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Contents

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6462A-01, Session 1

Pulse-width dependency of the fabricating resolution of the two-photon absorption photo-polymerization

H. J. Kong, S. W. Yi, D. Yang, Korea Advanced Institute of Science and Technology (South Korea); K. Lee, Hannam Univ. (South Korea); J. Kim, T. Lim, S. Kim, Korea Advanced Institute of Science and Technology (South Korea)

As an ultrafast laser has recently been developed, this leads to the innovative nanotechnology, the 3-D fabrication of the two-photon absorbed (TPA) photo-polymerization. The 3-D micro/nano structure by this method has a resolution of sub-hundred nm which is much smaller than the diffraction limit. Usually the 3-D polymer micro/nano structure by this method is made by stacking many of a unit polymer structure, so called 'voxel'. The size of the voxel is considered as the fabrication resolution. The size of a voxel, or the fabricating resolution is determined by several fabricating conditions such as the laser output power, the exposure time, the N.A. of the focusing lens, the types of polymerizing material, and the pulse-width. A voxel size due to power, exposure time and NA has been done by many research groups. Although the pulse-width is a very important condition for two-photon absorption, the study of influence on fabricating resolution by the pulse-width has not been done before. Therefore we studied the voxel size under the condition of increasing the pulse-width of the laser. To stretch the pulse-width, a single mode fiber (SMF) has been used. We demonstrated that the voxel size decreased as pulse-width stretched from hundreds femto-seconds to several picoseconds.

6462A-02, Session 1

Small-scaled and microfeatured functional prototypes by laser sintered polyetheretherketone

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Functional prototypes produced via laser sintering already address the sub millimetre region with resolutions in the low Micrometer range. The underlying manufacturing process is very suitable for small scale, micro featured functional polymer parts because of its ability to generate complex and fine shaped geometries including undercuts and pores. The parts are built up layer by layer from three-dimensional data generated by CAD programs or by technical micro computer tomography as a copy of already existing parts. Up to now this field is dominated by polyamide, a semi-crystalline polymer. This thermoplastic covers a wide range of applications but requirements concerning a high temperature resistance above 200 degrees Celsius and tensile strengths above 50 N/mm2, are not fulfilled despite glass fillings.

A change in the sintering material can solve this issue. Investigations show that polyetheretherketone (PEEK), which is a high performance polymer with a melting temperature of 343 degrees Celsius can be used for laser sintering. Manufacturing small scaled and micro featured parts with enhanced temperature and mechanical characteristics is possible using an adapted systems technology.

6462A-03, Session 1

Characterization of femtosecond laser ablation and deposition through spectral interferometry

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A novel femtosecond micromachining workstation that permits real-time measurement of ablation depth and transient reflectivity is demonstrated. This instrumentation is used to characterize two processes: micromachining of thin metal films, and laser induced forward transfer (LIFT).

Spectral interferometry was incorporated in a femtosecond micromachining system to enable real-time visualization of micromachined features as they are written into thin metal films- low energy (pJ) femtosecond oscillator pulses are used to probe the sample as it is cut by high energy (μJ) pulses. Sub-wavelength depths are readily resolved using this technique, making it possible to monitor the integrity of micromachined structures as they are created.

This technique can also be employed to characterize interesting processes such as laser induced forward transfer (LIFT) of thin metal films. LIFT essentially involves using a pulsed laser to pattern a structure by deposition as opposed to ablation. Using modest numerical apertures (0.65 or less) we have been able to produce submicron features using this method of femtosecond pulsed laser deposition. In order to further reduce the feature size, our spectral interferometry system is being used to quantify the LIFT process. Results of this study will be presented.

6462A-04, Session 1

Increasing femtosecond laser processing efficiency by hybridization with nanosecond laser

J. S. Yahng, B. H. Chon, C. H. Kim, Korea Research Institute of Standards and Science (South Korea); H. R. Kim, Bicronix Co., Ltd. (South Korea); S. C. Jeoung, Korea Research Institute of Standards and Science (South Korea)

The temporal coupling of the femtosecond laser and nanosecond laser induces a remarkable increase in the processing efficiency 12 times more than that with an independent laser exposure. When fs laser arrives before ns laser, the dependence of the ablation efficiency on the time delay between the fs and ns laser pulses is very close to the temporal profile of the ns laser. When fs laser arrives after ns laser, however, we observed an apparent delayed decaying component with a time constant of several hundreds of nanosecond in the ablation efficiency curve. Based on the current observation, we have explained the rather large enhancement in fs-laser ablation efficiency with synchronization between fs and ns laser in terms of silicon surface metallization due to the proceeding nanosecond laser. Such a progress in femtosecond laser micro processing makes it possible to maximize the processing speed and reduce the processing threshold energy, which eventually avoid the various high order nonlinear effects which are confronted when we focus high-power femtosecond laser pulses on the target under atmospheric conditions.

6462A-05, Session 2

Microfabricated 3D polymeric structure with SU-8

S. W. Yi, H. J. Kong, Korea Advanced Institute of Science and Technology (South Korea)

Complicated 3-D polymeric structures with a resolution of under 100 nm has been fabricated by two-photon absorption polymerization (TPA) by an extremely high power laser. This method can be applied to many scientific and engineering fields such as micro/nano-optics, MEMS, microfluidic system, and so on. Many 3-D structures by TPA fabrication have been made. However the stuctures made with an acrylate-based prepolymer material have seriously structural problems, such as shrinkage, collapse, distortion, etc. These problems make the fabrication of a large and fine 3-D structure difficult. Using an epoxy-based material like SU-8, which is widely used in the conventional lithography, the problems in the fabrication can be prevented. We demonstrated 3-D micro/nano structures with SU-8 from several fabricating methods, such as pin-point writing method, stage moving method, and so on. We also investigated the resolution of fabrication, or the size of voxel from the SU-8 structures.

6462A-06, Session 2

A new UV-lithography photoresist for fabrication of high-aspect-ratio microstructures

R. Yang, S. A. Soper, W. Wang, Louisiana State Univ.

We report a new type of negative-tone photoresist in this paper. The resist is based on a mixture of Epon resin 154 and Epon resin 165 (both from Hexion Specialty Chemicals, Inc., Columbus, OH 43215). These two epoxy resins are mixed together in some specific ratios and then dissolved into the gamma-butyrolactone (GBL) solvent. The mixture of these two epoxy resins is then photosensitized by adding a given amount of triaryl sulfonium salt.

The combinations of these two epoxy resins have some important properties suited for both ultraviolet (UV) lithography and X-ray lithography of ultra thick resist layer. There are four major advantages: 1) the proper molecular weights allow both of the fraction material dissolved into many kinds of organic solvents to form very high concentration mixtures (around 80% weight in solution) and high viscosity mixtures; 2) the new resist has very high optical transmission in the near UV spectrum and excellent lithography properties; 3) the new resist's good surface wetting properties helps to obtain excellent surface flats across the entire wafer area very easily; 4) the new resist has excellent adhesion capability. It does not require any special treatment of wafer surface; 5) minimal cracks were observed in the microstructures.

Our preliminary study has found that aspect-ratios up to 100:1 can be achieved using ultraviolet lithography of a 1mm thick photoresist film. Microstructures with height of more than 1000 μm and feature sizes of 10 μm were obtained. In this paper, the material properties and lithography properties of this new type of UV resist will be presented. The potential applications of the new resist in microfabrication and MEMS systems will also be discussed.

