules across the cell membrane. The bilayer-nature is verified using both fluorescent resonance energy transfer and fluorescence recovery after photobleaching. The evanescent tail of the microresonator is used to excite a Cy5-conjugated lipid located within the bilayer while the underlying optical device behavior is characterized at 633nm and 980nm. The emission wavelength of the Cy5 dye and the optical performance (Q factor) of the microcavity agree with theoretical predictions.

8103-12, Session 4
**Influence of DNA on J-aggregate formation of cyanine dyes**
Y. Kawabe, S. Kato, Chitose Institute of Science and Technology (Japan)

DNA plays an important role for the enhancement of luminescence from some organic dyes. On the other hand, interaction of dyes with DNA sometimes stimulates the formation of dye aggregates in solutions and solid films.

Studying the absorption and circular dichroic (CD) spectra for the solutions of PIC coexisting with DNA and polyvinylalcohol in aqueous solutions, we found that J-aggregates of pseudo-isocyanine (PIC) were formed with lower dye concentration than ever. The details of the effects from the dye concentration, the ratio to DNA, and the type of counter ions were investigated and optimized. One example is that J-aggregate peak has the largest magnitude when the molar ratio of DNA base pair/ PIC was 1/4. The J-aggregate characteristics were reproduced after fabricating films from the solution, the fact would be important for development of devices.

More than 20 types of water soluble cyanine dyes were studied by the same methods. Most of dyes show aggregates (not always J-aggregates) by interacting with small amount of DNA, and these aggregates dissociated with the addition of excess DNA. Concentration dependences of photoluminescence intensity and CD spectra suggest that the optical characteristics are strongly influenced by molecular size. Mechanism of dye-DNA interactions will be discussed.

8103-14, Session 4
**Photodegradation of melanin thin films by UV lithography**
C. W. Farley III, A. Kassu, A. Sharma, Alabama A&M Univ. (United States)

Effect of ambient humidity on the photodegradation of melanin is investigated using an interferometric technique to fabricate gratings on thin films. A low power 355 nm diode laser is used to fabricate gratings on melanin thin films, while a 1 mW He-Ne laser is used to probe grating formation. Effects at several different UV intensities, ranging from 1 mW to 30 mW, and ambient humidities, ranging from 15% to 98%, are investigated on melanin thin films of two different thicknesses: 22 nm and 40nm. It is found that humidity has a significant effect on the rate of photodegradation of melanin. It is also found that existing gratings on melanin thin films can be enhanced by raising ambient humidity. These results have implications in the biological evolution of many mammals; as well as implications in fabrication and effective lifetime oforganic electronics. The interferometric technique used shows great promise for fabricating grating to analyze photodegradation of different biomolecules under varying conditions. A simple mathematical model is also developed to help explain the contribution of light intensity and ambient humidity to the photodegradation of melanin.

8103-15, Session 4
**Fluorescence study on DNA based thin films with synthetic and natural chromophores**
I. Rau, A. Tane, Polytechnical Univ. of Bucharest (Romania); C. Andraud, Ecole Normale Supérieure de Lyon (France); A. Meghea, Polytechnical Univ. of Bucharest (Romania)

No abstract available

8103-16, Session 5
**Studies of charge transport in DNA films using the time-of-flight (TOF) technique (Keynote Presentation)**
P. P. Yaney, T. Gorman, Univ. of Dayton (United States); F. Ouchen, J. G. Grote, Air Force Research Lab. (United States)

Measurements were carried out on a variety of DNA-based films, including as-received DNA (molecular weight, MW>1000 kDa), DNA with MW<1000 kDa and DNA doped with conductive additives. The test specimens were spin-coated or drop-cast films on ITO-coated quartz slides with a gold charge-collecting electrode. To protect the films from atmospheric influences, the TOF devices were coated with a ~200 nm polyurethane passivation layer. A quadrupled 10 ns, pulsed Nd:YAG laser with output at 266 nm was used for charge injection. The photoconductive responses ranged from mildly to strongly dispersive with hole mobilities in DNA materials films ranging between 7E-6 to 7E-5 cm2/V-s.

8103-17, Session 5
**DNA-assisted fabrication of luminescent and Raman active silver nanoparticles for dual-modal bioimaging**
K. Ijiri, G. Wang, T. Nishio, K. Nambara, Y. Matsu, K. Niikura, Hokkaido Univ. (Japan)

No abstract available

8103-18, Session 5
**Keynote Presentation**
R. Zamboni, Consiglio Nazionale delle Ricerche (Italy)

No abstract available

8103-19, Session 5
**Bio-dielectrics based on DNA-Ceramic hybrid films for potential energy storage applications**
N. Venkat, Univ. of Dayton Research Institute (United States); D. Joyce, F. Ouchen, Air Force Research Lab. (United States); P. P. Yaney, Univ. of Dayton (United States); K. M. Singh, Air Force Research Lab. (United States); T. Miller, UES, Inc. (United States); S. R. Smith, Univ. of Dayton Research Institute (United States); J. Meghea, Polytechnical Univ. of Bucharest (Romania)

No abstract available
G. Grote, R. R. Naik, Air Force Research Lab. (United States)

The potential of DNA-based dielectrics for energy storage applications was explored via the incorporation of high dielectric constant (ε) ceramics such as TiO2 and BaTiO3 in the DNA-bio-polymer. The DNA-Ceramic hybrid films were fabricated from stable suspensions of the nanoparticles in aqueous DNA solutions. Dielectric characterization revealed that the incorporation of TiO2 rutile in DNA resulted in enhanced dielectric constant and decreased dielectric loss factor (tan δ) relative to DNA in the entire frequency range of 1 kHz-1 MHz. Variable temperature dielectric measurements, in the 20-80°C range, of both DNA-TiO2 and DNA-BaTiO3 films revealed that the ceramic additive stabilizes DNA against large temperature-dependent variations in both ε and tan δ. The bulk resistivity of the DNA-Ceramic hybrid films in the case of both TiO2 and BaTiO3 additives was measured to be two to three orders of magnitude higher than that of the control DNA films, indicating their potential for utilization as insulating dielectrics in capacitor applications. Results based on a comparison of the temperature-dependent dielectric behavior of DNA and DNA-CTMA complex films as well as their frequency-dependent polarization behavior are also discussed.

8103-20, Session 6

Origin of dielectric tunability in DNA-CTMA film at microwave frequencies

R. S. Aga, Jr., General Dynamics Information Technology (United States); C. M. Bartsch, Air Force Research Lab. (United States); B. Telek, G. Subramanyam, Univ. of Dayton (United States); E. M. Heckman, J. G. Grote, Air Force Research Lab. (United States)

No abstract available

8103-21, Session 6

Effective bio-imaging using two-photon absorbing nanoparticles

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

This presentation discusses the synthesis and use of nanoparticles with two-photon absorption for bioimaging. We present the synthesis of two-photon chromophores capable of forming fluorescent nanoparticle in the aggregated state. These chromophores are further complexed with materials like polysiloxane and phospholipids to aid their transport to and penetration of tumor cells. Derivatives of 4-bis(cyanostyryl)benzene (CSB)-based quadrupolar isomeric molecules (a- and b-CSB-TPs) were developed, owe to a general strategy recently established in the group.1 The second part will focus on new “cargo” systems that we have recently developed, with an accent put on the establishment of structure/ properties relationships

1/ Relatively few two-photon chromophoric structures that can efficiently sensitize singlet oxygen have been reported so far. Thus, we believe that molecular engineering has to be performed, with an accent put on the establishment of structure/properties relationships

2/ Two photons chromophores require a large conjugated carbon backbone, which makes them very hydrophobic compounds: chemical modification have therefore to be carried out, in order to allow their dispatching within the physiological medium, and cellular up-take.

These two aspects will be discussed in our presentation. The first part will deal with recent results in our group concerning the structural optimization of chromophores for two-photon induced dynamic therapy. The second part will focus on new “cargo” systems that we have recently developed, owing to a general strategy recently established in the group.1


8103-22, Session 6

Two-photon absorbing chromophores for photodynamic therapy: molecular engineering and in vivo applications

C. Monnereau, Univ. de Nantes (France); P. Lanoë, Univ. de Rennes 1 (France); T. Gallavardin, O. Maury, C. Andraud, Ecole Normale Supérieure de Lyon (France)

Photodynamic therapy (PDT) is a therapeutic approach based on the light induced production of cytotoxic molecular singlet oxygen, through irradiation of a photosensitizer near a tumoral tissue. In recent years, it has been used with success in the treatment of certain cancers and gliomas at their early stages; however, it suffers from one major limitation that hinders a more widespread use in cancer therapy: due to biological absorption and scattering of the incident light, it is impossible to effectively activate a conventional photosensitizer through more than few millimeters of tissue, making non-invasive deep tissue and organ therapy practically impossible.

Two-photon activation of the sensitizers, using lasers with wavelengths around 800-900 nm could be a very advantageous strategy to overcome these limitations. This range of wavelengths corresponds to the domain of transparency of human tissues, which would allow deeper penetration of the light. Another advantage is the highly confocal character of two-photon excitation, leading to very localized sensitizer activation, which is ideal to avoid undesirable damages of healthy tissues in the tumor's surroundings.

In spite of all its promises, two-photons PDT is still in its infancy, and practical issues now have to be addressed:

1/ Relatively few two-photon chromophoric structures that can efficiently sensitize singlet oxygen have been reported so far. Thus, we believe that molecular engineering has to be performed, with an accent put on the establishment of structure/properties relationships

2/ Two photons chromophores require a large conjugated carbon backbone, which makes them very hydrophobic compounds: chemical modification have therefore to be carried out, in order to allow their dispatching within the physiological medium, and cellular up-take.

These two aspects will be discussed in our presentation. The first part will deal with recent results in our group concerning the structural optimization of chromophores for two-photon induced dynamic therapy. The second part will focus on new “cargo” systems that we have recently developed, owing to a general strategy recently established in the group.1


8103-23, Session 6

All optical switching in a photochromic dye-doped biopolymeric matrix

J. Mysliwiec, A. Malak, J. Sikora, A. Miniewicz, Wroclaw Univ. of Technology (Poland); I. Rau, Politechnical Univ. of Bucharest (Romania); F. Kajzar, Politechnical Univ. of Bucharest (Romania) and Univ. of Angers (France)

All optical switching has been studied using the Optical Kerr Effect (OKE) configuration in a biopolymer matrix containing a photochromic molecule. The biopolymer system consisted of a deoxyribonucleic acid blended with cationic surfactant molecule cetyltrimethyl-ammomium chloride suitable for optical quality thin film fabrication. The excitation beams inducing birefringence were delivered from a continuous wave lasers at 473 and 532 nm and chopped using a variable frequency chopper. Additionally auxiliary nanosecond pulses coming from Nd:YAG laser were used. The birefringence was instantaneously monitored by a weak non-absorbed light from a cw He-Ne laser working at 632.8 nm under crossed polarizer system. An excellent switching times in the range
An Investigation on films used for chemcial and biological sensors

M. J. Curley, A. K. Chilvery, T. V. Kukhtareva, C. W. Farley, Alabama A&M Univ. (United States)

Bioterrorism as well as the use of explosive devices have been a key threat not only in Iraq and Afghanistan but also on the southern border of the United States. Biosensors as well as chemical sensors are mandatory in the field of sensing the existence of detrimental gases like methyl isocyanides, sensing the presence of bacteria’s like anthrax and detecting the presence of explosives like RDX, TNT’s etc. These biosensors combined with a low power lasers for remote sensing should be able to be used for biological and chemical detection. In this paper we also mentioned the importance of study of micro-organisms in the synthesis of nanomaterials is a possible viable alternative to the more popular physical and chemical methods currently in use. We shall discus the development of green and energy saving technologies in materials synthesis, environmentally caring nanoparticle synthesis processes that do not use toxic chemicals. Optimizing the characteristics and fabrication of biosensors with different nanoparticles for selective and sensitive detection will be performed. Testing using the method of Stimulated Emission Raman Scattering (SERS), FTIR, SEM and AFM measurements in our laboratories shall be disclosed. We have also investigated the presence of two photon compounds and Rhodamine B to determine if the prototype sensor will amplify the signals of biological agents as well as explosives. The results in this paper are promising in developing a Chemical and Biological sensors for the use in the Department of Defense, USDA and commercial applications.

N. Radu, Institutul National de Cercetare (Romania); M. Ferdes, Polytechnical Univ. of Bucharest (Romania); C. Corobea, D. Donescu, Institutul National de Cercetare (Romania); I. Rau, Polytechnical Univ. of Bucharest (Romania)

Monascorubrin obtained in submerged media from Monascaceae family can be used as biomaterials, in order to obtain nanoproducts with therapeutic properties. In this respect, using soluble monascorubrin obtained in submerged media and isopropylmitristate as conditioning agent, nanodispersions was obtained, with dimensions under 100 nm (determined by dynamic light scattering). The first preclinical tests performed on the main raw materials revealed that these nanodispersions could be used as adjuvant in skin disorders having an important role in tissular reparation in case of derma lesions.

Spiro-6, Poster Session

Characterization of some nanamaterials based on insoluble fungal poliketide

N. Radu, Institutul National de Cercetare (Romania); M. Ferdes, Polytechnical Univ. of Bucharest (Romania); C. Corobea, D. Donescu, Institutul National de Cercetare (Romania); I. Rau, Polytechnical Univ. of Bucharest (Romania)

Biopigments obtained in solid state biosynthesis was used as raw materials in order to obtain bioproducts used in the dermatology treatment. The main formulation was nanomaterials with dimensions under 60 nm according to dynamic light scattering measurements. The new nanoproducts which contain three biopigments biosynthesized on rice were characterised by fluorescence diffraction, FT-IR and mass spectrum, and the results indicate the presence in the nanoproduct of main poliketide based on monascorubrin and monascorubramin.

In this paper the main results concerning characterisation and possible applications of these new nanoproducts will be presented and discussed.
8104-01, Session

Green nanotechnology (Keynote Presentation)
G. B. Smith, Univ. of Technology, Sydney (Australia)

Nanotechnology, in particular nanophotonics, is proving essential to achieving green outcomes of sustainability and renewable energy supply at the scales needed. Coatings, composites and polymeric structures used in windows, roof and wall coatings, energy storage, insulation and other components in energy efficient buildings will increasingly involve nanostructure, as will solar cells. Nanostructures have the potential to revolutionize thermoelectric power and hence solar thermal power, and may one day provide efficient refrigerant free cooling.

The problem is that on terrestrial surfaces today, as well as in space, this is not the case. Nanomaterials enable us to optimize optical, opto-electrical and thermal responses to this urgent task. Optically harmonization of material responses to environmental energy flows involves two aspects, large changes in spectral response over limited wavelength bands and tailoring responses to environmental dynamics. The latter includes engineering angle of incidence dependencies and switchable (i.e chromogenic) responses. Nanomaterials can be made at sufficient scale and low enough cost to be both economic and to have a high impact on a short time scale. Issues that must be addressed however include human safety, plus property changes induced during manufacture, handling and use outdoors. Some unexpected multiple bonus’ have arisen in this work, for example the savings and environmental benefits of cool roofs may one day provide efficient refrigerant free cooling.

In addition to its high-throughput capability, NSL permits fabrication of devices on surfaces that are difficult to work with electron/ion beam techniques. Nanostencil lithography is a resist free process thus allows the transfer of the nanopatterns to any planar substrate whether it is conductive, insulating or magnetic. As proof of the versatility of the NSL technique, we show fabrication of plasmonic structures and metamaterials in a variety of designs on traditional and unconventional substrates. High-resolution Nanostencil Lithography enables plasmonic substrates and metamaterials supporting spectrally narrow far-field resonances with enhanced near-field intensities. Overlapping these collective plasmonic resonances with molecular specific absorption bands can enable ultrasensitive vibrational spectroscopy. We will also present our recent results on spectroscopic identification of proteins with antenna arrays fabricated by nanostencil lithography.


8104-04, Session 1

High-throughput nanofabrication of plasmonic structures and metamaterials with high resolution nanostencil lithography
S. Aksu, A. A. Yanik, R. Adato, A. A. Artar, M. Huang, H. Altug, Boston Univ. (United States)

In this talk, we will demonstrate a novel fabrication approach for high-throughput fabrication of engineered infrared plasmonic antenna arrays and metamaterials with high resolution nanostencil lithography (NSL). NSL technique, relying on deposition of materials through a shadow mask, offers the flexibility and the resolution to fabricate radiatively engineered nanoantenna arrays for excitation of collective plasmonic resonances. Spectral measurements and electron microscopy images faithfully confirm the feasibility of NSL technique for large area patterning of nanorod antenna arrays, plasmonic dimers (such as bowties) and metamaterials with high resolution that is achievable by electron-beam lithography. Furthermore, we show nanostencils can be reused multiple times to fabricate same structures with identical optical responses repeatedly and reliably. This capability is particularly useful when high-throughput replication of the optimized nanoparticle arrays is desired. In addition to its high-throughput capability, NSL permits fabrication of devices on surfaces that are difficult to work with electron/ion beam techniques. Nanostencil lithography is a resist free process thus allows the transfer of the nanopatterns to any planar substrate whether it is conductive, insulating or magnetic. As proof of the versatility of the NSL technique, we show fabrication of plasmonic structures and metamaterials in a variety of designs on traditional and unconventional substrates. High-resolution Nanostencil Lithography enables plasmonic substrates and metamaterials supporting spectrally narrow far-field resonances with enhanced near-field intensities. Overlapping these collective plasmonic resonances with molecular specific absorption bands can enable ultrasensitive vibrational spectroscopy. We will also present our recent results on spectroscopic identification of proteins with antenna arrays fabricated by nanostencil lithography.

on a chip was filled, irradiating the laser of the wavelength of 785 nm. Photocauterous measurement was also done on the chip, irradiated with the laser, of which intensity was modulated sinusoidally.

The local plasmon resonator with high absorption heats up the water on itself higher and generates stronger photoacoustic signal than that with low absorption. Furthermore, the photocauterous signal from the local plasmon resonators with high absorption is stronger than that from an Ag thin film by two orders of magnitude between 50 kHz and 100 kHz. These results suggest that heat generation from the Au nanoparticle layer can be spatiotemporally controlled by the interference and incident light intensity.


8104-06, Session 1

Monitoring the reactivity of Ag nanoparticles for different atmospheres by using in situ and real time optical spectroscopy

V. V. Antad, L. Simonot, D. Babonneau, S. Camello, F. Pailloux, P. Guérin, Univ. de Poitiers (France)

Surface differential reflectance spectroscopy (SDRS), an optical characterization technique, is sensitive enough to observe the minute changes in surface plasmon resonance (SPR) of noble metal nanoparticles (NPs), which is a collective oscillation of the electrons owing to their interactions with electromagnetic radiations, causing sharp absorption of light in the visible range. This SPR is extremely sensitive not only to the morphology and organization of the noble metal NPs but also to the chemical atmosphere surrounding them.

Hence, taking SPR as a signature phenomenon in the Ag NPs, we have studied their reactivity for different gases and their ions using an optical mean. For this purpose, a dedicated in-situ SDRS set-up has been mounted on a magnetron sputtering machine, with which real time optical characterizations were possible not only during the deposition of Ag NPs but also during their exposure to gases such as O2, N2, Ar, either non-ionized or partially ionized.