6462A-07, Session 2

Plasma etching of positively sloped silicon structures

S. Lai, K. D. Mackenzie, D. J. Johnson, R. J. Westerman, Oerlikon USA Inc.

The fabrication of 3D high aspect ratio structures with positively sloped profile has found extensive applications in both the front-end and the back-end semiconductor manufacturing. Often, high etch rates are required and plasma etching processes with F-based chemistries need to be employed. Of particular interest are the profiles with taper angle in the range of 50-80° and without so-called cusping at the top of etched structures. For 3D packaging applications, for example, even small cusping could degrade the step-coverage of diffusion barrier layer and metal seed layer in physical vapor deposition (PVD) and/or chemical vapor deposition (CVD) processes and cause void formation in subsequent metal filling processes.

The "Bosch" processes commonly used in deep silicon etching are limited to near vertical profile. Also, plasma etching of silicon in F-based chemistries generally results in cusping due to its isotropic nature. At Oerlikon USA Inc., a proprietary process scheme has been developed to etch deep positively sloped silicon structures (vias, trenches, etc.) at high etch rates while eliminating cusping with precise profile control. Using standard gases, such as SF6 and C4F8, sloped Si trenches with taper angle of ~60° are etched in both 6" and 8" wafers, at rates exceeding 6.5 μm/min. Etch selectivity to photoresist mask materials exceeds 100:1. The process scheme and underlying mechanism will be presented in this work.

6462A-09, Session 2

Processing parameters for the development of glass/ceramic MEMS

J. A. Stillman, Univ. of California/Los Angeles and The Aerospace Corp.; J. W. Judy, Univ. of California/Los Angeles; H. Helvajian, The Aerospace Corp.

For the past few years we have been investigating the photophysical and photostructurable properties of Foturan, a photostructurable glass ceramic (PSGC) manufactured by Schott Glass Corp. We now discuss results on using Foturan as a MEMS and MOEMS substrate. Foturan can be selectively chemically altered with focused pulsed laser light and subsequent heat treatment, converting native amorphous glass to crystalline lithium silicate. The degree and type of crystallization are sensitive functions of irradiation and thermal processing. The crystallized areas etch up to fifty times faster than the unexposed material in HF, with the etch rate varying with irradiation dose. Because Foturan is transparent at visible through IR wavelengths, it's possible to pattern complex 3D structures within a sample by direct-write XYZ exposure with a pulsed laser. Devices made from Foturan may be glass, a glass-ceramic composite, or ceramic, with the final material composition depending on the exposure and thermal treatment.

Excellent aspect ratios have already been demonstrated in Foturan. However, so far patterning control has either been severely limited in one dimension or required the use of complex optical setups. Our interest is in making simple true-3D MEMS structures by implementing cost-effective manufacturing solutions that produce consistent results with a resolution on the order of ten microns. We present our Foturan processing steps, as well as parameters for fabricating some basic MEMS building blocks, namely cantilevers and buried channels.

6462A-10, Session 2

Use of silane-based primer on silicon wafers to enhance adhesion of edge-protective coatings during wet etching: application of TALON(TM) wrap process

J. Dalvi-Malhotra, G. Brand, X. Zhong, Brewer Science, Inc.

Hydrolyzed silane primer solutions are made of an organosilane in glycolether diluted with a large amount of water with or without an acid as a catalyst. The newly developed primer compositions exhibit an extended shelf life of 3 months or more. The compositions were specially designed to accommodate ProTEK[TM] layer adhesion in the TALON[TM]-Wrap process. In this application, a spin-coatable polymeric material, ProTEK[TM], is applied as the protective coating to coat the edge and underside rim of the wafer in preparation for backside etching. By applying an underlayer of primer and an overlayer of ProTEK[TM] coating to the top edge and the bottom side rim of the wafer, an effective encapsulation of the wafer was achieved by use of a custom-designed baffle.

Each layer was applied by spin coating followed by baking at a wide temperature range. Thermal processing was followed by wet etching in KOH at an elevated temperature for long hours. Post-etched wafers were rinsed with deionized (DI) water. Excellent edge profiles without “knife-edges” were obtained after etching the unprotected areas of the wafer. The process is fully automated because it is carried out in the TALON[TM] automated wafer-processing tool. Intact films with no lifting or peeling were obtained during or after the KOH etch process/DI rinse for silicon substrates.

6462A-51, Session 2

Setting new standards in MEMS

M. K. Rimskog, Silex Microsystems Inc.

Silex Microsystems handles a wide range of customized MEMS components. This speech will be describing Silex work model for providing customized solutions based on MEMS in a cost effective and well controlled way.

Factors for success are the capabilities to reformulate a customer product concept to manufacturing processes in the wafer fab, using standard process modules and production equipment. A well-controlled system increases the likelihood of a first batch success and enables fast ramp-up into volume production.

The following success factors can be listed:

* Strong enduring relationships with the customers
* Highly qualified well-experienced specialists working close with the customer
* Process solutions and building blocks ready to use out of a library
* Addressing manufacturing issues in the early design phase
* In-house know how to meet demands for volume manufacturing.
* Access to a wafer fab with high capacity, good organization, high availability of equipment, and short lead times
* Process development done in the manufacturing environment using production equipment for easy ramp-up to volume production

The article covers Silex way of working to address theses factors:

* To have a long and enduring relationships with customers and having MEMS expertise working close with our customers translating their product ideas to MEMS components.
* To have stable process solutions such as Low ohmic vias, Spiked electrodes, Cantilevers, Silicon optical mirrors, Micro needles, etc, which can be used and modified for the customer needs.
* To use a structured development and design methodology in order to handle hundreds of process modules, and setting up standard run sheets. It is also very important to do the process development in the manufacturing line. It minimizes the lead-time for the ramp-up of production.
* To have access to a state of the art Wafer Fab well organised, controlled and flexible Wafer with high capacity and short lead-time for prototypes. It is crucial to have minute control of processes, equipment, organization, production flow control and WIP. This has been addressed by using a fully computerized control and report system.

6462A-11, Session 3

New emerging MEMS applications

E. Mounier, Yole Dévelopment (France)

This paper will present the trends for the years to come for the different MEMS markets and analysis for the 2005 - 2010 MEMS markets forecasts.

Consumer applications have really started to push the MEMS business in 2005. Many different devices are involved, like pressure sensors (altimeters), microphones, accelerometers, gyroscopes... One of the most significant consequences is that all the Top 50 semiconductor companies are now looking at these MEMS applications as possible growth areas. Another result of the growth of the MEMS market is the strong growth of the foundries and contract manufacturers. We have seen growth of more than 35% in 2005 compared to 2004 and we expect similar growth in the next 3 years. We will review the next MEMS applications which have currently a high growth: Si microphones, microdisplays (for RPTV, portable projectors or automotive HUDs), gyroscopes and micro-fuel cells. In the longer term, micro-source of energy could also become an important MEMS market.

In term of milestones, the following points will be discussed. In 2005 market, the MEMS market is 5.1 B$ worldwide and very fragmented in terms of companies and products.In 2010, it will be a 9.7 B$ market worldwide. MEMS foundries and contract manufacturers will account for at least 8 % of the world market with several being public companies. More than 50% of today’s systems companies who have integrated fabs will be using external manufacturers. Several large integrated companies will have created independent MEMS spinoffs and IC manufacturers will be deeply involved in MEMS manufacturing.

In 2015, it could be a 18 B$ market worldwide with no longer systems manufacturers with internal fabs.