This optical study reveals the reactivity of Ag NPs with non-ionized O2 in the form of changes in the SPR characteristics (width, amplitude and position of the absorption band) in contrast to N2 and Ar. Moreover, this study also elaborates the increased reactivity of Ag NPs due to the partially ionized gases where, on one hand, complete disappearance of the SPR can be seen in case of O2(+) and on the other hand, increased reactivity in Ag NPs can be seen for the N2(+) gas, whereas Ar remains non-reactive in both forms.

8104-07, Session 1

Surface plasmon resonance of super-periodic metal nano-slits structures

H. Leong, J. Guo, R. G. Lindquist, The Univ. of Alabama in Huntsville (United States)

We investigate surface plasmon resonance in super-periodic metal nano-slits arrays. A super-periodic metal nano-slits array consists of periodic metal nano-slits and periodic defects in the nano-slits array. Our simulation and experimental results show that spectral peaks measured in the zeroth order transmission and the first order diffraction reveal the surface plasmon resonances in the super-periodic metal nano-slits structure. The resonance wavelength can be tuned accordingly by adjusting the nano-slits period or the super-period of the device. The new metal nanostructure device functions as a resonant optical diffraction grating and can be used for integrated nano-fluidic surface plasmon sensors.

8104-08, Session 2

Nanostructure effects and the performance of optical interference coatings

O. Stenzel, U. Schulz, N. Kaiser, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany)

The theory of “classical” optical interference coatings is based on assumptions like ideal homogeneity and isotropy of the materials, as well as absolutely smooth and infinitesimally thin interfaces between the individual coating materials. Within the framework of these assumptions, there exists an elaborated theoretical apparatus for solving design and characterization tasks for optical coatings. At the same time, coating deposition techniques have been perfected in order to match with the requirements of homogeneity and smoothness of these coatings in practice.

Remaining discrepancies between the theoretically predicted and practically achieved coating performance can - at least partially - be attributed to the violation of the above-mentioned ideal assumptions. But a closer look on this matter reveals a more differentiated picture: Nanostructure effects can be tackled as additional degrees of freedom for coating design, and can lead to useful property combinations that are inaccessible to “classical” coatings prepared on the basis of the traditionally available coating materials.

This presentation deals with practical examples, where explicit violations of the usually assumed perfect homogeneity and smoothness of the coatings have resulted in novel and innovative coating material properties or coating designs. Examples include:

- Effects of noble metal islands embedded in semiconductor films: applications in photovoltaics
- Antireflection effects of nanostructured surfaces: motheye-structures
- Effects of nanoporosity in oxide films on refractive index, thermal shift and mechanical stress: balanced coating properties

The examples demonstrate the possible benefits of the exploitation of nanostructure-caused effects in interference coating science and technology.

8104-09, Session 2

Using a single anisotropic thin film as a phase retarder for oblique incident wave

Y. Jen, S. Wang, C. Lin, M. Lin, National Taipei Univ. of Technology (Taiwan)

This work presents a wide angle phase retarder by using a single anisotropic Ta2O5 columnar thin film. The single anisotropic Ta2O5 columnar thin film can provide phase retardation between p-polarization and s-polarization to modulate the polarization state of light reflected from the prism-coupling system (BK7 prism/anisotropic thin film/air). In experiment, glancing angle deposition technique is used to prepare single layer film of Ta2O5 tilted nanorod array with thickness 270nm. In this analysis, we use wave tracing based on the Berreman calculus to calculate the variations of reflection coefficient, transmission coefficient on the interface and the variations of phases of ordinary and extraordinary waves in the anisotropic thin film when the electromagnetic wave is incident to the prism-coupling system. The phase retardation is observed about ζ=100°(±5°) over the angle ranged from 61° to 75° and the wavelength ranged from 630nm to 680nm. A linearly polarized incident ray can be reflected as a specific elliptical polarized ray uniformly over the region. In addition, the phase retardation is varied smoothly over the designated range when the deposition plate is rotated from 90° to 45° with respect to the plane of incidence.
Quenched transmission of light through ultrathin metal films
N. A. Mortensen, S. Xiao, Technical Univ. of Denmark (Denmark)

It is well known that the transmission of light is prominent for an ultrathin metal film with the thickness comparable to its optical penetration depth. When the film is periodically modulated by subwavelength apertures, intuitively one expects that the ultrathin film could transmit even more light since less material is blocking the light. To much surprise, it was recently predicted by means of analytical and numerical calculations that the transmission can nevertheless be totally suppressed. This nontrivial phenomenon is opposite to the widely known extraordinary optical transmission of light through periodically modulated optical thick metal films, which was first reported by Ebbesen et al. Subsequently, the quenched transmission of light through ultrathin films pierced with periodic arrays of subwavelength apertures was experimentally demonstrated. In this paper, we experimentally demonstrate quenched transmission of light through ultrathin films when the films are periodically structured. We used E-beam lithography technology to fabricate the devices and free-space measurement setup to characterize them. The measured results show the transmission is significantly suppressed, which is an opposite phenomenon as compared with the extraordinary optical transmission of the light through the film when perforated by the subwavelength holes. We emphasize that the measurement demonstrates less light transmitted through the gold disks array. The physics behind it is also discussed and it turns out that this abnormal phenomenon is ascribed to the surface plasmon resonance effect.

Optical properties of UT-shaped plasmonic nanoaperture antennas
M. Turkmen, S. Aksu, A. E. Cetin, A. A. Yanik, H. Altug, Boston Univ. (United States)

The subject of light transmission through optically thin metal films perforated with arrays of subwavelength nanoholes has recently attracted significant attention [1]. In this talk, we will present numerical and experimental results on optical properties of a multi-resonant UT-shaped plasmonic nanoaperture antenna for enhanced optical transmission and near-field resolution. We will propose different structure designs in order to prove the effect of geometry on resonance spectrum and near-field enhancement. Theoretical calculations of transmission spectra and field distributions of UT-shaped nano-aperatures are performed by using three-dimensional finite-difference time-domain method [2]. The results of these numerical calculations show that transmission through the apertures is indeed concentrated in the gap region. In addition to theoretical calculations, we also performed a lift-off free plasmonic device fabrication technique based on positive resist electron beam lithography (EBL) and reactive ion etching in order to fabricate UT-shaped nanostructures. For further confirmation of the multi-resonant behavior, we checked the individual U- and T-shaped nano-aperture antenna responses. We also studied the parameter dependence of the structure to determine the control mechanism of the spectral response. Theoretical calculations are supported with experimental results to prove the enhanced field distribution and multi-resonant behavior which can be suitable for infrared detection of biomolecules, wavelength-tunable filters, optical modulators, and ultrafast switching devices.


Optical birefringence in a bideposited nanorod array with symmetric and periodic structure
Y. Jen, C. Yu, M. Lin, C. Lin, National Taipei Univ. of Technology (Taiwan)

A new kind of nanorod array grown with two orthogonal bideposited directions is fabricated and measured its birefringence optical property. The Ta2O5 nanorods arrays composed of several subdeposits are fabricated by serial bideposition (SBDD) technique. Each nanorod consists of several identical units and each unit consists of symmetrical sections ABA. The deposition planes for section A and section B are perpendicular to each other. The bideposited symmetric nanorod arrays can be equivalent to a homogeneous layer of the equivalent refractive index and phase thickness. For normal incident ray, the polarization-dependent refractive indices and phase thicknesses of the film are presented as functions of wavelength and optical constants of each layer. The transmittance spectra of symmetrical sections have a pass band property as the equivalent refractive indices are real. With each subdeposition thickness of 5 nm, samples bideposited at flux angles 65°, 70°, 75° and 80° are prepared. The principal indices associated with the two orthogonal polarizations are measured by ellipsometer. According to principal indices database, a phase retardation between the two orthogonal polarization directions can be designed for a specific wavelength. In order to apply the multilayered structure in changing the polarization state, a match layer is designed and arranged in the layered system to reduce the difference between the two orthogonal polarization transmissions.

Effective properties of metamaterials
C. Rockstuhl, C. Menzel, T. Paul, E. Pshenay-Severin, M. Falkner, C. Helgert, A. Chipouline, T. Pertsch, Friedrich-Schiller-Univ. Jena (Germany); W. Smigaj, J. Yang, P. Lalanne, Univ. Bordeaux 1 (France); F. Lederer, Friedrich-Schiller-Univ. Jena (Germany)

Optical properties of nanostructured thin films, i.e. metamaterials, are usually linked to the assignment of an effective permittivity and permeability and, if polarization conversion occurs, chirality. To consider the underlying constitutive relations as valid, it is required that only weak spatial dispersion occurs. At operational frequencies of optical metamaterials close to resonance this assumption ceases to be valid. In consequence, a description using effective material properties tends to be inadequate and new approaches are required. We outline here our latest achievements along this direction and discuss two approaches. The first assumes that if effective properties are pointless since they explicitly depend on the frequency and the incidence angle, a more primary source of information is sufficient to quantify metamaterials, i.e. the polarization resolved complex transmission and reflection; leading to a characterization of metamaterials in terms of Jones matrices. We discuss the implications of such description and show that all metamaterials can be categorized into five classes only, each supporting distinguishing properties which we disclose. Experimental results of measured complex Jones matrices of three-dimensional metamaterials underline the applicability of this approach. The second approach resort to an effective description but restricts its consideration entirely on a dispersion relation, characterizing the propagation of light in bulk metamaterials, and an impedance, characterizing the coupling of light into and from metamaterials to their surroundings. Feasible definitions of both properties linked to a single Bloch mode are discussed and metamaterials are introduced which can be homogenized while considering only the properties of this single mode.
8104-14, Session 3

On dipole emission from an infiltrated chiral sculptured thin film

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This study was motivated by the prospect of harnessing chiral sculptured thin films (CSTFs) as optical sensors based on chemiluminescent emission. A dipole source positioned inside a CSTF was considered. The void regions of the CSTF were filled with a fluid of refractive index greater than unity. The theory describing the emitted field far from the dipole source was developed, using a spectral Green function formalism. A combination of inverse and forward homogenization techniques were used to estimate the relative permittivity parameters of the infiltrated CSTF. This involved the extended Bruggeman homogenization formalism, which accommodates constituent particles that are small compared to wavelength but not vanishingly small. Our numerical studies, based upon a titanium oxide CSTF, revealed that left circularly polarized (LCP) light was preferentially emitted through one face of the CSTF while right circularly polarized (RCP) light was preferentially emitted through the opposite face, at wavelengths within the Bragg regime. A red shift in the centre wavelength for the preferential emission of LCP/RCP light took place as the refractive index of the infiltrating fluid increased from unity. Furthermore, this red shift was accentuated when the size of the constituent particles in the homogenization model was increased. In addition, as the refractive index of the infiltrating fluid increased from unity, the bandwidth of the preferential LCP/RCP emission regime was observed to decrease.

8104-15, Session 3

Homogenization of metallic metamaterials and electrostatic resonances

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It has been noted that the usual approaches for homogenization (e.g. Bruggeman) could lead to singularities when considering composites comprising materials with positive and negative permittivities. This situation is specifically encountered in the field of metamaterials, in particular in the visible range. The question then arises to understand if these resonances are just artifacts or possess, on the contrary, a clear physical meaning.

In this work, we study the homogeneous properties of a bidimensional structure that is made of a periodic set of metallic wires embedded in a dielectric host medium. The structure is considered in a region of wavelengths that are much larger than the period of the structure. The work comprises a theoretical part where we develop a two-scale approach to the homogenization of the structure. As it is the case for the common physical approach, it leads to an effective permittivity with strong (electrostatic) resonances as well. The theoretical results, and the presence of resonances, are confirmed by numerical computations based on a rigorous modal approach. In the numerical results we consider specifically the case of silver and gold nanowires, described by a dispersive negative permittivity. We show that the main parameters for the onset of resonances is the optical filling ratio of the structure. Keeping in mind the possibility of performing experiments, it is far easier to keep the geometrical filling ratio constant and to consider strongly dispersive materials in the range of wavelengths considered. Here, besides the crucial fact that they are widely used in nanotechnology, silver and gold nanowires comply with our needs in the visible region of the spectrum.

8104-16, Session 4

Engineering the optical response of hybrid plasmonic systems: fano resonances and applications for sensing

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We study the optical response of hybrid plasmonic systems composed of nanoparticles in strong interaction with a thin film. While the latter supports propagating surface plasmon-polaritons, the former supports localized plasmon resonances. Engineering the coupling between these two families of modes produces extremely sharp optical resonances - so-called Fano resonances - characterized by narrow spectral features and a very strong near-field enhancement. Furthermore, these features can be easily tuned by changing the geometry of the system: materials, film thickness, spacing between particles and film, or the shape of the particles. We show that it is possible to a large extent to determine a priori the spectral response of the coupled system, by analyzing the spectral responses of its individual components (i.e. the infinite film and the localized particles), in particular their modal overlap in the optical density of states space. With this approach, we design specific structures where individual particles, dipole antennas, or more complex arrangements of metallic nanoparticles are coupled to a metallic thin film. A conventional e-beam lithography followed by lift-off is used for their fabrication. Hybrid plasmonic systems prove extremely efficient for sensing: the strongly localized near-field associated with Fano resonances makes them very responsive to their environment and significantly enhances the figure of merit for sensing, when compared to individual structures such as isolated thin films or isolated nanoparticles.

8104-17, Session 4

Metamaterial and nanoplasmionic toolkit for spectroscopy and biosensing

H. Altug, Boston Univ. (United States)

No abstract available.

8104-18, Session 4

3D characterization of a TiO2-based photoanode for solar cells

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The performance of dye-sensitized (DSSC) and hybrid solar cells crucially depends on the structure of the photoanodes on the micro- and nanoscale. Transmission electron microscopy (TEM) is a good candidate for investigating such length scales, but the limitation of conventional TEM to extract only bi-dimensional information hinders our ability to have a full understanding of the three-dimensional structure and properties. We instead apply advanced TEM techniques to characterize a photoanode prototype, combining high resolution crystallographic studies with three-dimensional information obtained from dark field electron tomography. In this work we present the study of a TiO2-based photoanode where the titania layer has been produced via pulsed laser deposition. We employed a dual beam FIB (FEI Helios Nanolab) to prepare a cross-section of a polymer heterojunction solar cell based on said photoanode and acquired a tilt series in a FEI Tecnai F20 (200 kV acceleration voltage). The photoanode TiO2 layer is composed by small (10-20 nm) crystalline particles assembled in columnar aggregates, which constitute a forest-like film with high porosity. Such a hierarchical structure combines a large surface area with good electrical transport properties, leading to promising performance. The characterization provided information on...
surfaces and interfaces of the nanocrystalline titania, as well as a view of the fine scale cell architecture after the infiltration of the polymer hole transporter.

8104-19, Session 4

**Antireflective Nanostructured Thin Films and Their Applications in Solar Cells**

J. He, National Taiwan Univ. (Taiwan)

It is of current interest to develop the antireflection (AR) coatings with nanowire arrays (NWAs) since the ability to suppress the reflection over a broad range of wavelengths and incident angles plays an important role in the performance of optoelectronic devices, such as photodetectors, light-emitting diodes, optical components, or photovoltaic systems. Superior AR characteristics of NWAs, including polarization-insensitivity, omnidirectionality, and broadband working ranges are demonstrated in this study. These advantages are mainly attributed to the subwavelength dimensions of the NWAs, which make the nanostructures behave like an effective homogeneous medium with continuous gradient of refractive index, significantly reducing the reflection through destructive interferences. The relation between the geometrical configurations of NWAs and the AR characteristics is discussed. We also demonstrated their applications in solar cells. This report paves the way to optimize the nanostructured optoelectronic devices with efficient light management by controlling structure profile of nanostructures.

8104-20, Session 4

**Microspot surface enhanced fluorescence biosensing from sculptured thin films**

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Nano-sculptured thin films (STF) are prepared by the glancing angle deposition technique and take different forms of nano columnar structures. Varieties of STFs are investigated to find the optimum structure for biosensing based on the surface enhanced fluorescence (SEF). Comparative study is presented from STFs containing variety of nano structures different in their shape, height (h), tilt angle with respect to the surface (θ), thickness (d), arrangement, etc. The highest enhancement factor of the fluorescent signal is found for Ag based STFs on Si(100) giving an enhancement factor of x71, where h=400nm, d=75nm, ≈230 relative to Ag closed film using fluorescent dye Rhodamine 123. Based on this a demonstration of an E. coli bacteria sensor and fluorescent antibody sensors are presented. Bound antibody to the thiol self assembly monolayer on sample surface is then quantified by means of the fluorescent signal. Upon excitation of the fluorophore by Hg source light, a CCD camera with a controlled exposure time detects the pattern of fluorescent antibody/Ecoli bacteria colonies on the STF surface. A fiber optic holder attached to the microscope allowed quantitative measurement of the fluorescence spectrum on a microspot.

8104-21, Session 5

**Intimate effects of surface functionalization on biosensing performances with porous silicon microcavities**

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We study the effect of different surface functionalization methods on the sensing performances of porous silicon (PSi) microcavities when used for detection of various biomolecules. Previous research on porous silicon demonstrated versatility of these devices for sensor applications based on their photonic responses. The interface between biological molecules and the Si semiconductor surface is a key issue for improving biomolecular recognition in these devices.

PSi microcavities were fabricated to reveal reflectivity pass-band spectra in the visible and near-infrared domain. To assure uniform infiltration of proteins the number of layers of Bragg mirrors was limited to five, the first layer being of high porosity. In one approach the devices were thermally oxidized and functionalized to assure covalent binding of molecules. Secondly, the as etched PSi surface was modified with adhesion peptides isolated via phage display technology and presenting high binding capacity for Si. Functionalization and molecular binding events were monitored via reflectometric interference spectra as shifts in the resonance peaks of the cavity structure due to changes in the refractive index when a biomolecule is attached to the large internal surface of PSI. Improved sensitivity is obtained due to the peptide interface linkers between the PSI and biological molecules compared to the silanized devices. We investigate the formation of peptide-Si interface layer via vibrational FTIR spectroscopy, X-ray photoelectron spectroscopy and atomic force microscopy. When monitored via fluorescence and biphoton microscopy we observe that PSI microcavity structures strongly confine and localize light emission resulting in enhanced photoluminescence of the infiltrated molecules.

8104-22, Session 5

**Infiltration of Fe3O4-nanoparticles into porous silicon with respect to magnetic interactions**

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Mesoporous silicon (PS) is used as matrix for infiltration of Fe3O4 nanoparticles (5 and 8 nm). The structure and magnetic behaviour of such composites are investigated and a correlation between the morphology of the nanocomposite (structure of the matrices, size and distribution of Fe3O4 particles) and the magnetic properties of the system is figured out. Magnetic exchange interaction is excluded due to capping of the particles. This system shows a superparamagnetic (SPM) behaviour at room temperature and becomes ferromagnetic (FM) at lower temperatures. The transition temperature between SPM and a blocked state depends on the particle size, their coating and on their magnetic interactions. Dipolar coupling between the particles can be influenced by varying the PS morphology as well as by the filling factor. The blocking temperature (TB) of the composite is tunable and changes due to the variation of dipolar coupling of the Fe3O4-particles (distance between particles). To gain deeper information about the stoichiometric homogeneity and spatial distribution, dual electron energy loss spectroscopy is employed. This method provides areal and volumetric densities of each element over the investigated area. Electron tomography, a method to get full 3D characterization in the nanometer scale, is utilized whereas from reconstructions various parameters of the composite morphology can be obtained (size and spatial distribution of the particles and dependence of the local curvature of the pore walls with respect to the preferred docking site). These results together with the magnetic data lead to a more detailed knowledge of the Fe3O4/silicon nanocomposite system.
8104-23, Session 5

Controlled skeletal progenitor cell migration on nanostructured porous silicon/silicon micropatterns

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Nanostructured porous silicon (nanoPS) shows photoluminescence and wide-scale adaptable wettability as a result of its particular surface morphology and chemistry. These properties can be simultaneously exploited for the preparation of surface micropatterns to mimic cellular function. Surface patterns of nanoPS and Si can be engineered through high-energy ion-beam irradiation and subsequent anodization. Human skeletal progenitor cells are sensitive to one- and two-dimensional patterns and focal adhesion is inhibited on nanoPS areas. In spite of this anti-fouling characteristics, studies on patterns with reduced Si areas show that cells conform to nanoPS pathways favoring migration through cell protrusion, body translocation and tail retraction from two parallel Si traction rails. Moreover, migration can be blocked and cells tend to arrange when grid patterns with the appropriate dimensions are fabricated. The experimental results confirm that progenitor cells are able to exploit nanoPS anti-fouling designs by adapting to it for migration purposes.

8104-24, Session 5

Nanostructured porous silicon dioxide films as substrate for on-chip visible light photonic devices

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A variety of photonic devices are available at telecom wavelengths, implemented using on-chip silicon (n=3.5) waveguides where silicon oxide (n=1.5) can serve as a lower index substrate with sufficient contrast. However, waveguides made of materials suitable for visible light (e.g. silicon nitride n=1.9) can become lossy on top of oxide especially when the mode index is reduced by confinement. A Si-photonics compatible low index substrate can enable realization of on-chip photonic devices in the visible range.

We have developed a porous silicon dioxide substrate with exceptionally small pore sizes and low solid filling fraction. The index can be less than 1.2 while maintaining less than 2nm RMS surface roughness over thicknesses up to 10 micron. The films are generated by electrochemical etching of silicon in acid/organic solution. Thickness, porosity, and pore size can be controlled by adjusting voltage, time, and solvent concentration. To obtain filling fractions as low as 15% we repeatedly oxidize and chemically remove the surface layer of silicon inside the pores network. Finally, the substrates are fully oxidized at high temperature to convert the remaining silicon network into silicon dioxide. The smoothness and small pore size enables subsequent fabrication of devices on the substrate with very little interface scattering. While other low index geometries (such as aerogel and nanowire) have limited functionality due to surface roughness and processing, our easy to fabricate, fully Si-photonics and bio compatible substrates allow implementation of chip level visible wavelength devices such as single mode waveguides or transformation optics.

8104-25, Session 5

Investigation of the interfaces of a metal/porous silicon nanocomposite and its influence on the physical properties

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Metal-nanostructures are electrochemically deposited within the pores of porous silicon to achieve a hybrid material with specific magnetic properties. The metal structures can be precipitated with various geometries and different spatial distributions depending on an accurate control of the deposition conditions. This method allows to deposit structures as spheres, ellipsoids or wires with a size up to a few micrometers whereas the diameter corresponds to the pore-diameter. Furthermore small Ni-particles between 3 and 6 nm can be deposited in a densely packed arrangement on the pore walls forming a quasi metal tube. Analysis of this tube-like arrangement by transmission electron microscopy shows that the distribution of the Ni-particles is quite narrow, which means that the distance between the particles is smaller than 10 nm. Such a close arrangement of the Ni-particles assures magnetic interactions between them. Due to their size these small Ni-particles are superparamagnetic but dipolar coupling between them results in a ferromagnetic behaviour of the whole system. Moreover, to investigate the interface in more detail electron energy loss spectroscopy is employed, whereas in using multiple linear least square fitting procedure, EELS fine structure and absolute edge energy information can be added to map the oxygen bounded in different phases (SiOx, metal-oxide). Magnetic measurements show an anisotropy between easy axis and hard axis magnetization which corresponds to the behaviour of a metal tube. This composite is an interesting candidate for integrable magnetic and magneto-optic devices and also for spin-injection from a ferromagnetic metal into silicon.

8104-40, Poster Session

Nanostructured Lu2O3:Eu3+ phosphor thin film

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Nowadays oxide scintillating films are considered as promising materials for digital medical imaging. Lu2O3:Eu3+ is an inorganic scintillator which was introduced as one of the most perspective material for X-ray detectors due to excellent scintillation properties, chemical stability as well as high light conversion efficiency (approximately 80 % of CsI:TI). To obtain thin films of high optical quality possessing spatial resolution in the submicron range the uniform, smooth phosphor layers free from pores and cracks are necessary. Different methods are known to produce close-packed thin films [1]. Sol-gel technology is one of the most promising approaches to obtain nanostructured, transparent films with controlled thickness and homogeneous distribution of activator in the phosphor lattice [2,3]. The aim of this study is to obtain and characterize nanostructured Lu2O3:Eu3+ films with submicron thickness.

Simple sol-gel method has been used to fabricate homogeneous, transparent Lu2O3:Eu3+ (Eu3+=5 at. %) films with thickness in the 200-1200 nm range (1 - 6 layers) on sapphire substrates. The film morphology and structure has been studied by atomic force microscopy, scanning and transmission electron microscopy. The formation conditions of homogeneous films with average crystallite size of 10-50 nm have been determined. The luminescent properties of Lu2O3:Eu3+ films depending on annealing temperature and their thickness have been studied.

8104-41, Poster Session

**A double positive thin film comprising silver-pillar arrays at visible wavelengths**

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A thin film comprising silver-pillar arrays is deposited on a glass substrate by continuously rotating the substrate about its normal via glancing angle deposition. During deposition the rotation speed and the deposition rate are kept at 10 rpm and 1 nm/s, respectively. The deposition angle of 89 degree with respect to the substrate normal is chosen due to the fact that the lager deposition angle results in the higher porosity of the film. Here we use the effective-medium theory to investigate the magnetic responses in a pair of silver pillars. The simulated result shows that the conduct and displacement currents are induced as the applied electric field is perpendicular to the major axis of the pillar at normal incidence. A larger overlapping of the length of the pillars causes a stronger magnetic field, leading to the larger positive real part of the equivalent permeability of the film. Walk-off and polarization interferometers are employed in measuring the transmission and reflection coefficients of a 230nm-thick silver-pillar arrays film with a diameter of 175 nm in the visible regime. Experiment result shows its real parts of the equivalent permeability and permittivity are 2.441 and 0.846 at a wavelength of 639 nm, respectively. Together with our previous study, it is possible to grow metamaterials covering the whole quadrant in the permittivity-permeability diagram at visible wavelengths.

8104-42, Poster Session

**Tungsten nanostructured thin films obtained via HFCVD**

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By using the Hot Filament Chemical Vapor Deposition (HFCVD) technique tungsten thin films were deposited on both amorphous quartz and silicon substrates. To achieve this, a tungsten filament was heated at 1500 oC during one hour maintaining a constant pressure of 460 mTorr. The whole process was carried out into a quartz tube. Besides the filament temperature, and substrate temperature were determinant in the deposition of the tungsten. The latter was established at 750 oC in order to cover the substrate by a 200 nm tungsten thin film. The thin films were characterized by means of Scanning Electron Microscope, Atomic Force Microscope and X-Ray Diffraction. SEM micrographs revealed that the films have no more than 200 nm in thickness while XRD show evidence of the films crystalize in the (alpha)-tungsten modification. On the other hand, AFM shows a uniform surface composed with semi-spherical shapes whose diameters are below 200 nm. To the naked eye, the as-deposited films exhibit a highly mirror-like appearance.

8104-43, Poster Session

**Study on magnetic metamaterials of aluminum nanostructures in the visible range**

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In this work, the optical properties of pillar arrays of metal-dielectric metal-nanostructures are investigated. Based on the finite-difference time-domain (FDTD) simulation, the magnetic field reversal is observed due to the fact that the phases of the electric fields oscillating in the top and the bottom pillars are in the opposite directions. The anti-phase electric fields are coupled in the dielectric layer and the equivalent permeability of the film is negative. Compared with the dielectric pillar sandwiched by the Ag pillars, the aluminum(Al)-dielectric-aluminum(Al) film has a good transmission property because of its low absorption and large real part of dielectric constant at the short wavelengths. Whereas Ag pillar exhibits transverse plasmon mode around the wavelength of 350 nm, Al has the dipolar plasmon resonance at the wavelength of 250 nm. Moreover, the simulation result shows the strong magnetic field reversal in Al-SiO2-Al nanostructures of diameters 175 nm is induced at the wavelengths from 400 nm to 600 nm. The thicknesses about the structure are 100 nm for Al and 70 nm for SiO2 of the film is 270 nm. The blue-shift of the inverse magnetic intensity occurs as the diameters of the pillars decrease from 175 nm to 150 nm. Such the films provide a good candidate for achieving optical magnetic metamaterials in the visible regime.

8104-44, Poster Session

**Anisotropic optical property of an asymmetric bideposition TiO2 film: fabrication and measurement**

Y. Jen, C. Lin, T. Yu, C. Lai, National Taipei Univ. of Technology (Taiwan)

To develop diverse anisotropic thin films, asymmetric bideposition technique is introduced to fabricate tilt columnar TiO2 films with biaxial optical property. The asymmetric bideposition is achieved using two different opposite deposition angles (α+, α-) at the same pitch thickness or two different pitch thicknesses (d+, d-) at the same two opposite deposition angles. The two sets of TiO2 columnar thin films associated with deposited subdeposits (d+, d-)=(20,10) and (30,10) are prepared at the opposite deposition angles (α+, α-)=(70,-40), (70,-50), (80,-40), and (80,-50). Columnar thin films with various column angle and biaxial properties are measured their planar birefringence and three principal indexes. The larger column angle leads to lower planar birefringence and principal indices. Experimental result indicates that an anisotropic thin film deposited at (α+, α-)=(80,-50) with deposited subdeposits (d+, d-)=(30,10) could be applied in a prism coupling system (BK7 prism/ TiO2 anisotropic thin film/air) to have enhanced polarization conversion reflectance (PCR). As the film thickness is 887 nm, there is over 60% of PCR detected at the incident angle ranged from 55 degree to 75 degree.

8104-45, Poster Session

**The nanostructure and morphology of biodegradable PLLA films with DBS nanofibrils**

W. Lai, Tamkang Univ. (Taiwan)

The morphologies and nanostructures of neat 1,3:2,4-dibenzylidene-D-sorbitol (DBS) and DBS/poly(L-lactic acid) (PLLA) films have been investigated by polarizing optical microscopy (POM) and scanning electron microscopy (SEM). The morphology of neat DBS samples prepared from solution had unspecific structures, and no fibrils formed. In comparison, DBS molecules self-assembled into fibrils with diameters ranging from 100 nm to 1 µm when samples were prepared from the melt. The DBS fibrils were also found in DBS/PLLA systems, but the average diameter was only around 20 nm. The DBS architectures could be well tuned by varying the DBS contents and PLLA crystallization temperatures. Micron-sized fibrillar rings or disks due to the aggregation of DBS nanofibrils were found using SEM in samples with DBS contents more than 3 wt% and crystallized above 120 oC. Meanwhile, “concentric-circled” PLLA spherulites were observed by POM. The DBS nanofibrils largely formed at the circles, but some nanofibrils formed beyond the circles and were dispersed in the PLLA spherulites. These dispersed nanofibrils affected the orientation of PLLA lamellae and caused a change in birefringence, yet the growth rate of PLLA was not
significant influence by the formation of DBS nanofibrils. In addition, porous PLLA structures could be obtained by solvent extraction of the DBS nanofibrils.

8104-46, Poster Session
Effect of solar radiation on photovoltaic characteristics of Si-P3HT core-shell nanowire solar cells
S. Tsai, National Taiwan Univ. (Taiwan); H. Chang, C. Lin, H. Wang, J. He, National Taiwan Univ. (Taiwan)
We report an hybrid inorganic-organic solar cells (HSCs) fabricated by regioregular poly(3-hexylthiophene) (P3HT) on the n-type silicon (n-Si) nanowire arrays (NWAs). P3HT tends to order at n-Si NWAs under simulated sunlight, leading to a remarkable enhancement of power conversion efficiency (η) from 0.96% to 2.31% and broadband external quantum efficiency (EQE) values under AM 1.5G illumination for 90 minutes because of the core-shell structure (shown in fig. 1). The efficiency enhancement under simulated sunlight results from the increase in open-circuit voltage (Voc), short-circuit current density (Jsc) and fill factor (FF) due to the improved crystallinity of P3HT further characterized by absorption, external quantum efficiency (EQE), and Raman measurements.

8104-47, Poster Session
Nanowire arrays with controlled structure profiles for maximizing optical collection efficiency
H. Chang, K. Lai, Y. Dai, H. Wang, C. Lin, J. He, National Taiwan Univ. (Taiwan)
The Nanowire array (NWA) layers with controlled structure profiles fabricated by maskless galvanic wet etching on Si substrates are found to exhibit extremely low specular reflectance (< 0.1 %) in the wavelengths of 200-850 nm. The significantly suppressed reflection is accompanied with other favorable antireflection (AR) properties, including omnidirectionality and polarization-insensitivity. The NWA layers are also effective in suppressing the undesired diffuse reflection. These excellent AR performances benefit from the rough interfaces between air/NWA layers and NWA layers/substrate and the decreased nanowire densities, providing the gradient of effective refractive indices. The Raman intensities of Si NWAs were enhanced by up to 400 times compared with the signal of the polished Si, confirming that the NWA layers enhance both insertion and extraction efficiencies of light. This study provides an insight into the interaction between light and nanostructures, and should contribute to the structural optimization of various optoelectronic devices.

8104-48, Poster Session
Three methods of fabricating controlled Si nanowire arrays by self-assembling templates and etching for broadband and omnidirectional antireflection
H. Wang, K. Tsai, K. Lai, Y. Lin, Y. Wang, J. He, National Taiwan Univ. (Taiwan)
Ordered arrays of silicon nanowires have attracted great attentions because their unique properties and many potential applications in renewable energy technologies. However, it remains a challenge to fabricate such an ordered array with large scale, well-controlled and periodicity less than 100 nm (diameters less than 60 nm). Here, we demonstrate three methods for the fabrication of large scale ordered silicon nanowires arrays using reactive ion etching (RIE) or metal-assisted chemical etching though colloidal lithography or anodic aluminum oxide (AAO) templates. Si NWAs with desirable diameters could be obtained by shrinking the sizes of colloidal lithography or the pore sizes of AAO templates. The porous anodic alumina membrane with self-organized ordering is employed as the mask for the high-throughput patterning formation of hexagonal-close-packed hole array. Ordered arrays of silicon nanowires with 100 nm in periodicity (50 nm in diameter) can be cost-effectively fabricated. The reflection can be eliminated effectively over broadband regions by controlled NWAs; i.e., the wavelength-averaged total reflectance is decreased to 10.0 % at the wavelengths of 200-850 nm. The resulting nanostructures might have great potential applications in photovoltaics.

8104-49, Poster Session
Polarization anisotropy of oblique-aligned ZnO nanowire arrays
C. Chen, National Taiwan Univ. (Taiwan); J. Huang, National Cheng Kung Univ. (Taiwan); K. Lai, National Taiwan Univ. (Taiwan); Y. Jen, National Taiwan Univ. of Technology (Taiwan); C. Liu, National Cheng Kung Univ. (Taiwan); J. He, National Taiwan Univ. (Taiwan)
We demonstrated that a combined method of modified oblique-angle deposition and hydrothermal growth to grow a novel photonic metamaterial based on single crystalline ZnO nanowire arrays (NWAs) with highly oblique angles (75° - 85°), exhibiting large artificial in-plane birefringence and optical polarization degree in emission. The giant in-plane birefringence (0.11, exceeding by a factor of 10 that of natural quartz. The strong optical anisotropic in emission due to the optical confinement was observed. Unlike the conventional oblique-angle-deposited thin films, the NWAs also showed light emitting ability, leading us to conclude that the oblique-aligned NWAs not only could be applied in passive photonic components, such as optical waveplates and optical isolators, but also can open up important technological applications in polarized light sensing and emission devices.

8104-50, Poster Session
Antireflective nanostructured thin films and their applications in solar cells
J. He, National Taiwan Univ. (Taiwan)
It is of current interest to develop the antireflection (AR) coatings with nanowire arrays (NWAs) since the ability to suppress the reflection over a broad range of wavelengths and incident angles plays an important role in the performance of optoelectronic devices, such as photodetectors, light-emitting diodes, optical components, or photovoltaic systems. Superior AR characteristics of NWAs, including polarization-insensitivity, omnidirectionality, and broadband working ranges are demonstrated in this study. These advantages are mainly attributed to the subwavelength dimensions of the NWAs, which make the nanostructures behave like an effective homogeneous medium with continuous gradient of refraction index, significantly reducing the reflection through destructive interferences. The relation between the geometrical configurations of NWAs and the AR characteristics is discussed. We also demonstrated their applications in solar cells. This report paves the way to optimize the nanostructured optoelectronic devices with efficient light management by controlling structure profile of nanostructures.
Properties of RF sputtered ZnO thin films under different oxygen flux

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The microstructures, optical, and mechanical properties of zinc oxide (ZnO) thin films deposited on glass substrates by rf magnetron sputtering were studied. Microstructures were examined using atomic force microscopy (AFM) and X-ray diffraction (XRD), respectively. Optical property was measured by photoluminescence spectrum. The mechanical properties were measured by nanoindentation. The crystalline structures of ZnO thin films are well ordered with high c-axis (002) orientations and the crystallinity is strongly affected by O2 flux. Surface morphologies of ZnO thin films are smooth and grains grow and distribute uniformly. The hardness and Young’s modulus of ZnO thin films are ranged from 8.2 to 10.4 GPa and 105 to 120 GPa, respectively.

The stability of carbon nanostructures in silicon oxy carbide materials

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Silicon oxy carbide (SiOC) is a metastable material that has generated interest because of the great flexibility in properties that is attainable with a change in carbon-to-oxygen ratio. These materials have exhibited a strong propensity to include carbon-carbon - “free carbon” - bonding within the structure regardless of synthesis method, although the relative amounts can be controlled to some degree. Despite strong experimental evidence for the presence of this phase as nanostructures, models of the composite system have had difficulty producing a stable structure bonded to the matrix. Characterization techniques sensitive to ordered bonding in the length scale of roughly 0.5 to 5nm such as fluctuation electron microscopy (FEM), Raman spectroscopy, and nuclear magnetic resonance along with compositional studies by x-ray photoelectron spectroscopy and nuclear reaction analysis were used to produce a new view of the structural role of carbon in SiOC materials. Through coupling of these experimental approaches with molecular dynamics modeling, a new theory on the stability of these nanostructures is presented here.