6462A-12, Session 3

Design of high-sensitive acoustic sensor using PMN-PT single crystal

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As telecommunication technology grows, mobile terminals such as PDP and PMP are required to have higher quality of image, video, and sound service. In the area of sound service, sound contents are extended to natural musical sound range beyond human voice communication.

Microphone and speaker are used as acoustic devices in mobile terminal. Condenser type microphone widely has been used as acoustic sensor. It has advantages of high quality and low cost for manufacturing. However, it required high bias voltage, complex in manufacturing process. Another promising type of microphones is ferroelectric acoustic sensor that uses ferroelectric material such as PZT, ZnO, etc. These sensors have advantage of simple structure and manufacturing process. And they do not require bias voltage. However, they suffer from low sensitivity problems.

In this paper, high sensitive and simple structure acoustic sensor for mobile terminal is proposed. PMN-PT single crystal material is used as an acoustic diaphragm. PMN-PT single crystal inherently has bigger dielectric coefficient than other piezoelectric materials. That implies that it brings higher electron at the same mechanical stress due to sound pressure. Acoustic diaphragm shape is another important factor for higher sensitivity. Numerical analysis of acoustic sensor is performed, so that optimal diaphragm shape is determined based on systematic design process.

The manufacturing processes for acoustic sensor are as follows. PMN-PT thin wafer is obtained through polishing bulk PMN-PT wafer after bonding on silicon wafer. PMN-PT single crystal membrane is etched to have designed specification. Electrode is patterned on the top plate of PMN-PT based on numerical analysis of pressure distribution.

Finally, the performance of PMN-PT acoustic sensor is proved from the experimental results of diaphragm deflection measurement, natural frequency of diaphragm.

6462A-13, Session 3

Fabrication technology of Si microfluidic devices for microbial cell trapping

R. M. Badam, R. Nagarajan, L. Zhu, C. Y. Teo, X. Peh, H. Feng, N. Balasubramanian, W. Liu, Institute of Microelectronics (Singapore)

For the first time we report microfluidic filter devices with ultra fine gap and ultra high aspect ratio using single-mask and CMOS compatible pro-

cess. We demonstrate process technology to fabricate pillar-type Si-based filter devices to mechanically trap microbial cells such as pathogens for biological and environmental applications. Advantage of Si based platform technology has been fully exploited to design CMOS compatible and manufacturable process flow. A novel approach of combining silicon deep reactive ion etch (RIE) capability with subsequent gap-fill engineering enabled achieve wide range of filtration gaps from sub-micron size down to sub-100nm and high aspect ratios of >200. Si deep RIE etch process was optimized by applying dual passivation technique which enabled to realize sub-μm gap pillar-type filter structures and large reaction chambers simultaneously with only one-mask process. Deep reaction chambers (~30μm) thus formed provided capability to handle larger sample volumes which is highly desirable. Fluid injection channels for the device were fabricated through wafer back-side Si wet etch process. Final filter chips were obtained after anodic glass bonding and dicing. Device performance was characterized by trapping Cryptosporidium parvum, Geordia by 1μm gap filter chips and Escherichia coli cells by 100nm gap filter chips without the cells squeezing through, which was confirmed by fluorescence optical inspection and cross-section analysis. Wide range of gap sizes demonstrated using this technology can offer versatile applications for fine cell trapping such as protozoa, and bacteria. This is useful in assessing environmental water quality, food safety, diagnosis and even risks associated with bio-terrorism.

6462A-08, Poster Session

The silicon mold fabrication of a kind of micro-optical resonator and coupler

H. Ju, Wakayama Univ. (Japan)

We present the fabrication of a kind of hexagonal and triangular cavity mold, which can cast Polymethyl Methacrylate (PMMA) resonator and coupler. The mold is designed on (111) silicon wafer according to its crystal structure and anisotropic etching properties in the etchant of ethylene diamine, pyrocatechol, and water (EDP/EPW), forming sidewalls by six {110} crystal surfaces, which are perpendicular to the (111) plane and constitute precise hexagons and triangles. The RIE-ICP etching is used to define the depth of the triangle and hexagonal cavities, and the following EDP etching will smooth the sidewalls of cavities. Only high temperature EDP etching is proved to be able to get smooth sidewall. Before etching, the wafer is aligned to the right crystal orientation by pre-etched marks. The etched patterns of different geometrical cavities are analyzed and discussed based on the crystal structure.

6462A-14, Poster Session

Theoretical and experimental studies of a condenser-type miniature microphone with a flexure hinge diaphragm

H. Kim, S. Q. Lee, K. H. Park, Electronics and Telecommunications Research Institute (South Korea)

Generally, most miniature microphones are adopted by diaphragm-based condenser type because of the flat frequency response, small size, high signal-to-noise ratio and low power consumption. So far, an important number of reports with various membrane designs have been published to achieve higher sensitive microphones.

In this paper, we present a highly sensitive condenser type miniature microphone with a novel flexure hinge diaphragm. The finite-element analysis (FEA) has been used to evaluate the mechanical and acoustic performance. The fabrication sequences are as follows. First the grooves for acoustic holes are formed on the upper side of a 5” silicon wafer by dry etching. After patterning of the silicon oxide layer, the backplate electrodes are coated with silicon nitride. Next, we use the sacrificial layer to realize the devices in one single chip. Then, the thin membranes are deposited and patterned with the flexure hinge structure, and the upper electrodes of the device are formed on the membranes. Finally, these miniature microphones are completed by backside etching using Deep-RIE technique and by removing sacrificial layer using O2 ashing.

From the simulation and measurement results, the sensitivities of the miniature microphones with area of 1.5 mm x 1.5 mm were higher than 10 mV/Pa under 15 V dc bias. And the displacements at the center of these diaphragms were measured to be several times, compared with flat diaphragms, by using laser Doppler vibrometer. The miniature microphones have obtained -3 dB bandwidth of nearly 20 kHz by proper design of the flexure hinge diaphragms.

6462A-15, Poster Session

Replication technology as a means of implementing the polymer MOEMS

J. Kim, J. J. Ju, S. Park, S. K. Park, M. Kim, M. Lee, Electronics and Telecommunications Research Institute (South Korea)

Replication technologies have been recommended as an alternative means of high volume manufacturing of the polymer optical components with low-cost. We demonstrated the replication technology as a means of implementing the polymer-based MOEMS. To aim this, a polymer optical bench with embedded electric circuits was designed to integrate the functional planar-lightwave-circuit (PLC)-type optical waveguide devices; the designed packaging structures were realized using a novel fabrication process that incorporated with the UV imprint technique. In addition, the detail fabrication steps of the UV imprint process were investigated. The optical bench has v-grooves for the fiber ribbon and the alignment pits for opoelectronic interconnection. The plastic mold for imprinting the designed optical bench was made of UV-transparent perfluorinated polymer material. The designed optical bench was configured on the electric-circuit-patterned silicon substrate. Flip-chip bonded polymer optical waveguide device showed not only a good electric contact but also the coupling loss of 0.9 dB at a wavelength of 1.5 μm. It was concluded that the replication technology has versatile application capabilities in manufacturing the next generation optical interconnect systems.