Tunable Stoichiometry of BCxNy Thin Films through Multi-Target PLD with In situ Ellipsometry

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Much interest has been shown in Boron Carbon Nitride, BCxNy, with B4C, C, and BN each individually having unique properties: B4C - high hardness and stability, C - high thermal conductivity and electrical semi-conductivity, and BN - insulating with high band gap. Using these bulk materials in conjunction with pulsed laser deposition (PLD) provides stoichiometric material transfer from each laser target material to substrate surface, which when combined with multiple targets and a programmable mirror system provides tunability of the stoichiometry of the resulting thin-film. Initial laser pulses onto a target material create island growth that coalesces into a uniform film above a thickness threshold of a few nanometers. In situ ellipsometry allows determination of optical properties of a thin-film during growth including the real component of the index of refraction (n) and the extinction coefficient (k), which when coupled with a model provides for a real-time virtual measurement of thickness during deposition. Ellipsometry can be used to detect the transition of island growth to uniform film growth, but after the film becomes opaque no more optical variations can be detected. Two 5cm diameter targets, one graphite and one boron-nitride, were rotated inside a UVH deposition chamber evacuated to a base pressure below 0.1 mPa, while a Lambda Physik 248nm excimer laser was triggered in a synchronized fashion with a high speed galvanometer mirror system thereby delivering a programmable number of 250mJ 20nsec duration pulses on each target. Results presented will include stoichiometry of the thin-films measured with XPS.

Study on the structure and optical properties of plasma-polymerized ZrNxCyOz thin films

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A modified room temperature PECVD process was used to prepare plasma-polymerized (PP-)ZrNCO thin films, using tetraakis(diethylamido) Zr (IV) (TEDAZ) as a precursor. The structure and optical properties of the films were characterized by XPS, FT-IR, Raman, AFM, SEM, UV-Vis and spectroscopic ellipsometry. The preliminary results show that although there is no oxygen components in the monomer or carrier gases (N2 and Ar), due to the residual moisture and oxygen in reaction areas, the resulting PP-ZrNxCyOz films contained a certain amount of oxygen, from 15 to 30 atm%, depending upon the processing conditions. Additionally, the refractive index of the films does not scale proportionately with metal atom concentration as has been observed for PP - ferrocene, titanium isopropoxide and tetraphenyl lead. This suggests that morphological features that affect the film density such as microvoids have significant influence on the optical properties of the films. Further studies include a systemic investigation of the titanium analogue of TEDAZ to elucidate structure-property relationships that will have import when both organo-metallic precursors undergo co-polymerization to form broadband, UV protective coatings.

An investigation on magnetic responses in Ag-SiO2-Ag nanosandwich structures

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In this work, we investigate magnetic responses in various Ag-SiO2-Ag nanosandwich structures at visible wavelengths. The two electric resonant modes corresponding to the in-phase (symmetric) and anti-phase (asymmetric) electric dipole on the top and the bottom nanopillars are observed by the finite difference time domain (FDTD) simulation. In the asymmetric resonant mode, the phases of electric fields oscillating in the top and bottom pillars have opposite directions, leading to a virtual current loop that induces the magnetic field reversal. The nanosandwich structure produces a large enhancement of the magnetic field as the thickness of SiO2 nanopillars decreases. By increasing the diameter of nanopillars from 125 nm to 160 nm, the inverse magnetic response wavelength shifts from 550 nm to 650 nm. On account of the magnetic field reversal caused by the anti-phase electric dipole coupling, the real part of the equivalent permeability of the film is negative. Therefore, the wavelength range associated with the intensity of inverse magnetic response is tunable by varying the size of Ag-SiO2-Ag nanosandwich structure. The analysis can be applied to interpret extraordinary optical properties such as negative index of refraction from an Ag-SiO2-Ag sandwich array prepared by glancing angle deposition.
8104-30, Session 7
Scultpured thin films: nanorods, nanopipes, nanosmiles
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Atomic shadowing during physical vapor deposition causes exacerbated growth of surface protrusions and leads to a chaotic 3D layer growth, which can result in the development of well-separated nanorods, nanosprings, or nanopipes, which are surprisingly regular and have potential applications ranging from fuel cell electrodes and pressure sensors to self-lubricating coatings and nanoactuation. Glancing angle deposition (GLAD) causes particularly strong atomic shadowing and can be used to systematically investigate the effect of shadowing on the morphological evolution. These extremely rough layers cannot be described as a chaotic perturbation from a flat surface. However, using a model which describes them as a nanorod array with an average rod width that follows power law scaling results in experimental curves where all metals converge on a single master curve which exhibits a discontinuity at 20% of the melting point, associated with a transition from a 2D to a 3D island growth mode and a single homocatalyzed growth activation energy of 2.46 for surface diffusion on curved nanorod growth fronts, which is applicable to all metals at all temperatures. Also, under extreme shadowing conditions, the conventional structure zone model is simplified as there is a direct transition from an underdense (zone I) to a dense (zone III) structure at ~50% of the melting point.

8104-31, Session 7
Electrophoretic deposition of Cu-In composite nanoparticle thin films for fabrication of CuInSe2 solar cells
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Electrophoretic deposition (EPD) is traditionally used in ceramic industry for coating micron-sized ceramic particles. In this work, we applied EPD to metal nanoparticles in liquid solvents and successfully produced thin films of Cu-In composite nanoparticles. The nanoparticles were produced with pulsed laser ablation in the same liquid solvents. Pulsed laser ablation has recently been recognized as a promising method for producing high purity nanoparticles. We first demonstrated femtosecond pulsed laser ablation production of nanoparticles of various metals including elemental Cu, In, Ga, Se and their binary alloys and compounds. We found that the overall composition was preserved during laser ablation, which provided means of compositional control for thin film applications. The colloids were stable against agglomeration without stabilizing chemicals, and the mechanisms were explained based on charging of nanoparticle surfaces via electrochemical interaction with ambient solvents. We also found that the surface charge density was sufficient to enable migration of the nanoparticles in solvents under an electric field. The success of EPD of metal nanoparticles was explained based on charge transfer between the nanoparticle surfaces and the electrode. With atmospheric pressure annealing in selenium vapor, we have produced polycrystalline CuInSe2 films, and effective solar cell structures have also been made. The whole process was performed in non-vacuum ambient conditions, and can also be applied to flexible substrates such as metal foils. These results open up a new route of non-vacuum fabrication of thin film CuInGaSe2 solar cells.

8104-32, Session 7
X-ray absorption fine-structure and optical studies of AlZnO nano-thin films grown on sapphire by pulsed laser deposition
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Al-doped ZnO can replace tin-doped indium oxide (ITO) as a transparent conductive oxide (TCO) for optoelectronic applications. We investigated nanometer scale AlZnO thin films on sapphire from pulsed laser deposition (PLD) in 350–650°C. Synchrotron radiation X-ray absorption fine-structure spectroscopy at O K-edge showed that Al-doped ZnO can’t form alloy at 350°C without Al-O bonding feature. Al-O transition of AZO550 is stronger than AZO650, and crystalline qualities of AZO550 and AZO650 are much better than AZO350. Raman scattering and 266nm excitation micro-PL measurements further confirm these results. Al-doped ZnO at 350°C has weak and broad Raman and PL signals. Comparing Raman spectra between AZO350 and AZO650, the peak of E2 (high) mode is observed in AZO650 but not in AZO650. The E2 (high) mode is strong and narrow in AZO550. PLD grown AlZnO film on sapphire could get a better crystalline quality at 550°C than 350°C and 650°C.

8104-33, Session 7
Janus-like 3D tectons as functional nanostructures for self-assembled functional thin films towards nanophotonics
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In order to achieve the nanometer-scale control over the positioning and organization of functional molecules into monolayers at surfaces, we developed an original approach allowing the exact positioning of (photo)active organic molecules on the substrate (graphite) leading to the formation of nanostructured functional thin films. 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. We will present a series of such building-block exhibiting tunable wavelength emission. This strategy results in the precise organization of chromophores arrays (subwavelength-sized photon sources) a few Å above the conducting surface, as determined by scanning tunneling microscopy (STM), opening interesting perspectives for applications in nanophotonics.

8104-34, Session 8
Multifunctional organic-inorganic hybrids based on bacterial cellulose membranes
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Bacterial cellulose (BC) is produced by Gluconacetobacter xylinus strains in the form of highly hydrated (98% water) membranes. The chemical structure is the same of the one found for plants cellulose but strains in the form of highly hydrated (98% water) membranes. The chemical structure is the same of the one found for plants cellulose but BC presents a pure cellulose network, free of lignin and hemicellulose, composed of a random assembly of ribbon shaped fibers less than 100 nm wide. The unique properties provided by the nanometric structure have lead to a number of commercial products including dielectric fibers, headphone membranes, special papers, and textiles, medical applications including temporary skin substitution, contact lenses, optoelectronic devices (e-paper, OLEDs). We have been exploring this multifunctional character studying luminescence properties, photochromism and different application of BC as biomaterials. Photochromism is been explored by preparing BC membranes containing polyoxometalates and metal colloids. Light induced redox process (W6+ W5+) and tuning of the plasmon resonance energy
of metal (Au-Ag) colloids lead to different colors and photochromic materials. Luminescence is being explored by obtaining lanthanide containing luminescent species in the BC structure. Emission efficiency is observed to strongly depend on the specific interactions between the BC host and the lanthanide compounds. BC membranes are also being used as substrates for flexible organic light emitting diodes and emission efficiencies are found to be of the same order of glass OLED’s. Finally biomedical applications is being addressed. BC is being for decades used as substitutes for the skin in the treatment of difficult wounds. In our work antibacterial activity is being added to BC membranes by using Ag colloids and propolis.

8104-36, Session 8

Chromogenic behaviours of silver containing mesoporous titania films

Multicolour photochromism was reported few years ago on nanoporous titania films loaded with silver nanoparticles (NP). The formation of heterogeneous silver nanoparticles under UV light gives the films a brown color, whereas illuminations under a colored visible light change the film color to almost the same color as that of the incident light. This photochromic behaviour was interpreted as resulting from a selective oxidation of nanoparticles whose size corresponds to a surface plasmon resonance band centered on the illumination wavelength.

The use of mesoporous titania films as host matrix for the growth of silver nanoparticles is likely to lead to homogeneous NP size distributions and to changes in the photochromic behaviour. We firstly investigate the effects of three reduction processes on the formation of silver nanoparticles in mesoporous titania films. The later are impregnated with silver salt and then either exposed to UV laser light, chemically treated or annealed. Depending on the reduction process the in situ grown NP can be confined inside the mesopores or not, leading to different NP size distributions and to various film colors. These three TiO$_2$/Ag nanocomposite films also exhibit different photochromic behaviours when exposed to visible laser radiations. We characterize the color changes as well as the NP deformation and oxidation under visible illuminations and we propose new mesoscopic mechanisms to interpret our results.

8104-37, Session 8

Electron microscopy characterization of some carbon based nanostructures with application in divertors coatings from fusion reactor
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Nanostructured carbon materials have increasingly attracted the interest of the scientific community, because of their fascinating physical properties and potential applications in high-tech devices. In order to prepare nanostructured carbon-tungsten nanocomposite for the divertor part in fusion applications, the original method thermionic vacuum arc (TVA) was used in two electronic guns configuration. One of the main advantages of this technology is the bombardment of the growing thin film just by the ions of the depositing film. Moreover, the energy of ions can be controlled. Thermo-electrons emitted by an externally heated cathode and focused by a Wehnel focusing cylinder are strongly accelerated towards the anode whose material is evaporated and bright plasma is ignited by a high voltage DC supply.

The nanostructured C-W films were characterized by Scanning Electron Microscopy (SEM), Transmission Electron Microscopy (TEM) and Atomic Force Microscopy (AFM). Tribological properties in dry sliding were evaluated using a CSM ball-on-disc tribometer. The C-W films were identified as a nanocrystals complex (5 nm average diameter) surrounded by amorphous structures with a strong graphitization tendency, allowing the creating of adherent and wear resistant films. The friction coefficients (0.15 - 0.35) of the C-W coatings was decreased more than 3-5 times in comparison with the uncoated substrates proving excellent tribological properties. C-W nanocomposites coatings were designed to have excellent tribological properties while the structure is composed by nanocrystals complex surrounded by amorphous structures with a strong graphitization tendency, allowing the creating of adherent and wear resistant films.

8104-38, Session 8

Optical investigation on plasmonic effect of the nanostructured Surface Plasmon Resonance sensor chips fabricated by Langmuir-Blodgett technique
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The surface plasmon resonance (SPR) has been widely employed for biosensor applications because of the capability for label-free detection of biomolecular interactions. However, the sensitivity of SPR sensor is lower than the conventional labeling immuno-sensing methods. The metal nanostructure-amplified surface plasmon resonance analysis has been investigated to enhance the sensitivity. We used trigonal pyramid Au nanostructured SPR chips for SPR sensitivity enhancement and took a theoretical approach by evaluating optical properties of the Au nanostructures and nanostructured SPR chips in the point of localized surface plasmon (LSP)- surface plasmon polariton (SPP) conjugation. We used the Langmuir-Blodgett (LB) method for preparation of defect-free and large-area silica-nanoparticles-monolayer as a template for the fabrication of nano-scaled Au patterns on an Au substrate for surface plasmon resonance. Well organized, trigonal pyramid shaped Au nanostructures were able to construct on 34 separate chips in one fabrication process. The dimensions of trigonal pyramid nano-structures were precisely controlled by changing the particle diameter of the silica LB template as follows: 150, 300, 500, and 700 nm.

The nano-structure patterned substrate fabricated with 300 nm-sized silica nanoparticles demonstrated a sensitivity enhancement up to 120 % compared to a conventional SPR chip when 20% aqueous ethanol solution was used as an analyte. To improve the optical basis of the enhancement in the sensitivity, we measured the SPR curves to wavelength. Also we tried to measure UV-visible spectra of the Au nanostructured pattern in the attenuated total reflectance (ATR) mode to observe the LSP mode of each Au nanostructure.
8105-04, Session 2

Strategies for Nanoscale Contour Metrology using Critical Dimension Atomic Force Microscope

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Contour metrology is one of the techniques used to verify optical proximity correction (OPC) in lithography models. The use of these methods, which are known as resolution enhancement techniques ( RET), are necessitated by the continued decrease in feature sizes. Broadly speaking, RET are used to compensate for lithography errors such as corner rounding caused during image transfer from the mask to the wafer and subsequent processing. Contours extracted from the printed features are used to verify the OPC models. Currently, the scanning electron microscope (SEM) is used to generate and verify the contours. The critical dimension atomic force microscope, a reference instrument in lithography metrology, has been proposed as a supplemental instrument for contour verification. This is mostly due to the relative insensitivity of the CD-AFM to material properties, the three dimension data, and the ability to make the instrument traceable to the SI unit of length.

However, although the data from the CD-AFM is inherently three dimensional, the planar two dimensional data required for contour metrology is not easily compared with the top-down AFM data. This is mostly due to the effect of the CD-AFM tip and the scanning strategy. In this paper we outline some of the methods for acquiring contour data using the CD-AFM. Specifically, we look at different scanning strategies, the effect of tip types, contour extraction methods, and imaging modes. We compare contours extracted using our method to those acquired using the SEM and helium ion microscope.

8105-05, Session 2

Sidewall slope sensitivity of CD-AFM metrology

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CD-AFM is a metrology technique used as a reference measurement system to support accurate control of critical dimensions in precision high volume manufacturing. To test the process range of the AFM, we use a controlled variation in the sidewall across a range of samples to test measurement sensitivity over a critical range of probe types and scan parameters. We find sharp cutoff points in the ability of particular probes and modes to accurately track sidewall variation. We further use cross-section SEM and HR-TEM data as a reference check on the accuracy of CD-AFM sidewall measurements under varying scan conditions.

8105-06, Session 2

High precision surface-profile metrology by scanning the repetition rate of femtosecond pulses

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We report high precision surface-profile metrology using femtosecond pulse lasers as a low-coherence Interferometric light source. Unequal-path non-symmetric Twyman-Green interferometer is configured to test large-sized optics with small-sized reference surfaces, which is only feasible with ultrafast mode-locked pulses of the repeated temporal coherence and high spatial coherence. The time delay between the pulses from the reference and target optics is precisely scanned by tuning the repetition rate of femtosecond pulses referenced to the Rb clock of a time standard. This enables us to perform traceable high precision surface metrology following the SI definition of the meter and remove all the moving parts from the interferometer.

8105-07, Session 2

Progress in the development of the metrological Scanning Probe Microscope at NMIA


The design, manufacture and assembly of a metrological Scanning Probe Microscope (mSPM) is well underway at the National Measurement Institute Australia (NMIA). The mSPM is the key instrument in NMIA's SPM metrology facility, traceably linking dimensional measurements at the nanoscale with the realization at NMIA of the SI definition of the metre.

Here, we give an overview of recent progress in the establishment of the mSPM facility at NMIA and present first results of its operational and metrological characteristics.

The mSPM incorporates a quartz tuning fork oscillator-mounted tip operating in non-contact mode, a flexure-hinged, piezo-actuated three-axis translation stage providing a measurement volume of 100 µm × 100 µm × 25 µm, and a plane mirror differential heterodyne interferometry system for traceable measurement of the displacements between the scanned sample and the fixed probe. To achieve the target combined uncertainty of 1 nm for the position measurement, the mSPM body is designed to minimize uncertainties caused, in particular, by thermal expansion and distortion, alignment errors (particularly Abbé errors) and environmental vibrations. The interferometry system is designed to achieve high resolution and bandwidth to facilitate its use for closed-loop position control. The selection of materials with low thermal expansion coefficient for the manufacture of the mSPM body and the low power dissipation of the SPM probe detection system contribute to the excellent temperature stability of the instrument.

8105-10, Poster Session

ZnO nanorod arrays as antireflection layers for III-V solar cells

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Single-junction GaAs solar cells were grown by metal organic chemical vapor deposition with Veeco turboDisc E450 As/P system. The solar cells were fabricated with standard processes, including the top contact (Ti/ Au) formed by photo-lithography and e-beam evaporation, followed by the mesa definition with the area of 2×2 mm2, and the deposition of the bottom contact (Ge/Au). The syringe-like ZnO NRAs were synthesized using the one-step hydrothermal process. Before the synthesis, a 200-nm SiO2 passivation layer was deposited on the device by e-beam evaporation to prevent the potential shortage caused by the conductive ZnO. Subsequently, a ZnO seed layer was deposited by e-beam evaporation on SiO2 for the following growth of ZnO NRAs. The samples
with ZnO seed layers were then placed downward, positioned at the bottom of the beaker, and heated to 95 °C for 3.5 hours in the aqueous solution containing zinc nitrate hexahydrate (10 mM) and ammonia. Finally the obtained syringe-like NRAs were cleaned with ethanol and dried in air ambiance.