6462A-16, Poster Session

Verification of thin film processes in a virtual fabrication environment

T. Schmidt, Univ. Siegen (Germany); D. Ortloff, Cavendish Kinetics B.V. (Netherlands); K. Hahn, R. Brueck, Univ. Siegen (Germany); A. Hoessinger, SILVACO Technology Ctr. (United Kingdom)

The increasing variety of possible process steps, materials and effects as well as the increasing interdependencies between layout and process configuration suggest a CAD approach for the process development, management, simulation and visualization. Increasing side effects of certain processing steps and materials and constantly decreasing geometric dimensions require new process development approaches and process knowledge management.

This paper describes an approach towards process design and verification with a focus on the verification and visualization aspects. A process design and tracking environment developed currently in the PROMENADE project will be introduced. PROMENADE as a process management environment supports the design of fabrication processes aiming on silicon thin-film technologies, as well as the tracking of process development and process verification related data and the administration of processes carried out in the past.

Promenade addresses mainly process engineers. It offers tools, databases and interfaces to manage and create application specific process sequences. Based on a common database for process steps, materials, effects, and artifact data, PROMENADE provides tools for defining process steps and flows as well as their assessment and visualization by process simulations. New methods for tools accessed by graphical user interfaces have been implemented to facilitate the definition of process sequences as well as the support of means to simulate virtual DOEs (designs of experiment). The PROMENADE portfolio comprises e.g. a process flow editor, a consistency checker, a unit converter, process simulator together with a module that allows the tracking of physical experiments.

Conference 6462B: Micromachining Technology for Micro-optics and Nano-optics V

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6462B-17, Session 5

Nanoscale pattern transfer for MEMS and nano-optics

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Etching of Si surfaces using halogen plasmas is a central process in the microstructuring of semiconductors. There has been an extensive effort over the past decade to go from the microstructure regime to nanostructure regime to develop nano optic and nanoelectronic devices, Nano Electro Mechanical Systems (NEMS) and nanoresolution templates for Nano Imprint Lithography (NIL). Dry etching processes typically must fulfil a number of requirements: adequate etch profile and selectivity control with respect to the underlying material and mask, no significant substrate damage, and sufficiently high etching rates. In addition, several applications in photonics and NIL require extremely low sidewall roughness. However, meeting these stringent profile and CD goals is challenging in the absence of a simple link connecting the process variables (e.g., power, pressure, gas mixture, flow) and etching process results.

In this talk, I will discuss issues which must be overcome in dry etching at the nanoscale. In particular, I will show how we have successfully fabricated 25 nm node molecular electronic nano-imprint templates. Furthermore, I will show a novel, low ion energy, highly anisotropic, technique for etching nanoscale features with ultra-smooth sidewalls well suited for template and nano-optics and photonic applications. Using this new technique, pattern transfer of dense features as small as 10 nm at 10:1 aspect ratios and sub-50 nm isolated trenches with perfect verticality has been achieved.

6462B-18, Session 5

Grinding aspheric and freeform micro-optical molds

Y. E. Tohme, Moore NanoTechnology Systems LLC

Fueled by the need for better performing optics, glass optics are now replacing plastic optics in many industrial and consumer electronic devices. One of these devices is the mobile phone camera. The optical subassembly in a mobile phone includes several micro lenses that are spherical and/or aspherical in shape and require form tolerances in the sub-micron range. These micro glass lenses are mass produced by a replication process known as glass press molding. The process entails the compression of a glass gob between two precise optical quality molds at an elevated temperature, usually near the transition temperature of the glass material. The elevated forces and temperatures required in the glass molding process limits the materials of the molds to very tough materials such as tungsten carbide or silicon carbide. These materials can withstand large pressing forces at high temperatures without any significant deformation. These materials offer great mechanical properties for glass press molding but they are also a challenge to machine to sub-micron accuracy. The work in this paper discusses a deterministic micro grinding manufacturing process referred to as wheel normal grinding, which is utilized to produce these optical quality molds. Wheel normal grinding is more accurate and more deterministic than most other grinding techniques and can produce molds to the form and finish tolerances required for optical molding. This method relies on the ability to recognize and compensate for grinding wheel wear and machine repeatable errors. Results will be presented to illustrate the accuracy of this micro grinding technique.

6462B-19, Session 5

Focused ion beam applied to photonics and nano-imprinting

S. Cabrini, Lawrence Berkeley National Lab.

Focused ion beam lithography (FIB) is a very powerful technique for direct writing of patterns on many substrates; it is a mask-less and resist-less technique that allows a wide range of applications and good resolutions. This technique can be used where other techniques cannot be employed or are too difficult and complex to use. By using FIB and SEM contemporary in the same experimental chamber, it is possible to obtain prototype devices in a simple and fast way. In fact, the possibility to fabricate in the nanometer scale with the FIB and to align features, as well as to check in real time the final result by SEM, allows one to save much time and to optimize all the parameters of the process. In this presentation we will discuss the use of the crossbeam LEO ZEISS XB1540 composed by a 30 keV Gallium ion beam column plus a 30 keV electron beam GEMINI column, apply to photonic structures and to obtain nano-imprinting templates. Some 1D Photonic Crystals (PhC) on silica based optical waveguides are shown as well as the realization of 3D optical structures curved directly on silica and used subsequently as master for imprinting.

By exploiting FIB Milling (FIBM), FIB Gas Assisted Etching and Focused Ion or Electron Beam Induced Deposition (FIBID or FEBID) with the same instrument, it is possible to open a wide number of possible applications and to obtain new devices with a resolution that goes down to the nanometer scale.

6462B-20, Session 6

Optical meta-materials fabricated by nano-imprint lithography

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Negative index meta-materials (NIM) that exhibit unique refractive and focusing properties have recently become a focus of research worldwide. They have opened up new opportunities in nano-photonics and optical integration. The important issue of how to fabricate these meta-structures with high-precision, high-throughput, and low-cost remains a challenge, especially for short wavelengths of radiation (e.g. infrared or even visible range). Here, we report on the development of a fabrication procedure of optical meta-structures using nanoimprint lithography (NIL).

We will report two types of meta-structures: L-shaped resonators (LSRs), which have a negative permeability at 5 micron range and “fishnet” structure, which is supposed to have both negative permittivity and permeability, hence negative refractive index at around 1.5 micron range. We fabricated the LSRs with smallest feature at 45 nm and better than 10 nm critical dimension (CD) control. LSRs on various substrates, such as Si, Si with Si3N4 film and free standing Si3N4 membrane were characterized and consistent with theoretical predictions.

We also studied the metal/dielectric/metal stack fishnet structure10 which is more scalable for shorter wavelength. Our theoretical simulation shows that the structure has both negative permittivity and permeability, therefore negative refractive index at 1.5 μm range. More details in theoretical studies and fabrication issues will be presented too.

6462B-21, Session 6

The value, solutions, and costs of patterning LED's

M. P. C. Watts, Impattern Solutions; M. E. Zoorob, J. McKenzie, Mesophotonics Ltd. (United Kingdom)

High resolution patterning of LED's has shown the potential to significantly increase the light output. There are 3 different imprint strategies being proposed to manufacture these devices. This paper will provide a review of the literature on patterning impact on LED performance, and provide a overview of manufacturing solutions. The net result is an assessment of the value and costs of patterning in LED's.

The latest white LED's are achieving outputs of 50-100 lm/W out of a possible 250, implying that 40-50% of the light is being extracted in today's state of the art process that uses a combination of surface roughening and encapsulation. These LED are built in 3-5 μm thick layers on sapphire or SiC substrates. Without surface treatment and encapsulation, only 8% of the light is extracted because of the high refractive index of GaN compound semiconductors

Patterning the LED with photonic crystal (PC) structures has been shown to control the shape of the output beam from these thick LED structures, which makes them very useful for illumination applications such as projection displays where spot size is critical. The demonstarted advantages of Photonic Quasi Crystals on Ultra thin LED's will be used to illustrate the potential in high brightness LED's.

6462B-22, Session 6

Combined nano-imprint and photolithography (CNP) of integrated polymer optics

M. B. Christiansen, M. Schøler, A. Kristensen, Danmarks Tekniske Univ. (Denmark)

We demonstrate wafer-scale fabrication of integrated polymer optics, comprising nm to mm features, by combined nanoimprint and photolithography (CNP). Distributed feed-back (DFB) polymer dye lasers are integrated with polymer waveguides. The laser devices are defined in SU-8 resist, doped with Rhodamine 6G laser dye, shaped as planar slab waveguides on a Borofloat glass buffer substrate, and with a 1st-order DFB surface corrugation forming the laser resonator. In the CNP process, a combined UV mask and nanoimprint stamp is embossed into the resist, which is softened by heating, and UV exposed. Hereby the mm to micron sized features are defined by the UV exposure through the metal mask, while nm-scale features are formed by mechanical deformation (nanoimprinting). The UV exposed (and imprinted) SU-8 is crosslinked by a post-exposure bake, before the stamp and substrate are separated, and the un-exposed resist is dissolved. Polymer waveguides are added by an additional UV lithography step in a film of un-doped SU-8, which is spincoated on top of the lasers and substrate. When optically pumped at 532 nm, lasing is obtained in the wavelength range 576 nm - 607 nm, determined by the grating period. Our results, where 14 laser devices are defined across a 10 cm diameter wafer substrate, demonstrate the feasibility of CNP for wafer-scale fabrication of advanced nano-structured active and passive polymer optical components.

6462B-23, Session 6

Application of nano-imprint lithography to nano-optics: wire grid polarizer and photonic crystal LED

K. Lee, LG Electronics Institute of Technology (South Korea)

Two optical devices incorporating nanoscale subwavelength stuructures have been fabircated by using nanoimprint lithography (NIL): wire grid polarizer and photonic crystal LED.

1) The wire grid polarizer (WGP) is one of key optical components for projection displays with liquid crystal

microdisplay. Although WGP with 140 nm pitch is commercially available now, it still pose a problem with low contrast ratio (CR) for blue color. Since the CR can be increased by reducting the pitch, fabrication of a WGP with 100 nm pitch was attemped by NIL. We successfully developed the thermal nanoimprint and aluminum dry etching processes. The fabricated WGP showed twice higher extiction ratio than 140 nm pitch one.

2) The photonic crystal (PC) structures on LED have been known to enhance the light extraction significantly. Although e-beam lithography has been used for the proof of principle, it is far from real production method. We applied thermal NIL to fabricate PC structures in p-GaN layer of green LED. To identify the PC effect, two structures were fabricated and compared. One structure makes the green light of 525 nm wavelength fall within the photonic band gap (PBG) while the other puts it outside of PBG. The former structure showed 23-fold increment of photoluminiscence compared to LED without PC structures, while the latter showed only 4-fold increment.

6462B-24, Session 7

Polarization engineering through nano-engineered morphology

A. Lakhtakia, The Pennsylvania State Univ.

Bandwidth engineering at its simplest requires isotropic achiral materials placed in some periodic arrangement, whereas polarization engineering requires the use of anisotropic and/or chiral materials. Both can be accomplished by nanoengineering the morphology of a complex substance such that it is both anisotropic and periodic and/or structurally chiral. Sculptured-thin-film technology, a platform technology developed during the last decade, enables simultaneous engineering of both polarization and bandwidth for a variety of direct and indirect applications of optics. Several emerging directions will be discussed.

6462B-25, Session 7

Fabrication of photonic crystals using chemical lithography

P. Yao, M. Murakowski, L. M. Prather, G. J. Schneider, J. A. Murakowski, D. W. Prather, Univ. of Delaware

Planar PhCs, which are mostly explored and employed for integrated optical circuits, are usually patterned using photolithography or e-beam lithography. For many applications operating in near-IR or optical range, the photonic circuits contain both sub-micron features in photonic lattice and large features in other waveguiding elements. In these cases, most of the research-end photolithography tools are not capable of patterning the smallest features, while e-beam lithography is inefficient and time consuming for the large structures. Here, we present a new lithography method, chemical lithography (ChemLith), for the fabrication of planar PhCs. Using a template, this method potentially can be used for low-cost, parallel fabrication of PhC circuits for near-IR or visible wavelength applications.

The concept of ChemLith is based on the fact that most of the commonly used photoresists change their solubility upon an acid-catalyzed chemical reaction. Unlike photolithography, where the acid catalyst is generated by photon exposure, ChemLith physically introduces the acid to a resist film using a previously prepared template, and facilitates the desired subsequent chemical reactions to change the solubility. Since no photon is used, the resolution of this method is not limited by the wavelength or the imaging system. As a result, small PhC lattice and large waveguiding components in the photonic circuit can be rapidly and simultaneously patterned. we present in this paper both lithography and etching results of PhCs patterned using Chemical lithography.

6462B-26, Session 7

Holographic optical elements for the extreme-ultraviolet regime

P. P. Naulleau, SUNY/Univ. at Albany and Lawrence Berkeley National Lab.; F. H. Salmassi, E. M. Gullikson, E. H. Anderson, Lawrence Berkeley National Lab.

As extreme ultraviolet (EUV) lithography progresses towards commercialization, interest grows in the extension of traditional optical components to the EUV regime. The strong absorption of EUV by most materials and its extremely short wavelength, however, makes it very difficult to implement many components that are commonplace in the longer wavelength regimes. One such component is the holographic optical element used, for example, in illumination systems to efficiently generate modified pupil fills. Here we demonstrate the fabrication and characterization of EUV binary phase-only computer-generated holograms allowing arbitrary far-field diffraction patterns to be generated. Both transmission and reflection mode devices are described.

6462B-27, Session 7

Deposition of periodic tungsten nanoripples induced by a single femtosecond laser beam

M. Tang, H. Zhang, J. McCoy, T. Her, The Univ. of North Carolina at Charlotte

We demonstrate deposition of periodic tungsten nanoripples on different substrates using a single 400-nm femtosecond laser beam at room temperature. The laser beam generated by frequency doubling the output from a mode-locked 80-MHz Ti: sapphire oscillator was applied in a laser-induced chemical vapor deposition (LCVD) configuration in which tungsten hexacarbonyl was used as precursor. The deposition strongly depended on laser polarization. With linearly polarized light, periodic ripple structure with willow-leaf shape was formed inside the exposure area. The ripple orientation was found parallel to the laser polarization direction. Affects of laser power and exposure time on ripple formation were investigated. By translating the substrate with respective to the laser beam, longitudinal or transverse grating structure was observed. The nanoripples on sapphire have a periodicity ~ 150 nm and a maximum feture size of ~ 70 nm. Simply by programming the translation of the substrate, large area patterns and other patterns such as circles and characters were generated. Similar ripple and grating structures were observed on all the substrates we investigated, including insulators, semiconductors and metals, indicated that ripple formation might be a universal phenomenon. Considering the simplicity of this process and material flexibility of laser CVD, this technique may provide a novel cost-effective patterning method to produce periodic subwavelength nanostructures of a wide range of materials.