8105-23, Poster Session

Development of multichannel rotating-polarizer ellipsometers based on generic data acquisition method

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A data acquisition method based on a novel Fourier analysis of irradiance waveform was introduced to capture Fourier coefficients for multichannel rotating-element ellipsometers [1]. Most of detector line arrays used for common rotating-element ellipsometers are integrating photometric detectors because their output signals are proportional to not only the light intensity but also the integration time. For earlier studies [2], the photodiode arrays did not respond when the light amount accumulated in each pixel during an integration time was read out and the status was initialized. To reflect this effect, measured exposure is corrected by the primary approximation of the non-response time [3]. To obtain accurate Fourier coefficients without the approximation, we adopt a discrete Fourier transform on the exposures measured with a detector-dependent non-response time and an arbitrary integration time. This analysis gives a generic function that encompasses the Hadamard transform [3] or the discrete Fourier transform, depending on the specific conditions. Thus, the novel Fourier analysis is applicable to various line arrays with either non-overlap or overlap readout-mode timing. To assess the effects of the generic Fourier analysis, we built a multichannel rotating-polarizer ellipsometer composed of a white light source, a fixed polarizer, a rotating polarizer, a sample, a fixed analyzer, and a spectrometer in which the fixed polarizer is introduced to remove source polarization. The ellipsometric data for SiO2 thin films on c-Si were measured with the custom-built ellipsometer, using the novel Fourier analysis with various numbers of scans, integration times, and rotational speeds of the polarizer.

References


8105-26, Poster Session

Vector modulation method for north finder capability gyroscope

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This paper deals with the implementation of Vector Modulation Method (VMM) to an open-loop North Finder Capability Gyroscope (NFCG), designed in TÜBİTAK UME (National Metrology Institute of TURKEY). The method proposes a use of a secondary modulation/demodulation with AD630 to derive voltage information, depending on the periodic variation of the orientation of the sensing coil sensitive surface vector with respect to geographic north at laboratory latitude in time domain. The resultant DC voltage of the secondary modulation/demodulation circuit, proportional to 1st kind Bessel function based on Sagnac Phase Shift for 1st order, is obtained as a throughput vector modulation together with Earth rotation.

8105-09, Session 3

Verification of scatterometer design and data processing

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Scatterometric applications demand strategies for the selection from the various basic scatterometer principles as well as detailed design rules to fit the final optical instrument, the data processing and user interface into the requirements of the application in scope. In recent years we proposed methods based on the optical properties of various basic measurement structures to support the synthesis process for scatterometers, including the decision for the structure itself.

In continuation of last year's paper on design rules for catadioptric scatterometers the present paper is dedicated to the metrological verification of the proposed design methods for devices with elliptical mirrors in off-axis alignment. Further questions of data processing and analysis, especially the necessary coordinate transformations and calibration procedures will be discussed, practical examples included.

8105-11, Session 3

IR nanoscopy and nanoimaging

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Infrared (IR) spectroscopy is a well developed method for characterizing chemical composition. Imaging materials using IR spectroscopy is extremely valuable where sample heterogeneity presents challenges to analysis using topographical imaging alone, such as in pharmaceuticals or cell biology. Optical imaging using far-field methods is limited by diffraction to length scales at approximately equal to lambda/2. We present a technique for infrared nanoscopy and nanospectroscopy based on an induced resonant phenomena to enable IR imaging with a resolution beyond the diffraction limit. Our method enables the surface features of a sample to be chemical characterized via inspection of the resulting local IR spectra and images. This was achieved by combining a phase matched optical parametric oscillator laser as the IR source and an atomic force microscope as the detection mechanism. The technique applies a diffraction limited tuneable excitation source and the resulting light-matter interaction is probed by the AFM tip resulting in IR imaging with nanoscale resolution. We apply this method to image protein bio-systems with a spatial resolution < lambda/100.

8105-12, Session 3

Quantification of the systematic and random measurement uncertainty of a polarimetric scatterometry system designed for enhanced E-field device characterization

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Enhanced E-field metamaterials feature the careful selection of restricted nanoparticle or nanofeature geometries and complementary materials to develop nanoscale-level extremely high local electric field strengths when the metamaterial is illuminated by appropriate electro-magnetic energy. Enhanced E-field metamaterials improve sensitivity and spectral location of remote sensing techniques such as Localized Surface Plasmon Resonance (LSPR) and facilitate extremely low concentration detection of compounds or biological factors of interest. Early detection at low concentration levels can allow for the medical treatment of life-threatening conditions such as Alzheimers and the rapid detection of hazardous airborne biological agents. A unique model-based Dual-Rotating-Retarder (DRR) polarimetric scatterometry system has been
developed to characterize enhanced E-field metamaterials by measuring their effective medium full Mueller-matrix (Mm) scatter characteristics at wavelengths of 544 and 633 nm and 3.39 and 10.6 m. The system has been enhanced by automation, addition of multiple light sources, an improved sample positioning and orientation interface, and enhanced data-analysis software. The system features multiple systematic and random uncertainty sources. Systematic measurement errors are reduced by generation of eigen-polarizations and measurement of their angularly dependent scatter response due to position dependent surface scatter from optical components. Random measurement errors are reduced by careful application of system condition number and a rigorously model based measurement analysis. Several measurement examples for canonical Fresnel targets and enhanced E-field geometries are presented. The goals are to improve understanding of application of effective medium theory to Metamaterials and to improve instrumental sensitivity to allow polarimetric probing of enhanced E-field “meta-atoms.”

8105-13, Session 4

**Experimental investigation of non steady state photo-EMF effect induced by 1-D light pattern and its application for Talbot self images localization**

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Recently, the analytical expression for non-steady-state photoelectromotive force (photo-EMF effect) current density in a case of light distribution containing only odd harmonics had been derived, and the results demonstrated, that the photo-EMF current was proportional to the sum of the squares of the spatial harmonics visibilities. Furthermore, an adaptive photodetector based on the photo-EMF effect, have been proposed for efficient localization of the Talbot patterns or self-images (planes with minimal and maximal visibility) generated by periodic object in real time, high spatial resolution and without any image processing. Here, we present the experimental analysis of the photo-EMF effect induced by an arbitrary 1-D periodical light pattern and the possibility for localization of the Talbot self-images was also investigated.

8105-14, Session 4

**Linear variable filter based oil condition monitoring systems for offshore windturbines**

B. R. Wiesent, D. G. Dorigo, A. W. Koch, Technische Univ. München (Germany)

A major part of future renewable energy will be generated in offshore wind farms. The used turbines of the 5 MW class and beyond often feature a planetary gear with 1000 liters lubricating oil or even more. Monitoring the oil aging process gives early indication of necessary maintenance and oil change. Thus maintenance is no longer time-scheduled but becomes wear dependent thus providing ecological and economical benefits. This paper describes two approaches based on a linear variable filter (LVF) as dispersive element in a setup of a cost effective infrared miniature spectrometer for oil condition monitoring purposes. Spectra and design criteria of a static multi element detector and a scanning single element detector system are compared and rated. Both LVF miniature spectrometers are appropriately designed for the suggested measurements but have certain restrictions. LVF multi-channel sensors combined with sophisticated multivariate data processing offer the possibility to use the sensor for a broad range of lubricants just by a software update of the calibration set. An all-purpose oil sensor may be obtained.

8105-16, Session 4

**Two-photon fluorescence near-field pH measurement for mitochondria activity**

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A proton distribution in the vicinity of mitochondria attracts interest due to its influence to a necrotic cell death. Mitochondria produce by ATP using proton concentration gradient generated across the membrane. Accordingly, pH distribution in the vicinity of mitochondria changes from time to time. However, if mitochondria are excited by physical and/or chemical stresses, proton concentration gradient disappears and ATP couldn’t be produced. As a result, the necrotic cell death happens. This process is considered as a part of the reason of the necrotic cell death. Therefore, it is expected that measuring pH distribution in the vicinity of mitochondria leads to clarification of a mechanism of the necrotic cell death. However, it is very difficult to measure pH in vicinity of mitochondria accurately, because a spatial resolution of the conventional microscope is limited. In this study, we propose pH measurement method based on two-photon fluorescence excitation of dual wavelength pH sensitive dye and scanning near-field optical microscopy (SNOM) to improve spatial resolution. This method utilizes a femtosecond pulse laser to generate two-photon absorption and excites the dye locally. Then the fluorescent signal is collected by a near-field probe. The fluorescent signals for each wavelength are detected separately by cooled photomultiplier tubes, and their intensity ratio is calculated as a figure of pH. The calibration of the pH using proposed method is achieved, and temporal variation of the pH by dropping acid is successfully observed.

8105-17, Session 4

**Real-time monitoring of indium bump reflow and oxide removal enabling optimization of indium bump morphology**

F. Greer, M. R. Dickie, T. J. Jones, M. E. Hoekn, S. Nikzad, Jet Propulsion Lab. (United States)

Flip chip hybridization, also known as bump bonding, is a packaging technique for microelectronic devices which directly connects an active element or detector to a substrate readout face down, eliminating the need for wirebonding. Indium bump technology has been a part of hybridization for many years and has been extensively employed in the infrared imager industry. However, obtaining a reliable, high yield process for high density patterns of bumps can be quite difficult in part due to the tendency of the indium bumps to oxidize during exposure to air. In this study, plasma, thermal, and wet chemical methods were screened to determine their ability to remove indium oxide from indium bumps and reflow them. Plasma processes using methane, argon, and/or hydrogen were developed to remove indium oxide from indium bumps after prolonged air exposure. A novel hardware configuration was developed to optically monitor indium bump morphology in real time during reflow to optimize and control the process and therefore, the indium bump contact angle, to obtain unique, highly wetted bump morphologies. These methods were tested by fabricating fully hybridized visible CMOS detectors and imaging a standard test pattern. The results of these tests, and a discussion of the mechanisms and merits of the different plasma chemistries and approaches will be discussed.

8105-18, Session 4

**Light confinement by structured metal tips for antenna-based scanning near-field optical microscopy**

J. D. Jambreck, Fraunhofer-Institut für Integrierte System und
This paper discusses a series of studies to improve silicon-based SNOM, a large ratio of the near-field signal to the background signal resulting from far-field excitation and detection is highly desirable. In this work, we improve this ratio in the case of sharp conical metal tips by optimizing the local field enhancement, the origin of the near-field signal, using focused ion beam (FIB) structuring. Electrochemically etched conical metal tips are widely used for antenna-based SNOM. Compared to these quasi-infinite structures, finite length antennas and particle-like probes are expected to provide stronger field enhancement. To limit the effective size of our probes, we fabricated surface plasmon Bragg reflectors in suitable distance to the tip apex. These reflectors are realized by appropriate multiple FIB structuring all around the tip.

The design of the structures and the fabrication strategies are discussed. Scanning electron microscopy images, optical raster scans at the targeted wavelength, and optical spectra at different positions of the tips before and after FIB modification are analyzed. An increase of the light confinement of 60% is observed after structuring the tips as determined from the apex-to-shaft contrast in confocal PL images. The results show that optimized design, FIB patterns, FIB parameters, and structures are crucial to achieve increased signal-to-background-ratios.

8105-19, Session 4

See-through-silicon inspection applications study based on traditional silicon imager

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See-through-silicon inspection is becoming an essential quality control method for semiconductor manufacturing in three-dimensional integrated circuit (3DIC) and chip-stacking and related industries such as crack inspection in solar panel manufacturing. Due to silicon’s band-gap structure silicon wafers are transparent to light beyond 1.2 micron wavelength range, so silicon-based detectors have very low sensitivity to this wavelength range. InGaAs detectors are typically favored for such applications, even with much higher cost, larger pixel size and smaller detector resolution. This paper discusses a series of studies to improve silicon-based imagers’ detection signal-to-noise ratio for this see-through-silicon inspection application. Silicon based detector sensitivity increases when light wavelength shifts shorter from 1.2 micron. But both photon penetration depth and the percentage of penetrated photons drop accordingly. Non-through-penetrated photons are scattered in all directions both at the wafer top surface and inside of the silicon material. A portion of scattered photons will be collected by inspection optics and reach the imager eventually, to cause a white noise background in images out of silicon based detectors. This essentially results in low image contrast. Effectively removing this background noise is the key to fundamentally improve the signal-to-noise ratio of silicon based detectors for this application. We studied a series of methods, including simple image processing methods, advanced frequency domain analysis and reference subtraction, and compared each method’s pros and cons for industrial inspection applications.

8105-20, Session 4

Whole field curvature and residual stress determination of silicon wafers by reflectometry

C. S. Ng, A. K. Asundi, Nanyang Technological Univ. (Singapore)

Reflectometry, a simple whole-field curvature measurement system using a novel computer aided phase shift reflection grating method has been improved to certain extend. The similar system was developed from our earlier works on Computer Aided Moiré Methods and Novel Techniques in Reflection Moiré, Experimental Mechanics (1994) in which novel structured light approach was shown for surface slope and curvature measurement. This method uses similar technology but coupled with a novel phase shift system to accurately measure surface profile, slope and curvature.

In our previous paper, “Stress Measurement of thin wafer using Reflection Grating Method", the surface curvature and residual stresses were evaluated using the versatility of the proposed system. The curvature of wafers due to the deposition of backside metallization was evaluated and compared with a commercially stress measurement system from KLA-Tencor. In this paper, some aspects of the work is extended. Our proposed system is calibrated using a reference flat mirror and spherical mirror certified by Zygo Corporation. The mirrors together with the camera calibration toolbox allow the system to acquire measurement accuracy that is demanded by semiconductor industry. Finally, the results obtained from Reflectometry are compared and contrast with results from KLA Tencor System.

8105-21, Session 5

Common-path laser encoder system for nanopositioning

C. Wu, C. Cheng, Tamkang Univ. (Taiwan)

Scanning probe microscopy and nanoimprint are powerful and promising techniques for nanotechnology. In order to get precise dimensions of microstructures, the displacement sensor is required for precise displacement feedbacks. Out of all displacement sensors, the laser encoder has been an important subsystem and widely adopted for advanced manufactures such as semiconductor industry. However, the used laser encoders inevitably suffer from environmental disturbances or noises, which mainly result from atmospheric influences, background vibration, thermal drift, and elec-tronic high frequency noises. In this paper, a common-path laser encoder for nanopositioning is proposed. Based on the common-path optical configuration, our system can offer high stability and high resolution displacement measurements. An expanded laser source is focused on the grating scale. The grating then diffracts the focus beam. The zero order diffraction beam overlaps partially with the first one. This interference beam is divided into two parts by the polarization beam splitter (PBS). When the grating scale moves delta(x), the Doppler effect will induce the phase variation phi =2*π*delta(x)/d in first order diffracted beam. Here d is the grating pitch. According to the Jones calculation, the light intensities on the detectors D1 and D2 can be written as: I1 proportional to 1+cos(π*phi) and I2 proportional to 1+cos(-π*phi), respectively. As the phase difference Phi=2*phi between I1 and I2, the displacement delta(x) of the grating scale can be obtained by the following equations: delta(x)=Phi*d/(4*π). The principle of the displacement measurement and the method of the positioning method will be detailed and the system performance will be provided.


8105-22, Session 5
Quasi static short range lidar for volume scatterometry
C. F. Hahlweg, Helmut-Schmidt Univ. (Germany)

In continuation of previous publications the use of short range Lidar techniques for measuring volume scatter behaviour of semi-transparent materials is investigated with focus on budget designs power modulated FMCW devices in GHz range. Standard components as supplied for telecom transmission lines are used. A main topic is the definition of the scatter geometry for goniometric measurements. Further the use of short range Lidar in imaging scatterometers is discussed. Theoretical and practical investigations are presented.

8105-24, Session 5
Rapid defects detection of bonded wafer using near infrared polariscope
C. S. Ng, A. K. Asundi, Nanyang Technological Univ. (Singapore)

Wafer bonding has emerged as an important processing step in wide range of MEMS manufacturing applications. During the manufacturing process, even in the modern clean room, small defects result from trapped particles and gas exist at bonded interface. Defects and trapped particles may exist on the top and bottom of the wafers, or at the interface of bonded wafer pair. These inclusions will generate high stress around debond region at the wafers bonded interface. In this paper, inspection of the bonded interface will be the area of investigation.

Since silicon wafer is opaque to visible light, defect detection at the bonded interface of silicon wafer is not possible. Due to the fact that silicon wafer is transparent to wavelength greater than 1150nm, an Near Infrared Polariscope which has showed some promises on residual stress measurement on silicon devices has been adapted and developed. This method is based on the well known photoelastic principles, where the stress variations are measured based on the changes of light propagation velocity in birefringence material. The results are compared and contrast with conventional Infrared Transmission Imaging tool (IRT) which is widely used to inspect the bonded silicon wafer.

In this research, the trapped particles that are not visible via conventional infrared transmission method are identified via the generated residual stress pattern. The magnitude of the residual stress fields associated with each defect are examined qualitatively and quantitatively. The stress field generated at the wafers bonded interface will look like a ‘bow tie’ pattern.

8105-25, Session 5
Circular Si waveguides from bulk Si by using laser reformation technique
S. Hung, S. Shiu, J. Chao, C. Lin, National Taiwan Univ. (Taiwan)

Silicon is on the verge of the choice for the photonics industry. Sub-wavelength optical wires fabricated using CMOS (Complementary Metal-Oxide-Semiconductor) materials and techniques promise economic integration of optics and electronics. On the CMOS transistor layer, which necessitates thermal conduction through the silicon substrate, the SiO2 layer typically has a thickness of below 100nm. However, such thin SiO2 underneath the Si waveguide creates excessive optical loss into Si substrate. It makes an incompatibility for the integration of optics and electronics. Here, we present a novel method to fabricate Si/SiO2 waveguides from regular Si wafers using laser reformation technique. Deep silicon ridges were firstly created using typical lithography and dry-etching process. Then, high-power excimer laser was used to illuminate the Si ridges. Under proper illuminating condition, the top portion of Si ridges would be melted and reshaped to circular-profile structure. The principle of laser reformation is to melt the Si ridges by a high-power laser pulse. During the period of liquid-phase Si, the surface tension forces the surface area to be the minimum, so the Si ridges are transformed to a circular-profile structure. Finally, high-temperature oxidation process was used to oxidize the unmelted portion below the top reformed structure. The circular cross section has a maximum diameter of about 600nm. The final oxidation of the unmelted neck, still over 1 um long, prevents optical loss due to negligible light coupling from the waveguide to the substrate. This technique allows great flexibility in design and fully compatible with the CMOS circuitry.

8105-27, Session 5
Development of cavity ring-down ellipsometry with spectral and submicrosecond time resolution
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Cavity-enhanced ellipsometry, using nanosecond pulsed lasers and without moving parts, is demonstrated to have submicrosecond time resolution. The ellipsometric phase angles are measured from the Fourier transform of the cavity ring-down experimental signals, with a sensitivity 0.01 degrees. The technique is applied to highly reflective surfaces, including total internal reflection, where the samples are placed within the evanescent wave. The technique can be generalized to broadband sources, such as from supercontinuum generation, allowing spectral resolution of thin films and monolayer samples.
Development and performance of zinc selenide nanowire based photodetectors

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This work will showcase recent developments in the growth and performance of zinc selenide (ZnSe) nanowire (NW) based photodetectors. Specifically the ability to transition from single NW devices to arrays of detectors will be discussed. We have demonstrated the growth of semiconducting nanowires (NWs) using the physical vapor transport (PVT) method and have found that the growth orientation can be controlled to generate NW arrays. These arrays show promising optical properties, including high transparency and for photoluminescence a high ratio of band edge/deep level defect emission. Such properties are critical for producing high quality photodetectors.

As-grown material was also used for fabrication of photodetectors. Metal-semiconductor-metal (MSM) structures were fabricated from an array of ZnSe NWs and Ti/Au contacts. The array of devices was tested using a 150W tungsten halogen lamp and an automated probe station. Current-voltage plots from -20 to 20V show generally symmetric behavior, with schottky barriers from the Ti/Au contacts. Upon illumination through a microscope objective lens, the nanowire devices showed orders of magnitude increase in photocurrent. These results will provide the foundation for developing nano-avalanche photodiodes (nanoAPDs), in which p-type and n-type NWs will be utilized to create high efficiency, low noise junctions.

Nanowire based heterostructures: fundamental properties and applications

A. Fontcuberta i Morral, M. Heiss, Ecole Polytechnique Federale de Lausanne (Switzerland)

Nanowires are filamentary crystals with a diameter of few to a hundred of nanometers. Thanks to their dimensions they are the perfect playground for fundamental studies and for improving devices such as solar cells. Nanowires are typically obtained by the vapor-liquid-solid method in which a metal catalyst is used for the gathering of the precursor species and nanowire growth. In most of the cases gold is used, though it has been shown to affect negatively the electronic and optical properties of semiconductors.

We fabricate ultra-high purity GaAs nanowires by avoiding the use of gold and by the use of molecular beam epitaxy (MBE) [1]. MBE offers also the unique possibility of growing with epitaxial quality on the nanowire facets [2]. Prismatic quantum wells and Stranski-Krastanov quantum dots are obtained with a very high quality, as demonstrated by the optical spectroscopy measurements [3,4]. Finally, we show how these nanowires are excellent candidates for the fabrication of solar cells [5] and high mobility transistors by using a modulation doped structure.

References:

Poole-Frenkel effect and phonon-assisted tunneling in GaAs nanowires

F. Leonard, Sandia National Labs., California (United States)

We present electronic transport measurements of GaAs nanowires grown by catalyst-free metal-organic chemical vapor deposition. Despite the nanowires being doped with a relatively high concentration of substitutional impurities, we find them inordinately resistive. By measuring sufficiently high aspect ratio nanowires individually in situ, we decouple the role of the contacts and show that this semi-insulating electrical behavior is the result of trap-mediated carrier transport. We observe Poole-Frenkel transport that crosses over to phonon-assisted tunneling at higher fields, with a tunneling time found to depend predominantly on fundamental physical constants as predicted by theory. By using in situ electron beam irradiation of individual nanowires, we probe the nanowire electronic transport when free carriers are made available, thus revealing the nature of the contacts.

Intentional doping and epitaxial regrowth of radial p-n silicon nanowires grown with alternative catalysts

J. M. Redwing, The Pennsylvania State Univ. (United States)

No abstract available

TBD

D. L. Huffaker, Univ. of California, Los Angeles (United States)

No abstract available

Epitaxy: an atomistic and kinetic view for all length scales (Keynote Presentation)

A. Madhukar, The Univ. of Southern California (United States)

No abstract available

CuO thin-film and nanowire for e-textile applications

J. Han, NASA Ames Research Ctr. (United States); A. J. Lohn, N. P. Kobayashi, Univ. of California, Santa Cruz (United States); M. Meyyappan, NASA Ames Research Ctr. (United States)

Device fabricated from materials in low dimensional structures can provide performance enhancement as well as open a new application. Integration of electronics into textile, referred as e-textile, offers an opportunity of future technologies. Here, copper (Cu) and copper oxide (CuO) based nanostructures are embedded for e-textile. Metallic Cu wire is utilized for a growth substrate, which is simultaneously used as a fiber
of mesh textile. Among various metals, Cu is promising as it is non-toxic and relatively abundant on earth. The motivating factor in Cu is ease of growth of nanostructure; the nanowire and thin-film are synthesized by self-catalytic vapor-solid growth. Simply heating Cu with oxygen gas can form CuO nanowire and thin-film according to the growth conditions. As key building blocks in e-textile, memory, transistor, and interconnect are presented. The resistive memory is comprised of CuO thin-film sandwiched within two orthogonal Cu fibers. For a metal semiconductor field effect transistor (MESFET), Schottky junction is used for gate to channel barrier. The Cu fiber and CuO thin-film are devoted for the gate and channel, respectively. For an interconnection, the neighboring fibers are electrically connected by transforming CuO nanowire into Cu nanowire. The thermal reduction of CuO is proved to be effective to make conductive nanowires.

8106-09, Session 2

**Growth of Group III nitrides: from films to nanowires to hybrid structures**

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In addition to traditional thin film structures, Group III nitride nanowires (NWs) have attracted considerable attention due to their high structural quality and unique physical properties enabling their use in nanoelectronics. To realize new applications, the controlled fabrication of NWs with defined geometries and electronic properties as well as their integration with planar device structures are required. Thus, it would be beneficial to develop a combination of 2D (films) and 3D (NWs) growth processes in a single reactor using traditional nitride technology to enable fabrication of novel hybrid structures. In this paper the enhanced capabilities of horizontal Halide Vapor Phase Epitaxy (HVPE) reactor are demonstrated by growth of: (a) GaN NWs and nanotubes (NTs), (b) GaN NW core/shell n/p epitaxial heterostructures (p-type shell over n-type core), (c) AlN NWs, and (d) GaN films on top of AlN NWs. Examples from (a) include the first demonstrations of vapor-liquid-growth growth of GaN NWs and vapor-solid growth of GaN NTs by HVPE. The [0001]-oriented GaN NWs were grown on Al2O3 (0001) substrate from catalytic gold particles and were 1 µm to 5 µm in length and 50±10 nm in diameter. The [0001]-oriented GaN NTs were grown by casting GaN shells over InN NWs with subsequent removal of InN core material by thermal decomposition and/or chemical etching. GaN NTs were 1 µm in length with typical wall thickness of 40±10 nm. The growth models, nanostructures/films/substrates epitaxial relationships, and correlation of growth conditions to the morphological/structural/electronic properties of NWs, NTs and hybrid structures will be presented in details.

8106-10, Session 2

**InGaN/GaN nanostructures grown by selective area growth for solid-state lighting**

T. Yeh, Y. Lin, L. Stewart, P. D. Dapkus, B. Ahn, S. Nutt, The Univ. of Southern California (United States)

Ordered GaN nanorod and nanosheets arrays were successfully grown by selective area growth using metalorganic vapor phase deposition (MOCVD). Hexagonal GaN nanorods with six non-polar planes and vertical nanosheets with parallel continuous non-polar sidewalls were grown on the patterned c-plane GaN bulk material using a pulsed MOCVD growth mode. A wurtzite crystal structure in the rods was confirmed by high-resolution transmission electron microscope (HRTEM) analysis. Unlike the general III-V nanowires, no stacking faults were found in the GaN nanorods eliminating the possible influence of the stacking faults on the electrical conductivity along the nanorods. InGaN/GaN multiple quantum wells (MQWs) were grown on GaN nanostructure arrays. Cross-section TEM images reveal a core-shell heterostructures on GaN nanorods and nanosheets. Photoluminescence measurements were performed to confirm the light emission from the MQWs. Strong emission peaks were observed from the nanostructures. We believe the dominant emission peak results from the large exposed surface area of the nonpolar (1-100) sidewalls of GaN nanostructures. Active regions formed on nonpolar planes have reduced piezoelectric fields and potentially increase the radiative recombination efficiency for the LED applications. This work was supported in part by NSF through Award ECS-0507270 and by the Center for Energy Nanoscience, an Energy Frontier Research Center funded by the U.S. Department of Energy, Office of Basic Energy Sciences under Award Number DE-SC0001013.

8106-12, Session 3

**Towards epitaxial integration of metallic nanostructures into photonic devices**

S. R. Bank, A. M. Crook, H. P. Nair, V. D. Dasika, The Univ. of Texas at Austin (United States)

The epitaxial integration of metals and semiconductors offers tantalizing possibilities to realize new functionality from (nano)photonic devices. Unfortunately, metals are typically relegated to the periphery of semiconductor devices, due to practical challenges associated with their integration, including interfacial instability and epitaxial incompatibility. ErAs and the other semimetallic rare-earth monopnictides provide a potential pathway to integration, because they may be epitaxially integrated with high-quality III-V semiconductors as both nanostructures and films, with thermodynamically stable interfaces. Such materials could greatly benefit the field of plasmonics where progress towards active devices, such as light-emitting diodes that make use of the Purcell enhancement, is hampered by the design constraint that metallic (nano) structures must remain at the device periphery. Indeed, this limitation renders even structures as simple as a quantum well/dot surrounded by parallel metal plates exceedingly challenging to fabricate. We show how this and other similarly tantalizing structures can now be grown directly in a single epitaxial growth run, using ErAs and III-V semiconductors. We review our on-going efforts to epitaxially integrate semimetallic hetero- and nano-structures into the heart of III-V devices, highlight some important device applications, and discuss key challenges. In particular, we examine the optical quality of III-V material surrounding the ErAs nanostructures and demonstrate that high-quality III-V emitters may be brought into very close proximity to ErAs nanostructures, ~10 nm, without degrading their emission characteristics. This finding is very promising for harnessing Purcell enhancements in light-emitting diodes. The authors acknowledge ARO, AFOSR, and NSF for support.

8106-13, Session 3

**Integrated amplifying nanowire FET for surface and bulk sensing**

C. O. Chui, K. Shin, Univ. of California, Los Angeles (United States)

Quasi-one-dimensional semiconductor nanowires are uniquely suitable for very high sensitivity detection applications. Their large surface area-to-volume ratio and tiny volume are respectively attractive for surface sensing, e.g. biochemical molecules, and bulk detection, e.g. radiation. Commonly configured as the substrate-gated field-effect transistor (FET) channel, the exposed semiconductor nanowires atop an insulator layer have exhibited very high detection sensitivity on immunoglobulins and nucleic acid molecules. For charged biomolecule sensing in particular, the charge-to-current signal transduction occurs at the nanowire FET front-end which thereby minimizes parasitics and thus noise. This scheme additionally requires no imaging equipments and the sensors themselves are readily interfaced and integrated with readout electronics. The detection sensitivity, and especially the limit of detection (LOD) and limit of quantification (LOQ) that takes into account the blank and signal
8106-14, Session 3

Fabrication and in situ testing of solid-state all nanowire Li ion batteries
A. A. Talin, D. Ruzmetov, H. Lezec, V. Oleshko, A. V. Davydov, S. Krylyuk, National Institute of Standards and Technology (United States)

The ability to measure the morphological, chemical, and transport characteristics with nanoscale resolution in electrochemical energy storage devices is critical for understanding the complex interfacial reactions and phase transformation that accompany cycling of secondary batteries. In this paper we will describe the use of an all-nanowire Li ion battery for in situ characterization of charge and discharge reactions. The nanobatteries consist of a metalized core, a LiCoO2 cathode, LiPON solid electrolyte, and a thin film Si anode. Measuring several micrometers in length and several hundred nanometers in diameter, the nanobatteries can be readily imaged in a transmission electron microscope. We test the nanobatteries using a piezo actuated electrical nanoprobe. In addition to being well suited for in situ electrochemical testing, nanowire batteries may also have other advantages, such as superior strain accommodation. To investigate this hypothesis, we also characterize in situ thin film batteries fabricated using similar methods.

8106-15, Session 4

Thin film semiconductor strain engineering for optoelectronic devices
M. S. Leite, E. Warmann, H. A. Atwater, California Institute of Technology (United States)

Historically in materials science, the limited number of substrates available in bulk form significantly limits epitaxial growth versatility. We suggest an approach to elastically relax the strain of single crystalline materials. Thus, it is stable against crack formation. The film is then bonded to a handle cheap substrate, e. g. SiO2/Si. X-ray diffraction and transmission electron microscopy measurements were used to quantify the template relaxation and reconstruct its unit cell, in very good agreement with Vegard’s Law. Photoluminescence measurements showed the dependence of band gap offset and strain relief. The creation of a dislocation-free template with arbitrary lattice parameter has the potential for new crystalline material designs for technologies such as solar cells, which will be discussed.

8106-16, Session 4

Recent advances toward III-V based micro/nano pillar solar cells

No abstract available

8106-17, Session 4

Metal oxide nanowire growth for nanotechnology-enhanced device applications
M. Oye, NASA Ames Research Ctr. (United States)

No abstract available

8106-18, Session 4

Synthesis of crystalline ZnO nanostructures on arbitrary substrates at ambient conditions
P. Nayyar, K. Vabbina, N. Pal, Florida International Univ. (United States); A. P. Nayak, M. S. Islam, Univ. of California, Davis (United States)

No abstract available

8106-19, Session 5

Transport in fused InP nanowire device in dark and under illumination: Coulomb staircase scenario
T. Yamada, Santa Clara Univ. (United States) and Univ. of California, Santa Cruz (United States); H. Yamada, Univ. of California, San Diego (United States); A. J. Lohn, N. P. Kobayashi, Univ. of California, Santa Cruz (United States) and Univ. of California, San Diego (United States)

Detailed DC electron transport analysis is performed for a device consisting of fused conical indium phosphide nanowires (InP NWs) bridging two hydrogenated n+-silicon electrodes. These NWs are a few microns long and 100 nm wide. The current-voltage (I-V) plot at room temperature exhibits an unusual staircase shape with a period of ∼1 V in dark, but under increasing light illumination, the device conductance gradually increases and the staircase gradually disappears. We explain this observation in terms of the Coulomb staircase scenario - a tiny Coulomb island is created between two tunneling barriers (possibly around the fused portion) and transport is dominated with tunneling. Electrons tunnel in and out of the Coulomb island in a correlated manner, resulting in the staircase I-V in dark. Light illumination raises the electron quasi-Fermi level and the relevant tunneling barriers are buried, causing the staircase I-V to disappear. Although multiple NW pairs bridge electrodes, one pair practically dominates transport. This is because tunneling depends exponentially on the barrier width with the sensitivity as small as Angstroms (hence this is the principle of STM), and unavoidable scattering in physical dimension around the tunneling barriers will result in a significant conductance difference from one NW pair to another. Based on the Coulomb island dimension deduced from the voltage period, NWs are shown unintentionally n-doped with 10^15-16 cm^-3. The quasi-Fermi level difference in dark and under light
illuminated is about 25-85 meV, and this is interpreted as a tunneling barrier height.

8106-21, Session 5

Local carrier dynamics in InGaN quantum wells studied by scanning near-field optical microscopy

A. Kaneta, M. Funato, Y. Kawakami, Kyoto Univ. (Japan)

The progress of growth technology has led to the achievement of highly efficient InGaN-based light-emitting diodes (LEDs) in the violet to blue spectral region. However, further improvement of emission efficiency is required, overcoming the problem of the efficiency droop. Many research groups have studied emission mechanism in InGaN quantum wells (QWs). However, most of them were based on macroscopic spectroscopy. The emission mechanism is unclear because nanometer scale potential fluctuation is strongly correlated with recombination dynamics in InGaN QWs. Therefore, nanoscopic spectroscopy is necessary to clarify the correlation between local structures and recombination mechanisms of InGaN QWs. To date, we have developed temporally and spatially resolved photoluminescence (PL) spectroscopy using a scanning near-field optical microscope (SNOM) to investigate the recombination dynamics in InGaN single QWs (SQWs). As an example, we have succeeded in clarifying the correlation between the radiative/ nonradiative recombination processes and threading dislocations as well as carrier diffusion/localization processes by comparing SNOM-PL mapping and atomic force microscope taken at the same scanning area. However, a conventional SNOM based on one fiber probe cannot detect the detailed carrier motion diffused out of an aperture. Therefore, we have developed a dual-probe SNOM, where a photoexcitation probe is fixed at specific position while a light collection probe is scanned around the photoexcitation probe, and succeeded in visualizing the anisotropic carrier diffusion in an InGaN SQW. Thus, it is worth emphasizing that this technique can be a versatile tool for assessing photonic phenomena such as transport and recombination processes of various elemental excitations.

8106-22, Session 5

Scanning photocurrent microscopy in single nanowire devices

D. Yu, Univ. of California, Davis (United States)

No abstract available

8106-23, Session 5

Epitaxial growth of ZnO nanowires on retroreflector microspheres and the resulting light channeling and plasmonic properties

S. M. Prokes, U.S. Naval Research Lab. (United States)

No abstract available

8106-24, Session 6

Nanoepitaxy of regularly arranged GaN-based nanocolumns and related nano-devices

(K keynote presentation)

K. Kishino, S. Ishizawa, K. Yamano, J. Kamimura, A. Kikuchi, T. Kouno, Sophia Univ. (Japan)

No abstract available

8106-25, Session 6

Growth of ZnO-based nanorod heterostructures and their photonic device applications

J. Yoo, S. T. Picraux, Los Alamos National Lab. (United States); G. Yi, Seoul National Univ. (Korea, Republic of)

Position-controlled and vertically-aligned semiconductor nanoscale heterostructures can serve as ideal components for photonic devices because the structures provide not only integratable building blocks but also give unique properties such as enhanced light absorption, waveguiding, and large active volumes compared to thin films and bulk materials. This good versatility and performance of photonic devices based on nanomaterials can be accomplished by fabrication of nanoscale heterostructures with compositional modulation along either the axial or the radial direction. Semiconductor nanorods are particularly promising since high-quality semiconducting building blocks can be easily obtained. Additionally, growth of semiconductor nanorods can give insight into the nanoepitaxial growth on various substrates. Such novel nanoepitaxy techniques make it possible to fabricate monolithic integrated circuits and sophisticated quantum devices on otherwise incompatible substrates.

Here, we present research results on ZnO nanorod heterostructures and their photonic device applications from the viewpoint of using position-controlled growth for integration and fabrication of quantum structures for controlling physical properties. In this research, we used a combination of catalyst-free metal-organic vapor phase epitaxy and lithographic techniques to prepare position-controlled vertically aligned ZnO nanorod heterostructures. Using the combined approach, ZnO/MgZnO and ZnO/InxGa1-xN nanomaterial heterostructures were prepared successfully. The position-controlled ZnO-based nanomaterial heterostructures exhibited quantum confinement indicating the formation of well-defined heterostructures. Based on these structures three-dimensional nanooarchitecture photonic devices such as light-emitting diode arrays and embedding quantum structures are demonstrated.