6462B-28, Session 8

Advances in integrated hollow waveguides for on-chip sensors

A. R. Hawkins, E. J. Lunt, M. Holmes, B. Phillips, Brigham Young Univ.; D. Yin, M. I. Rudenko, H. Schmidt, Univ. of California/Santa Cruz

We have previously produced antiresonant reflecting optical waveguides (ARROWs) with hollow cores that can guide light through liquid or gas media. In order to utilize these structures in sophisticated sensing applications, we have improved our initial designs and fabrication methods to increase yield, lower waveguide transmission loss, and incorporate structural features into the waveguides themselves. Yields have been increased by optimizing PECVD film conformality leading to greater sidewall strength for hollow waveguides. Waveguide loss has been reduced by initial etching of the substrate material to surround the resulting waveguide with an air layer in the lateral direction. In the past, yield on these devices has been limited by a re-alignment step done after substrate etching. A new self-aligned process eliminates this problem. Sensing applications require interfacing hollow waveguides with solid waveguides on the surface of a substrate to direct light on and off a chip and into and out of a test media. Previous interfaces required light transferring from solid to hollow waveguides to pass through the anti-resonant layers, with measured transmission efficiencies of about 30%. By removing the ARROW layers at the interfaces, transmission efficiencies at these interfaces can theoretically be improved to nearly 99%. We also demonstrate the fabrication of micropore structures on the hollow waveguides to be used for chemical sensing. A fabrication method has been developed that allows for removal of the thick top oxide and nitride ARROW layers leaving only a thin nitride membrane directly over the hollow core allowing controlled access to test media.

6462B-29, Session 8

High-efficiency waveguide bends in Perfluorocyblobutyl (PFCB) waveguides and stress reduction with polyimide substrates

Y. Lin, The Univ. of Alabama in Huntsville; S. Kim, G. P. Nordin, Brigham Young Univ.

We have demonstrated that dramatic reductions in the size of waveguide bends for materials with low core/clad refractive index contrast can be achieved with single air interface bends (SAIBs) based on total internal reflection. However, high optical efficiency for such bends requires vertical interfaces with low surface roughness that are precisely placed with respect to the waveguides. We have developed a fabrication process based on electron beam lithography (EBL) and inductively coupled plasma reactive ion etching (ICP RIE) to simultaneously satisfy these criteria. We report the fabrication and measurement of 45° bends with a loss of only 0.124 dB/bend (97.2% bend efficiency) for TE polarization and 0.166 dB/bend (96.2%) for TM polarization at a wavelength of 1550 nm. We also examine the use of polyimide instead of silicon as the substrate material and find a dramatic reduction in stress-induced film cracking. We discuss how to overcome the deleterious effects of the polyimide substrate's lower thermal conductivity on highly anisotropic ICP RIE etching.

6462B-31, Session 8

Pulsed laser ablation for volume fabrication of micro-optical arrays on large-area substrates

J. E. A. Pedder, Imperial College London (United Kingdom); K. L. Boehlen, R. M. Allott, Exitech Ltd. (United Kingdom); A. S. Holmes, Imperial College London (United Kingdom)

Pulsed UV laser machining is an established method for production of 2.5D and 3D features in a wide variety of materials. Laser mask projection techniques have also been used for the patterning of thin films and micro structures over large panels where established micro-structuring methods like e-beam milling, diamond turning or reflow techniques have reached their limits. Many application areas, for example rear projection display panels, anti-counterfeit packaging materials and 3D displays have become increasingly dependent on laser processing.

The laser mask projection technique Synchronized Image Scanning (SIS) has been developed for the efficient fabrication of dense arrays of repeating 3D microstructures with high accuracy and precision on large area substrates. Large master panels are typically machined in a polymer film which is then electroformed to produce a mould for replication for the manufacture of devices. SIS is well suited to machine features with an outstanding repeatability from a few microns up to a few hundreds of microns regardless of the complexity of the profile. This paper discusses an extension of this technique using half-tone mask features in the SIS mask to improve surface quality in optical structures.

Results will be discussed demonstrating arrays of micro-optical features with low surface roughness machined into polymer substrates.

6462B-32, Session 8

Challenging micro-optical applications demand diverse manufacturing solutions

G. T. Borek, J. A. Shafer, MEMS Optical, Inc.; P. W. Weißbrodt, M. Schrenk, W. Hill, JENOPTIK Laser, Optik, Systeme GmbH (Germany)

The fabrication challenges of the microoptics business are diverse and tend to resist a widely accepted manufacturing process such as has been implemented for CMOS fabrication. Many of the challenges that have been addressed with various solutions include wave band of operation (from DUV through LWIR), material systems, cost of manufacturing for the intended application space, feature sizes based on device functionality, and fabrication technology based on the manufacturing volume. Some of the technologies to be discussed include device patterning by optical lithography, e-beam lithography, replication or soft lithography, plastic replication, and direct CNC machining and polishing. This paper discusses the process flow required for these fabrication methods as well as tolerances achievable with the method. It is intended to provide the reader with a road map for selecting a manufacturing method appropriate for the reader's application.

6462B-33, Session 9

Complex three-dimensional materials for photonics

G. von Freymann, Forschungszentrum Karlsruhe (Germany) and Univ. Karlsruhe (Germany); M. Deubel, M. Hermatschweiler, A. Ledermann, Univ. Karlsruhe (Germany); S. Linden, Forschungszentrum Karlsruhe (Germany); M. Thiel, Univ. Karlsruhe (Germany); S. Wong, Forschungszentrum Karlsruhe (Germany); N. Tétreault, Univ of Toronto (Canada); L. Cademartiri, G. A. Ozin, S. John, Univ. of Toronto (Canada); D. S. Wiersma, Univ. degli Studi di Firenze (Italy); M. Wegener, Forschungszentrum Karlsruhe (Germany)

Photonic crystals as a new class of optical materials allow to significantly altering the flow of light by designing the photonic density of states. For maximum design flexibility, one not only has to be able to three-dimensionally structure dielectric (or metallic) materials with below 10 nm precision but also has to choose dielectric materials with desired linear and non-linear optical properties. In this talk I will give an overview over our recent progress in the fabrication of three-dimensional photonic crystals. After an introduction into the fascination photonic crystals create, I will briefly discuss state-of-the-art technology for their fabrication: Direct laser writing is an extremely versatile technique for rapid prototyping. Here, photosensitive materials are exposed via two-photon absorption, allowing for true three-dimensional writing of features with sizes down to 100 nm. Direct laser writing in high index of refraction, and highly non-linear chalcogenide glasses results after wet chemical etching in directly written photonic crystals with a complete photonic band gap, while photoresist structures act as templates for silicon inversion and replication or as functional structures by themselves. This will be demonstrated with three examples: 1. Photonic crystal 3D-2D-3D heterostructures, which might act as building blocks for photonic crystal circuits; 2. Chiral photonic crystals, which are able to suppress the propagation of left-circular polarized light compared to right circular polarized light, allowing for the creation of ultra-compact optical diodes or optical isolators; 3. First realizations of three-dimensional photonic quasicrystals for near-infrared frequencies.