8106-26, Session 6

Metal-organic frameworks: charting a course to device integration

M. D. Allendorf, Sandia National Labs., California (United States)

Among the new classes of nanomaterials created during the past decade, metal-organic frameworks (MOFs) are possibly the most versatile. MOFs represent the “inside out” of nano: these supramolecular, crystalline materials are nanoporous and display record-setting surface areas. Unlike many other nanoporous materials, MOFs are inorganic-organic hybrids composed of an organic “linker” group connected to a metal ion such as Zn(II). This feature creates unprecedented synthetic flexibility, combining the vast organic reaction chemistry with rational structural design enabled by metal-linker coordination bonds. As a result, both pore geometry and chemical features can be tailored for specific applications, which to date include gas storage, separations, drug delivery, and chemical sensing. However, integration of MOFs with electronic devices is still in its infancy, even though their highly ordered structure suggests the potential for defect-free electronics in the single-digit nm scale. This presentation will provide an introduction to MOFs and their properties that are attractive for use in electronic devices. Specific examples developed will then be presented, including growth of thin films on micro-electromechanical systems (MEMS) for chemical sensing, nanolithography to create nanoparticles and nanowires from silver-infiltrated frameworks, and luminescent MOFs in which manipulation of nanoscale structure enables the spectrum, intensity, and timing of light output to be tuned. Finally, we will introduce a roadmap to MOF device integration intended to stimulate new research efforts and interdisciplinary collaboration.
8106-27, Session 6
Enhanced conductivity of ErAs nanoparticle containing tunnel junctions via bandgap engineering
R. Salas, E. M. Krivoy, A. M. Crook, H. P. Nair, S. R. Bank, The Univ. of Texas at Austin (United States)

Low-loss tunnel junctions are essential components of a number of optoelectronic devices and are particularly important for serially connecting the junctions in multijunction solar cells. Placing semimetallic ErAs nanoparticles at the pn junction greatly enhances tunneling currents by breaking the band-to-band tunneling process into two smaller back-to-back Schottky barriers. Modifying the size and density of the embedded ErAs nanoparticles provides a route to enhance the conductivity of the junctions. In addition, tuning of the Schottky barrier height through compositional grading of the III-V material can further improve the conductivity by lowering the bandgap of the material at the interface of the barrier. We investigated the combined benefits of both techniques in this work by refining the growth parameters of the nanoparticles and digitally grading the GaAs to In(x)Ga(1-x)As on the n-type side. Samples were grown on a Varian Gen II molecular beam epitaxy system on n-type GaAs (100) substrates. Abrupt junctions and compositionally graded junctions of varying thicknesses and strains were grown with and without nanoparticles at the interface. Graded regions were kept thin to avoid increased optical absorption and performance degradation. Preliminary results show a 7x improvement in the forward bias current over abrupt nanoparticle junctions. Further enhancements are anticipated with the use of lattice matched dilute-nitrides for the n-type side and mixed arsenide-antimonide-nitrides for the p-type side. These improvements in conductivity have the potential to advance the performance of many optoelectronic devices, especially concentrator multijunction solar cells.

8106-28, Session 7
Nanocomposites for thermoelectric power generation: rare-earth metal monoaonitomide nanostructures embedded in InGaSb and InSbAs ternary alloys
N. P. Kobayashi, T. Onishi, Univ. of California, Santa Cruz (United States); E. Coleman, G. S. Tompa, Structured Materials Industries Inc. (United States)

Technologies that can harvest untapped waste heat energy by utilizing thermoelectrics are gaining strong attention. Thermoelectrics that convert heat directly into electric power are solid-state heat engines in which energy conversion efficiency is limited by the second law of thermodynamics. Thermoelectric figure of merit (ZT) depends on three material properties; electrical conductivity, thermal conductivity, and Seebeck coefficient. ZT of a thermoelectric material needs to be at least 1.0 to envision practical implementations. Despite extensive investigation on both material and device aspects of thermoelectrics to improve energy conversion efficiency, traditional bulk semiconductors have been suffering from ZT ∼ 1.0 or below for many years. Maximizing ZT simply requires that electrical conductivity and Seebeck coefficient be high to reduce Joule heating and to increase energy conversion efficiency while thermal conductivity needs to be low to maintain temperature gradient across a thermoelectric material. Unfortunately these three material properties are closely correlated each other in homogeneous bulk semiconductors. Recent demonstrations that employ various semiconductor materials tuned at the nanometer-scale (nanomaterials) have shown great promise in advancing thermoelectrics. Among a wide range of nanomaterials, we focus on “nanocomposites” in which semimetallic nanostructures are epitaxially embedded in a ternary compound semiconductor host to tune the three material properties independently. We demonstrate co-deposition of erbium monoaonitomide (ErSb) and In1-xGaxSb or InAsySb1-y ternary alloy to form nanometer-scale ErSb structures within the ternary alloys using low-pressure metal organic chemical vapor deposition (LP-MOCVD). The grown nanocomposites are structurally and thermoelectrically analyzed to assess their potential for advanced thermoelectric power generation.

8106-29, Session 7
Growth of semimetallic ErAs films epitaxially embedded in GaAs
A. M. Crook, H. P. Nair, D. A. Ferrer, S. R. Bank, The Univ. of Texas at Austin (United States)

We investigate the critical growth parameters for expitaxially embedding ErAs films in GaAs, with application to electronic and photonic devices. Traditionally, growth of GaAs on ErAs films resulted in antiphase domain formation, due to the additional rotational symmetry of the rocksalt crystal structure of ErAs, compared with the zincblende GaAs. We leverage the recent discovery that, below a critical areal density during growth, surface erbium adatoms will preferentially incorporate into subsurface ErAs nanoparticles. As compared to traditional layered heterostructure growth, this method offers the advantage that a thin layer of GaAs floats on the surface and remains registered to the substrate, preventing antiphase domain formation during subsequent III-V growth. Samples were grown on a Varian Gen II solid-source molecular beam epitaxy system to investigate the role of ErAs growth rate and GaAs cap thickness on the formation of a surface ErAs nanoparticle layer - one of the experimentally observed failure mechanisms for the embedded growth mode. High resolution transmission electron microscopy (HR-TEM) was used to characterize the integrity of the film as well as to observe the formation of antiphase domains in the GaAs overgrowth. By keeping the GaAs cap sufficiently thin and the ErAs growth rate sufficiently low, we show full ErAs films can be embedded in GaAs without exceeding the critical areal density of surface erbium for formation of a surface ErAs nanoparticle layer. This approach provides a path towards the realization of plasmonic devices based on the epitaxially integration of a semimetal/semiconductor system.

8106-30, Session 7
Epitaxial rare-earth nanostructures in III-V semiconductors
B. Schultz, Univ. of California, Santa Barbara (United States)

No abstract available

8106-31, Session 7
Broadband photodetection in Si:Ge alloy nanocrystals
M. Jo, Pohang Univ. of Science and Technology (Korea, Republic of)

No abstract available

8106-32, Session 8
III-V nanowires and nanowire heterostructures: controlling the growth and nanoscale properties
S. Gradecak, S. K. Lim, S. Crawford, M. Tambe, Massachusetts Institute of Technology (United States)

No abstract available
Dopant and heterostructure profiles in semiconducting nanowire
D. E. Perea, S. T. Picraux, Los Alamos National Lab. (United States)

The fundamental operation of many silicon and germanium nanowire devices relies on the ability to controllably modulate the composition to create both heterostructures as well as and modulation-doped nanowires with compositionally-abrupt junctions. The vapor-liquid-solid (VLS) growth process is an approach to bottom-up nanowire synthesis that provides an apparently straightforward route to axial heterostructure formation and dopant incorporation. However, the formation of abrupt heterojunctions remains a challenge utilizing VLS growth from the conventional gold catalyst. Moreover, controlled doping with electronic impurities also remains an important challenge in large part due to a lack of a technique or tool sensitive enough to directly quantify the distribution and dopant concentration in individual nanowires. In this talk, I will discuss use of atom probe tomography (APT) as a tool to directly map the 3D dopant distribution and axial heterojunction profiles between Si and Ge nanowires. Dopant depletion studies along the nanowire growth axis reveal a long depletion profile of hundreds of nanometers which is much longer compared to the Si-Ge heterojunction width which is on the order of the nanowire diameter. A dopant incorporation model suggests that the interfacial width depends on the solute solubility in the liquid catalyst. I will further discuss a new approach of using a liquid AuGa alloy catalyst to create a sharper axial heterojunction in Ge-Si, relative to that obtained using pure Au. Finally, I will conclude with some results of increasing the pn-junction sharpness in Si and Ge nanowires using an alloy catalyst.

Ultralow-voltage and efficient electrostatic precipitation using metal catalyzed silicon nanowhiskers
J. Oh, A. P. Nayak, Univ. of California, Davis (United States); S. Kaya, Ohio Univ. (United States); M. S. Islam, Univ. of California, Davis (United States)

This paper presents our experimental results on gas ionization at atmospheric pressure at very low bias voltages (less than 100 Volts) using gold-catalyzed silicon nanowhiskers. An advantageous combination of field enhancement on nanoscale silicon tips, surface states introduced by defects, metal impurities and bandgap widening through quantum confinement contributes to such lowering of ionization voltage. Usual range of ionization voltage is 5,000 - 15,000 Volts in standard electrostatic precipitators used for pollution control in oil and coal-fired industrial power plants or in the removal of toxic and harmful solid particulate from the gas exhaust stream. Our results show that VLS processes offer distinctive benefits by synthesizing nanostructures with unrivaled dimensions along with high density of surface states contributed by the impurities and immobilized free radicals on the whisker-surface.

Indium phosphide nanowires integrated directly on carbon fiber
A. J. Lohn, T. J. Longson, N. P. Kobayashi, Univ. of California, Santa Cruz (United States)

Much attention has been given to integration of group III-V semiconductors onto silicon platforms to combine superior optical and electrical properties of group III-V semiconductors with mature processing capabilities of silicon. Less effort however, has been directed towards integration on other group IV elements such as carbon. Carbon fiber is generally utilized as a structural material in a wide variety of products because of its light weight and large stiffness and tensile strength. Carbon fiber can also offer additional advantages of large electrical and thermal conductivities when integrated with group III-V semiconductors. We have demonstrated the growth of a group III-V semiconductor binary alloy, indium phosphide (InP), directly on carbon fibers thereby enabling a union of semiconductor and structural materials. Carbon fibers with diameter approximately 500 nm were prepared by electrospinning solutions of polyacrylonitrile (PAN) and dimethylformamide (DMF) followed by carbonization at 750 C in inert atmosphere. Gold nanoparticles were dispersed on the fibers to catalyze metal organic chemical vapor deposition (MOCVD) growth of InP nanowires. X-ray diffraction indicates that despite the graphite surface, InP nanowires adopt primarily zinc blende crystal structures. Geometrical parameters have been determined by scanning electron microscopy and elemental analysis has been carried out using energy dispersive spectroscopy. Optical properties of InP nanowires integrated on carbon fibers are also investigated. Our demonstration is a first step towards direct integration of semiconductors onto one of the important structural materials with the view toward a new class of material platform for solid-state devices.
8107-01, Session 1

Light-induced disorder in liquid-crystalline elastomers for actuation
A. Sanchez-Ferrer, ETH Zurich (Switzerland)

Liquid-Crystalline Elastomers (LCEs) are materials which combine the entropic properties of a crosslinked polymer melt with the enthalpic properties of a liquid-crystalline state of order. LCEs show unique characteristics: visco-elasticity and order at the same time in one system. The elastic and the viscosity properties come from the crosslinking and friction of the polymer chains, respectively, while the orientation comes from the mesophase which keeps the polymer backbone aligned. LCEs behave as normal polymer networks or rubbers when no energy-storing mesophase is present. This state of disorder can be induced by means of temperature or light. Thermally, the change in shape of LCEs can easily reach 300% when all the enthalpy stored by the mesophase is released and the crosslinked polymer chains are free to move and adopt a random coil conformation. The light-induced local disorder can be achieved when shape-changing molecules are incorporated in the LCE matrix. These compounds are able to absorb light, rearrange themselves in a new shape and thus disturb the mesophase. This results in the molecules that are keeping the order no longer being able to sustain the retractive force from the polymer backbone, and the material contracts exerting an actuating force. But, how does a light sensitive side-chain LCE elastomer behave? And a main-chain LCE? What about nematics or smectics? Is a different kind of actuation, besides the common retractive force possible? To answer this questions, new chemistry needs to be developed, together with new physics to understand the systems, and new applications need to be created.

8107-02, Session 1

In-situ control of shape and molecular order in liquid crystalline polymeric nanoparticles
S. Tsoi, J. Zhou, U.S. Naval Research Lab. (United States); S. Wu, Agilent Technologies, Inc. (United States); C. Spillmann, J. Naciri, N. Hashemi, U.S. Naval Research Lab. (United States); T. Ikeda, Tokyo Institute of Technology (Japan); B. Ratna, U.S. Naval Research Lab. (United States)

Two types of stable 100-nm liquid crystalline polymeric nanoparticles were synthesized and when immobilized on solid substrates, actuation of their shape and internal molecular order, respectively, experimentally demonstrated. The first type contains azo-benzene-based liquid crystals fused into an elastomeric network. The shape of the nanoparticles can be reversibly altered by illumination with light. AFM measurements reveal that exposure of the immobilized nanoparticles to UV radiation results in reduction of their height and concomitant increase of the lateral size. Conversely, exposure to visible light increases the height of the nanoparticles and decreases their lateral size. The amount of the strain achieved is controlled by the exposure dosage and can reach values as high as 20%. The second type of nanoparticles studied is gel-like and contains cyanobiphenyl liquid crystals 5CB and 8CB. The nanoparticles are immobilized on a metallic substrate and Scanning Kelvin Probe Microscopy is employed to probe effect of electrostatic field on them. Experimental data and finite element modeling suggest that exposure to the field induces collective mesogen re-orientation inside the nanoparticles without noticeable change in their shape.

8107-03, Session 1

Opto-mechanical parameters of liquid crystal elastomers with carbon nanotubes
N. Torras, K. E. Zinoviev, H. Campanella, C. J. Camargo, J. Esteve, Ctr. Nacional de Microelectronics (Spain); E. M. Campo, Univ. of Pennsylvania (United States); J. E. Marshall, E. M. Terentjev, Univ. of Cambridge (United Kingdom)

Nematic liquid-crystal elastomers (LCE) have demonstrated great potential as actuators. Due to unidirectional orientation order of the mesogenic groups the material suffers uniaxial contraction when heated. The heat might be supplied from outside or generated inside the material and the latter gives additional functional capabilities for a range of applications. Energy generation inside the material can be provided by illumination of the material if the elastomer contains light absorption component. Liquid crystal elastomers enriched with the carbon nanotubes combine thermoelastic properties of nematic LCEs and the capability of carbon nanotubes (CNT) to absorb infrared and visible light and transform it into thermal energy. The studies of photo induced actuation of LCE-CNTs present lack of phenomenological step despite intuitive simplicity and the existing theory of contraction mechanism. This work was aimed at experimental characterization of the material with the purpose of general understanding the macro properties of it and of behavior of the elastomer when illuminated by light and with the final objective to facilitate the design of optical actuators on the basis of LCE-CNTs. The parameters like absorption spectra and absorption coefficients of the material as a function of CNTs concentration have been studied. Temperature induced three dimensional deformations were compared with the photo-induced deformations monitored using SEM and conventional optical microscopy techniques combined with thermal imaging done with the IR camera. The basic test structures, cantilever beams and circular plates, have been applied for studies of thermal and mechanical properties of the material. The work was done within the EU FP7 project (NMP 228916).

8107-04, Session 1

Light-responsive actuation materials based on the photodeformable liquid crystal polymers
Y. Yu, Fudan Univ. (China)

In recent years, photodeformable polymer materials have experienced a vigorous development due to their potential applications such as artificial muscles, photomobile actuators, Micro Opto Mechanical System (MOMS) and so on. On the other hand, as a combination of polymer networks and liquid crystals (LC), crosslinked LC polymers (CLCPs) exhibit such unique properties as elasticity, anisotropy, stimuli-responsiveness and molecular cooperation effect. In this work, a good method was developed to incorporate widely-used photodeformable trigger molecules, azobenzenes, into side chains of polymer networks, in which the azobenzenes units are able to act as mesogens. Then the cooperative motion of liquid crystals was utilized to magnify the microscopic structural change of azobenzene units to a significant macroscopic deformation of the whole material upon irradiation of UV light. For example, photoinduced bending was successfully achieved by inducing an asymmetry contraction in the azobenzene CLCP films. Recently, such interesting motions as a motor rotation, an inchworm walk, and a robotic arm motion fully controlled by light have also been demonstrated with the use of CLCP/polyethylene laminated films. Most lately, azotolane-containing liquid crystal polymer networks have been developed whose deformations can be induced by visible light and even directly by sunlight. Furthermore, full-light-driven microrobots,
microwaves and micropumps have also been fabricated. With these modes of deformations and all plastic actuators, one can convert the light energy directly to mechanical energy, which leads to such applications as micro- or nano-mechanical machines.

8107-05, Session 1

Light-activated shape memory of glassy, azobenzene liquid crystalline polymer networks

K. Lee, H. Koerner, R. Vaia, T. J. Bunning, T. White, Air Force Research Lab. (United States)

We present a distinctive approach to generating reconfigurable light-activated shape memory behavior of glassy azobenzene liquid crystalline polymer network (azo-LCN). Linearly polarized, eye-safe 442 nm light is used to photo-fix temporary shapes in both cantilever and free-standing geometries. The original permanent shape is all-optically recovered with exposure to circularly polarized light. All-optical, isothermal shape memory cycles (photo-fixing and photo-recovery) will be discussed. Due to the glassy nature of the azo-LCN materials utilized here, the all-optical shape memory can be combined with thermal-shape fixing that is independent of the photo-fixing of the material, yielding substantial functionality in a single adaptive material.

8107-06, Session 1

Photoactuators on the base of polymeric elastomers and carbon nanotubes

I. Krupa, M. Omastová, J. Mosnáček, M. Micušik, K. Czaniková, M. Iliciková, P. Kasák, Polymer Institute (Slovakia)

Carbon nanotubes (CNT) represent attractive and challenging structures for formation various, especially electro-conductive polymeric nanocomposites. Other interesting feature of polymer/CNT nanocomposites is their photoactuating behaviour. The main problem is that CNT do not spontaneously suspend in polymers, thus the chemistry and physics of filler dispersion is a major issue in actual research. One way to achieve a homogenous CNT dispersion is to decrease the surface energy of this filler via surface modification. This work is focused on the non-covalent modification of CNT by various surfactants and their characterization. Modified CNT were used for preparation of nanocomposites with an elastomeric matrix from solution. The orientation of CNT within a matrix was ensured by cross-linking.

Acknowledgements.

Project NOMS which is funded by the European Commission under contract no. 228916

8107-07, Session 2

Nanotube micro- and nano-opto-mechanical systems

B. Panchapakesan, P. Xu, Univ. of Louisville (United States)

Ever since the discovery of carbon nanotubes, its electro-mechanical actuation has been well studied. However no such investigation has happened in the area of photomechanical actuation of nanotubes. When light is irradiated on nanotubes, they undergo stretching, relaxation, bending and actuation. Several attempts have been made in the past to combine nanotubes with polymeric materials to create photomechanical actuators that release the stored energy on infra-red trigger. However these polymers are neither compatible with MEMS process nor the actuation was reversible.