6462B-34, Session 9

Biologically inspired optics: beetle exoskeleton

K. N. Buhl, P. Srinivasan, J. D. Brown, A. Mehta, E. G. Johnson, College of Optics & Photonics/Univ. of Central Florida

Evolution in nature has adapted distinctive optical properties for many biological life forms. One adaptation is how pigment color differs from the observed color. Since the pigment color of an exoskeleton is not the observed color, most beetles have multilayer coatings. The green beetle is disguised in the leaf surrounding by having a comparable reflection spectra as the leaves. However, the Manuka beetle has a concave structure in addition to the multilayer effects. This combination is equivalent to layered negative micro-mirrors with a smooth layer-to-layer connection between neighboring micro-mirrors. Light incident at any angle on the concave structures produce matching reflection spectra.

We replicated the reflection spectra of the beetle exoskeleton by creating a multilayer surface covering convex micro-lenses. The imitation of the beetle exoskeleton demonstrates the large angle of incident light yielding comparable reflection spectra unlike a planar multilayer structure. The replication of these biological life forms will help us become more efficient in the production of various optical properties just as nature has evolved over the past millions of years.

6462B-35, Session 9

Soft-lithographic replication of 3D polymeric microstructures created with MAP

J. T. Fourkas, C. N. LaFratta, L. Li, Univ. of Maryland/College Park

Multiphoton fabrication techniques make possible the creation of three-dimensional structures of virtually arbitrary complexity with feature sizes as small as 100 nm. The most common such technique is multiphoton absorption polymerization (MAP), in which a tightly-focused laser beam is used to expose a photoresist solely within the focal volume. Structures are created by scanning the focus of the laser beam, after which any unexposed material is removed. One notable shortcoming of MAP and related techniques is that structures must be created on a voxel-by-voxel basis. As a result, production of structures on the wafer scale is too slow to be commercially viable for most applications. To circumvent this problem, we have used structures created with MAP as masters for molding via soft lithography. When elastomeric materials such as polydimethylsiloxane are used to create molds, it is possible to replicate structures that have high aspect ratios and/or sizeable overhangs. We have also developed a technique, which we call membrane-assisted microtransfer molding, that makes possible the replication of structures with closed loops. These techniques represent an important step towards the ability to mass produce 3-D microstructures created with MAP.

6462B-36, Session 10

Crystalline colloidal arrays: applications from sensors to organic lasers

S. H. Foulger, Clemson Univ.

The research we are performing at Clemson University is grounded in the fundamental aspects of crystalline colloidal array derived photonic bandgap (PBG) materials and the extension of photonic crystal research into functional polymeric composites. Since the original proposal that three-dimensional periodic dielectric structures could exhibit a photonic bandgap, considerable attention has been focused on developing these materials into a form that is suitable for use in photonic applications. Unfortunately, the general exploitation of visible photonic crystals as devices has been hindered by the challenges in creating 3D periodic dielectric structures with a feature size comparable to the wavelength of visible light, as well as achieving significant dielectric contrasts that result in a strongly scattering system. To surmount these challenges, current effort is being directed at systems which undergo self-assembly at a nanometer length scale, such as colloidal crystals.

Our group has focused on electrostatically-stabilized crystalline colloidal arrays. A crystalline colloidal array is a three dimensionally ordered lattice of self-assembled monodisperse colloidal particles, most commonly amorphous silica or a polymer latex, dispersed in aqueous or non-aqueous media. At high particle concentrations, long-range electrostatic interactions between particles result in a significant inter-particle repulsion

which yields the adoption of a minimum energy colloidal crystal structure with either bcc or fcc symmetry. The ordering of the particles in the media results in spatial periodicities that range from ca. 100-1000 nm, often resulting in optical bandgap effects. The three main research thrusts within my group on these systems include (1) particle synthesis; (2) self-assembly & collective properties; and (3) device development. These three thrusts will be the major themes of my talk and will be presented in detail.

6462B-37, Session 10

Production of 3D photonic components with ultrafast micromachining

M. Boyle, A. Neumeister, R. V. Kiyan, C. Reinhardt, U. Stute, B. N. Chichkov, Laser Zentrum Hannover e.V. (Germany)

Infrared, femtosecond laser pulses are ideal for the fabrication of 3D structures in transparent media. Due to the low absorption cross-section, 2 or more photons are necessary for absorption. This multi-photon effect limits the affected volume to the focal area allowing for sharp features on the order of the wavelength of light. One possible multi-photon reaction is the photo-destruction (ablation, decomposition,) or photo-polymerization of materials.

We have used ultrafast laser pulses to remove polystyrene (PS) spheres (diameter ~ 500 nm) at the surface and also inside a colloidal crystal of PS spheres. To optimally focus inside the bulk, an index matching (ORMOCER) material has been infiltrated. By selectively removing the PS spheres in a crystal lattice, we are inscribing defects into the 3D periodic structure. With proper placement of defects, 3D photonic components, i.e., waveguides, splitters, and filters, can be created.

This presentation will focus on the ultrafast micromachining of polystyrene spheres to develop 3D photonic components.

6462B-38, Session 10

Silvered three-dimensional polymeric photonic crystals having a large mid-infrared stop band

S. M. Kuebler, A. Tal, Y. Chen, R. C. Rumpf, E. G. Johnson, College of Optics & Photonics/Univ. of Central Florida

Interest in three-dimensional (3D) metal photonic crystals (MPCs) has grown considerably given their potential applications in optics and photonics. Yet experimental studies of such materials remain few because of the difficulties associated with fabricating 3D micron- and sub-micron-scale metallic structures. We report a route to MPCs based on metallization of a 3D polymeric photonic crystal fabricated by multi-photon direct laser writing. Polymeric photonic crystals (PCs) having simple-cubic symmetry with periodicities varying from 2.0 to 2.4 microns were created using a cross-linkable acrylate pre-polymer. The resulting dielectric PCs were metallized by electroless deposition of silver. Analysis of the metallized structures in cross-section by scanning electron microscopy (SEM) and energy dispersive X-ray spectroscopy shows that silver deposited conformally onto the entire micro-porous lattice. The dielectric and metallized PCs were characterized by Fourier transform infrared (FTIR) spectroscopy in the (001) direction. The polymer photonic crystals exhibit a stop band resulting in circa 70% reflectance centered at 4.0 to 4.8 microns, depending upon the lattice period, with a full-width at half-maximum (FWHM) of 500 nm. Interestingly, FTIR spectra of the metallized PCs show widened stop bands of nearly 6 microns FWHM that reflect 60 percent of the incident light, while the center wavelengths were red shifted and ranged from 6 to 7 microns. The appreciable broadening of the stop band due to the presence of the deposited silver is a result consistent with previously reported theoretical and experimental data for all-metallic 3D PCs. Thus, the approach described here appears suitable for fabricating 3D MPCs of many symmetries and basis sets and provides a path for integrating such structures with other micron-scale optical elements.

6462B-39, Session 11

Plasmonics: a route to nanoscale imaging optical systems

H. A. Atwater, California Institute of Technology

Since the development of the light microscope in the 16th century optical imaging systems have been limited by diffraction. Photonic imaging systems of today are composed of dielectric materials with modest dielectric constants, and this has limited the resolution of microscopic imaging and lithographic printing systems. However subwavelength spatial confinement in plasmonic structures enables one to access very high effective optical indices for and short wavelengths for propagating beams that cannot be realized by other means. In this talk I will describe recent developments in chip-based far field optical imaging with subwavelength components that exploit plasmonic materials with both large positive and large *negative* refractive indices.