In this paper we discuss our efforts in the development of micro/nano-optomechanical actuators. Using a combination of SU8 patterning process and carbon nanotube films, we demonstrated micro-optomechanical actuators that exhibited a displacement of 24 microns for 400 micron long cantilever at 170 mW of laser power. Since then several new devices has been created using the same process. In one such study micro-grippers were shown to manipulate polystyrene microspheres and cells at about 240 micro-watts of laser power. In another study, we were able to demonstrate photomechanically actuated micro-mirrors about 500 microns in diameter with large rotational angles of 19 degrees at only 170 mW. Finally, we integrated optical filters on the rotational micro-mirrors to demonstrate 10:1 and 20:1 wavelength selectivity of the mirror using red and green filters and their corresponding wavelengths. All these studies show the potential for new area of optomechanical systems that can rival silicon based electrically driven MEMS technologies. Currently we are working on integrating our process with all silicon technologies. Further, integration of 50 nm nano-needles with both SU8 as well as silicon grippers creating the first opto-mechanically actuated nano-grippers for nano-positioning and manipulation. Such grippers have the potential for nano-manipulation of particles, nano-assembly and nano-lithography. We will discuss our efforts in all these new area of nano-opto-mechanical systems.

8107-08, Session 2

Microstamped opto-mechanical actuator for tactile displays

C. J. Camargo, N. Torres, H. Campanella, Ctr. Nacional de Microelectrónica (Spain); J. E. Marshall, Univ. of Cambridge (United Kingdom); K. E. Zinoviev, Ctr. Nacional de Microelectrónica (Spain); E. M. Campo, Univ. of Pennsylvania (United States); E. M. Terentjev, Univ. of Cambridge (United Kingdom); J. Esteve, Ctr. Nacional de Microelectrónica (Spain)

Over the last few years, several technologies have been adapted for use in tactile displays, such as thermo-pneumatic actuators, piezoelectric polymers and dielectric elastomers. None of these approaches offers high-performance for refreshable Braille display system (RBDS), due to considerations of weight, power efficiency and response speed. Optical actuation offers an attractive alternative to solve limitations of current-art technologies, allowing electromechanical decoupling, elimination of actuation circuits and remote controllability. Creating these optically-driven devices requires liquid crystal - carbon nanotube (LC-CNT) composites that show a reversible shape change in response to an applied light. This work thus reports on novel opto-actuated Braille dots based on LC-CNT composite and silicon mold microstamping. The manufacturing approach succeeds on producing blisters according to the Braille standard for the visually impaired, by taking shear-aligned LC-CNT films and silicon stamps. For this application, we need to define specifically-shaped structures. Some technologies have succeeded on elastomer microstructuring. Nevertheless, they are not applicable for LC-CNT molding because they do not consider the stretching of the polymer which is required for LC-CNT fabrication. Our process demonstrates that composites micro-molding and their 3-D structuring is feasible by silicon-based stamping. Its work principle involves the mechanical stretching, allowing the CNTs alignment, which is an important aspect to act the LC-CNT due to the alignment-dependence of its actuation.

Our European Union FP7 NOMS (Nano Optical Mechanical Systems) Consortium aims at building a tactile tablet for the visually-impaired, by taking shear-aligned LC-CNT films and silicon stamps. For this application, we need to define specifically-shaped structures. Some technologies have succeeded on elastomer microstructuring. Nevertheless, they are not applicable for LC-CNT molding because they do not consider the stretching of the polymer which is required for LC-CNT fabrication. Our process demonstrates that composites micro-molding and their 3-D structuring is feasible by silicon-based stamping. Its work principle involves the mechanical stretching, allowing the CNTs alignment, which is an important aspect to act the LC-CNT due to the alignment-dependence of its actuation.

Our European Union FP7 NOMS (Nano Optical Mechanical Systems) Consortium aims at building a tactile tablet for the visually-impaired. This will be the main application of the microstamped optomechanical actuator concept presented in this work.

8107-09, Session 2

Opto-thermal actuation in double layer polymer microcantilevers

C. Martin-Olmos, L. G. Villaneva, A. Llobera, Ctr. Nacional de
Microeléctrica (Spain) and Instituto de Microeléctronica de Barcelona (Spain) and Consejo Superior de Investigaciones Científicas (Spain); A. Voigt, G. Gruetzner, Microresist Technology (Germany); M. Arroyo, M. Calleja, Ctr. Nacional de Microeléctronica (Spain) and Instituto de Microeléctronica de Madrid (Spain) and Consejo Superior de Investigaciones Científicas (Spain); F. Perez-Murano, Ctr. Nacional de Microeléctronica (Spain)

Actuation at the micro scale and nanoscale without direct contact is of high interest in different areas, as for example the manipulation of small objects for cell manipulation. We present a simple fabrication process of photo-thermal actuators using low-cost modified photosensitive materials.

The fabrication of these photo-thermal actuators was performed using two layers of polymers: one layer is epoxy-based resist with high optical transparency that allows the realization of high aspect ratio patterns for micromachining applications with high resolution. The second polymeric layer is obtained using the same resist but doped with polyaniline. Polyaniline is an organic dye that changes the absorbance spectrum of the bare epoxy based resist, providing the polymer with absorbance bands in the visible-infrared range. Absorbed photons undergo a phononic transition, resulting in localized thermal effects.

Cantilevers with dimensions in the following ranges have been fabricated: length: 200-450 µm; width: 50 µm and thickness: 4-8 µm. According to this, the elastic constant of these cantilevers range from 0.4 N/m to 0.05 N/m (assuming a Young’s modulus value of 4.02 GPa).

Two sets of experiments have been performed, one at a constant temperature and measuring deflection (only thermal actuation) and the other locally applying a constant incident power by means of laser focused in the actuator, and measuring the deflection (opto-thermal actuation).

Using the theoretical calculations to analyze the experimental data, it has been possible to determine the coefficient of thermal expansion (CTE) and the thermal conductivity of the doped resist. These measurements show that systems fabricated with such technology will be valid as actuators, with a very low fabrication cost and high displacement.

8107-11, Session 3

Materials science: the key to revolutionary breakthroughs in micro-fluidic devices

M. Czugała, B. Ziółkowski, R. Byrne, D. Diamond, F. Benito-Lopez, Dublin City Univ. (Ireland)

Nowadays, precise flow control, provision of exact reagent amounts, contamination prevention between reagents, autonomy, disposability, and low-cost manufacture are factors that can not be found together for micro-fluidic valves.

Valves made using photo-responsive materials are of great interest as functional materials within micro-fluidic systems since actuation can be controlled by simple light irradiation, without physical contact, offering improvements in versatility during manifold fabrication, and control of actuation. Nevertheless, their poor versatility, slow response times and limited robustness render them currently as scientific curiosities rather than ideally functioning devices.[1]

The incorporation of photo-responsive gels with ionic liquids (ILs) produces hybrid ionogels with many advantages over conventional materials. For example, through the tailoring of chemical and physical properties of ILs, robustness, acidity/base character, viscosity and other critical operational characteristics can be finely adjusted. Therefore, the characteristics of the ionogels can be tuned by simply changing the IL and so the actuation behaviour of micro-valves made from these novel materials can be more closely controlled.[2]

We have investigated the potential use of spiropyran-modified ionogels for controlling fluid within micro-fluidic channels. This remote ability could greatly simplify specific device design and cost. We have effectively incorporated ionic liquids into hydrogels to attain specific material contraction performance.[3] An advantage of using ionic liquids is the plethora of synthetic and material design options that can be used to design devices optimized for certain performance parameters or behaviours.

concentrations, temperature, weight of objects attached to the bottom of the muscle, or current flowing through the device will be presented. Lineal evolutions are obtained for the electrical energy consumed by the artificial muscles to move across a constant distance as a function of the studied experimental variable. Both signals, the actuating current and the sensing potential response, are included by the same two connecting wires, opening a new paradigm for those devices including chemical reactions.

8107-13, Session 3
Self-powered system for structural vibration sensing
P. Gaudenzi, F. Capece, S. Gabriele, Univ. degli Studi di Roma La Sapienza (Italy)

The problem of investigating the structural integrity is a critical aspect for a great number of complex system; an airplane, for instance, needs scheduled revisions to check the perfect status of each component. Many problems arose when a component to be inspected lies in a position requiring the disassembly and successive reassembly of many structural elements, and the consequent time during which the vehicle, or every other equipment which status needed to be checked, is not available due to maintenance, imply additional costs. Therefore, a system that can remotely monitor the components, without the need to physically inspect them, should constitute an advantageous mean for reducing costs and time.

Such a system could be a network of sensors, which sense the vibration stressing the structure, integrated with a system able to remotely transmit the data collected: this kind of system, known as WSNs (Wireless Sensor Networks) have drawn significant attention in monitoring plants, resources, and infrastructures. For the supply of energy needed to this system to work we propose to develop some energy harvesting form the structural elements, and the consequent time during which the vehicle, or every other equipment which status needed to be checked, is not available due to maintenance, imply additional costs. Therefore, a system that can remotely monitor the components, without the need to physically inspect them, should constitute an advantageous mean for reducing costs and time.

A critical issue of the system is the evaluation of the level of power needed by the sensing system. Furthermore, differently from some application, in which the inspections can be carried out only post-operation, i.e. with the vehicle or resources not working, such a system can continuously and on-line test and sense the structural behaviour of the under-investigation components.

8107-14, Session 3
Some electrical transport properties of PLA/MWCNT composites
S. Kumar, E. Marwah, R. Cardona, J. J. Santiago-Aviles, Univ. of Pennsylvania (United States)

Super-capacitors are becoming commonplace, which makes its environmental friendliness an important attribute. For high capacitance, we need suitable materials, formulations and electrodes. Super-capacitors can store energy as part of double layer capacitance (a purely physical effect) or through the charge and discharge of an electro-active polymer (Faradaic, or electro-chemical contribution). Of course, both schemes need a compliant and flexible packaging material with particular electrical and thermal properties. In this abstract we would like to briefly describe how the authors addressed some issues in these types of materials. For this work, we utilize commercially available biodegradable electrosyn polymer fibers. In this case, Poly Lactic Acid (PLA) which is a popular corn derived material. It is synthesized by corn fermentation, which generates Lactic Acid. As received, PLA is a solid resin in pellet form. It is dissolved in dichloroethane as to achieve the proper electrospinning kinematic viscosity. Once in the liquid phase, the material is mixed with commercially available dispersed multiwall CNT at concentrations varying from 2 to 5 w/o. This mixture is then spun at room temperature using a home built electrospinning apparatus capable of depositing randomly oriented fiber mats or oriented fibers onto different substrates, ranging from oxidized Si wafers, Alumina squares or glass microscope slides. The fibers diameters and lengths are statistically distributed following a log-normal distribution and the mean and dispersion are controlled by spinning parameters. One of the challenges achieved in this work lies in obtaining fibers with a small as possible mean diameter, ideally, in the nano-scale range.

Once the fibers are obtained, they are compositionally, morphologically and structurally characterized using thermal analysis, EDX (Energy dispersive X-rays), SEM images, Raman scattering and XRD. The electronic transport properties as function of temperature were measured from 2K to room temperature on a computer controlled superconducting cryostat. Results point to the formation of a PLA / CNT composite with a conductive filler and insulating binder, and where the electronic transport properties strongly correlate with the filler to binder ratio. The room temperature photoconductivity using a visible / near IR monochromator points to a charge carriers photo-transport dominated by the CNT filler as expected.

8107-15, Session 3
The continuing quest for the ‘Holy Braille’ of tactile displays
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The Boston-based National Braille Press has established a Center for Braille Innovation (CBI), whose mission is to research and develop affordable braille literacy products. The primary focus has been to facilitate the development of dramatically lower cost electronic braille display devices, and the much-sought-after “Holy Braille” of a full-page braille display.

The NBP specs include braille dot dimensions, spacing, displacement, lifting force, and response time requirements. In addition to summarizing the technical requirements and specifications for braille and other tactile displays. We discuss human factors issues, such as why multiplexing with only a single braille character display is not acceptable for most applications. Several of the common and repeated pitfalls and assumptions that have led many previous tactile display developments astray are reviewed. We briefly summarize the past efforts to use optical actuation in tactile displays. Finally, we list what appear to be the remaining challenges to developing practical tactile displays employing Electro Active Polymer actuator materials.

8107-16, Session 3
Nano opto-mechanical systems (NOMS) as a proposal for tactile displays
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Nano-opto mechanical Systems (NOMS) based on the photoactuation of photoactive polymer actuators and devices is a much sought-after technology. In this scheme, light sources promote mechanical actuation producing a variety of nano-opto mechanical systems such as nano-
grippers. The European Union NOMS consortium is a multidisciplinary team assembled to build a tactile tablet for the visually-impaired. The consortium is formed by experts in materials, optics, microsystems, neuropsychology, as well as end users, and commercial partners. In this paper, we will provide a series of specifications that the NOMS team is targeting in the development of a tactile display using optically-activated smart materials. Indeed, tactile displays remain mainly mechanical, compromising reload speeds and resolution which inhibit 3D tactile representation of web interfaces, much needed by the visually impaired. We will also discuss how advantageous NOMS tactile displays could be for the general public. Tactile processing based on stimulation delivered through the NOMS tablet will be tested using psychophysics and neuroscience methods, in particular event-related brain potentials. Additionally, the NOMS tablet will be instrumental to complete basic neuroscience research.

8107-17, Session 4

A nonlinear model an actuator

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We consider a mixture of carbon nanotubes (CNT’s) with a polymer matrix. Laboratory experiments have shown that this composite reacts mechanically to infrared irradiation (IR). Ahir and Terentjev (2005) proposed a model based on linear elasticity in which the mechanical behavior of the CNT is assumed to be that of an incompressible material. The mechanical properties of the polymer do not enter into their model. Stress vs strain test of an actual specimen of this composite shows that at approximately 10% applied pre-strain, there is a crossing of the corresponding stress responses with and without IR stimuli. Ahir and Terentjev’s model predicts this crossing at a 20% compression or reduction of the CNT’s actual experimental data shows the crossing at a 1-2% compression. We propose to improve on this by including the mechanical response of the polymer into the model and by using more general models of material response. The actuator process is incorporated into the model as a constitutive equation for the CNT’s which changes its behavior in response to an external stimuli. We use a variational model in which the potential energy function corresponds to one for a mixture of two phases. To compute approximate minimizers we use a finite element method which incorporates the requirement that the stresses within the composite are continuous, yet it allows for jump discontinuities in the deformation gradient across interfaces. We perform calculations both in two and three dimensions and compare our numerical results with previous experimental data.

8107-18, Session 4

Mechanical modeling of thermally actuated LC-CNT composite

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Optoactive polymer actuators and devices (OAPAD) are, undoubtedly, promising technologies. Analytical and finite element models describing dynamics of photo-induced deformation in OAPADs have already been developed, particularly for liquid crystal elastomers (LCE). Advanced materials like LCE - Carbon Nanotube (CNT) composites, require a more complex physical analysis involving different coupled phenomena like photochemistry, photophysics and chemomechanical coupling. The need for rigorous modeling of such complex physics as well as the imminent implantation and development of ground-breaking practical OAPADs like tactile tablets, demand a fast way to model the light-induced deformation of the material.

Our European Union FP7 NOMS (Nano Optical Mechanical Systems) Consortium aims at building a tactile tablet for the visually-impaired. Hence, modeling of optoactive polymer blister - Braille dot - geometries is the basis of further tactile tablet design.

The purpose of this work is to build a finite element model serving as a bridge between basic elastomer physics and device engineering and design. We take advantage of experimental actuation data to build an empirical model describing the material deformation. The concept that sets the basis of the model is explained: the light irradiation provokes the heating of the material mainly thanks to the absorption properties of the CNTs. Thus, we can consider that CNTs behave as internal heat generators. Consequently, an opto-mechanical system based on LCE-CNT can be evaluated and the mechanical response optimized.

8107-19, Session 5

Education and dissemination strategies in photoactuation

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Photoactuation is a novel property where a material system actuates upon light irradiation. Few material systems have shown this effect; such as carbon nanotubes (CNTs) and CNT-polymer composites. Recent efforts aim at promoting photoactuation to mainstream research and development. Indeed, these efforts span from developing a basic understanding of mechanisms behind photoactuation, to creating methods within microsystem technologies to integrate these smart materials into practical devices. Ultimately, we envision optical actuation in multiple environments such as intracellular motors, artificial muscles, and tactile displays for the general public.

In the current information age, scientists and educators are urged to disseminate scientific findings in a prompt manner for increased public acceptance later on in the market place. Customer acceptance of highly novel technologies is an education-driven effort that requires attention early-on during the stage of technology development, particularly where nanoparticles are employed. Another driving force to disseminate photoactuation is to generate interest and curiosity amongst the K-12 population that could eventually lead to increased enrollment of graduate students in the physical sciences.

In this paper, we present a work plan for the dissemination of photoactuation to society at large; from K-12 to the general public. The work plan will be designed in accordance to the logic model and will include a thorough assessment plan to gauge the effectiveness of deploying these education programs. We also discuss the prompt integration of photoactuation on the academic curriculum, striving to emphasize the similarities amongst other smart systems such as electro and thermal actuators.

8107-20, Session 5

CNT dispersion and precursor synthesis for electrospinning of polymer-CNT composites

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In electrospinning, the reported ease of use combined with the spatially controlled deposition of fibers in adequately patterned substrates, could open unexplored avenues in micro and nano-systems technology manufacturing. In the context of nanocomposites, electrospin fibres appear to yield well-aligned CNTs; critical to the advent of these
nanocomposites in practical applications. In fact, great effort is being
dedicated to develop effective methods for dispersion and alignment
of CNTs; for which some researchers have proposed electrospinning
and pyrolysis. Following this trend, and combining the advantages of
electrospinning with the promise of actuating nanocomposites, we study
the suitability of electrospinning to synthesize photoactuators.

Dispersed MWCNTs were dissolved in a Poly(dimethylsiloxane)/
Poly(methylmethacrylate) precursor solution which was then fed into
a homemade electrospinning apparatus. Electrospun nanofibers were
collected on a (25 x 25) cm cardboard with two strips of aluminum foil
to improve alignment. The nanofibres were irradiated with a visible light
source of 40W and a deformation of approximately 1mm was observed
as discussed elsewhere. In this work, we study the effects of different
filler concentrations on dispersion and in-matrix distribution, as well as
the subsequent response of the composite to light.

8107-21, Session 5

 Electrospun polymer-CNT actuators

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Electrospinning of technology-relevant compounds could offer a simple
bottom-up solution to integrate one-dimensional nanostructures in
practical devices. Electrospun nanocomposites present well-aligned
CNTs; presumably a critical factor in actuation. Electrospun polymer-CNT
fibers discussed here, exhibited faceted morphologies of 1µm width. In
the physical properties space, polymer-CNT composites are known to
have increased thermal, electrical, and mechanical properties. Contrary
to their thin-film counterparts; little effort has been dedicated to examine
the active behavior of electrospun polymer-CNT composites. In this work,
we report evidence of photoactuation in electrospun PDMS/PMMA-
CNT composites. In this scheme, micron-width fibers were collected in
a mesh pattern and then weaved onto threads. When irradiated with a
visible light source, the threads bent by 1mm. However, no deformation
was observed when the composites were irradiated with a heat source;
suggesting the actuation mechanism is of optical nature.