6462B-40, Session 11

Dielectric and metallic plasmonic components

C. Reinhardt, R. V. Kiyan, S. Passinger, B. N. Chichkov, Laser Zentrum Hannover e.V. (Germany)

Renewed and growing interest in the field of surface plasmon polaritons (SPPs) comes from a rapid advance of nanostructuring technologies. In this contribution we study the application of two-photon polymerization (2PP) technique and nonlinear maskless femtosecond laser lithography for the fabrication of dielectric and metallic SPP-structures, being used for localization, guiding, and manipulation of SPPs on a subwavelength scale. Both these technologies are based on nonlinear absorption of near-infrared femtosecond laser pulses. Resolutions down to 100 nm are already achievable. Characterization of these structures is performed by detection of the plasmon leakage radiation [1]. 2PP allows the fabrication of dielectric waveguides, splitters, and couplers directly on metal surfaces [2]. The fabricated dielectric structures on metal films are demonstrated to be very efficient for the excitation of SPPs. Using these structures, excitation and focusing of the resulting plasmon field can be achieved. Further results on the fabrication and characterization of metallic SPP-structures and components on dielectric substrates fabricated by nonlinear femtosecond laser lithography will be presented and discussed.

6462B-41, Session 11

SiO2 phase gratings fabricated by UV laser ablation patterning

J. Ihlemann, J. Klein-Wiele, J. Békési, P. Simon, Laser-Lab. Goettingen e.V. (Germany)

Patterning of SiO2 materials like fused silica, crystalline quartz, or SiO2-thin films by laser ablation is very challenging based on their high transparency in the whole spectral range from the deep UV to the near IR. Therefore laser micro-fabrication of UV-optical elements, e.g. silica micro lenses is rather difficult. However, in those cases when only a shallow surface relief on a silica slab is required, like for instance in the case of phase gratings, an new approach provides a flexible solution.

The novel fabrication process consists of three steps. First, a silicon suboxide coating (SiOx with $x < 2$) with a predefined thickness is deposited on a fused silica substrate. Second, utilizing its strong UV-absorption, this coating is removed in defined areas by excimer laser ablation at 193 nm or 248 nm leading to the desired phase pattern in form of a binary depth profile. Third, by applying a thermal annealing process, the remaining SiOx-coating is oxidized to UV-transparent SiO2. This results in a SiO2-surface relief element with excellent UV-transmission. The precisely defined interface between substrate and layer allows for ablation with exact depth control and perfect optical surface quality.

Various irradiation concepts for the fabrication of low line density grat-

ings (period ~ 10 μm) and high line density gratings (period < 1 μm) are demonstrated. The fabricated phase masks can be used in various laser applications like fabrication of Bragg gratings in optical fibers or micro patterning by high power laser ablation.

6462B-42, Session 11

Aluminum nanowire polarizing grids: fabrication and analysis

V. Pelletier, Princeton Univ.; K. Asakawa, Toshiba Corp. (Japan); M. W. Wu, D. H. Adamson, R. A. Register, P. M. Chaikin, Princeton Univ.

We have produced aluminum wire grids with 33 nm periodicity using a thin film of a self-assembling cylinder forming diblock copolymer as a template. These grids, supported on fused quartz wafers, function as transmission polarizers for visible and near-ultraviolet lights and are a thin design, compared to commercially available polarization prisms. Their polarization efficiency is measured to be near 50% in the visible. Quantitative comparison with a new theoretical analysis of such wire grids indicates that they should perform well into the far UV. This analysis also explains a reversal in polarization direction at short wavelengths which we observe in our specimens.

6462B-43, Poster Session

Fabrication of microlens arrays by negative copying of honeycomb-like microporous films

H. Yabu, Hokkaido Univ. (Japan) and FRS, RIKEN (Japan); M. Tanaka, Hokkaido Univ. (Japan); M. Shimomura, Hokkaido Univ. (Japan) and FRS, RIKEN (Japan) and CREST JST (Japan)

We have reported that honeycomb-like microporous films can be prepared by casting a polymer solution under humid conditions using condensed water droplet arrays as templates. Water droplets were condensed on the surface of polymer solution by evaporation cooling, and then, the microporous film was formed after evaporation of solvent and template water droplets. By using this method, hexagonally arranged microporous structure ranging from submicron to micron scale was formed. Furthermore, pincushion like structure was formed after peeling the top layer of the film.

When the surface structure of honeycomb and pincushion films were molded by the polydimethylsiloxane prepolymer or other polymer precursor, hexagonally arranged micro lens arrays were formed after removing the template structure by selective solvent. Spherical and hemispherical micro lens arrays were formed by using honeycomb-like microporous film and pincushion film as templates. To measure the optical properties of the prepared micro lens arrays, projection of light (the shape of the light was letter “F”) was performed. The hexagonally arranged spots of light, which were shaped “F”, indicated the prepared film worked as micro lens arrays. The hemispherical micro lens arrays had better resolution than the spherical one.

6462B-44, Poster Session

Cantilever-based thermolithography for micro- and nanomanufacturing

D. Lee, Y. Choi, Chonnam National Univ. (South Korea)

This paper particular focused an array of heater-integrated cantilevers for micro- and nanolithography. The novel system employing an array of heaters with various sizes utilizes controlled and localized heating to enable economic fabrication of precisely defined micro- and nanoacle patterns. In the scanning thermal cantilever, electrical power is mainly dissipated within the tip area which led to a localized temperature rise. Induced thermal power is expected to be diffused to a sample surface by heat conduction. By applying thermomechanical power to photoresist(PR) layers on spin-coated silicon wafers or mask substrates, thermochemical cross-linking occurs at local areas. Exposed areas have a capability that can stand against commercial PR developers during a developing process. Unheated area is easily removed by immersing the sample in the developing solution.

To optimize the thermal characteristics of the micro-heater, we utilize the process simulation software and numerical analysis. Because it, especially how fast it could be heated or cooled, is a critical issue since it is related to the generation speed of patterns on a wafer. Further improvement in the pattering speed is achieved due to an array of cantilevers operating in parallel. By employing an electrostatic actuator integrated on each cantilever, we can select suitable size of a heater from micro- to nanoscales. Sizes of the patterns generated on the wafer have a strong dependence of heating time and heater size. The novel concept for the SPM-based nanolithography is successfully demonstrated using the fabricated cantilever and a commercial SPM system. Details of the works will be presented at the conference.

6462B-45, Poster Session

Fabrication of thermally durable subwavelength periodic structures upon hybrid materials by nano-imprinting method

D. Kang, B. Bae, Korea Advanced Institute of Science and Technology (South Korea); J. Nishii, National Institute of Advanced Industrial Science and Technology (Japan)

Micro- and nano-sized periodic structures are important components for wavelength dispersion, conversion, signal processing and modulation of optical signals. Thus, many micromachining technologies for the micro- and nano-sized patterns have been recently studied. Especially, nano-imprinting lithography has been rapidly developed as an attractive, low-cost alternative to photolithography and other lithographic techniques. Meanwhile, newly optimized materials for the specific nano-imprinting process have been continually required.

Recently, the functionally modified inorganic-organic hybrid materials were found to have a highly efficient thermal curability, a high optical transparency in the visible and near infrared wavelength regions, and excellent mechanical and thermal properties once fully cured.

In this study, we could successfully fabricate the micro- and nano-sized periodic structures by thermal nano-imprinting process using our original functionally modified hybrid materials. The fabricated structures exhibited the excellent uniformity and surface smoothness through a large imprinted area. In addition, the optical transparency is more than 90 % within visible and near infrared wavelength regions. These nano-imprinted periodic structures showed the highly thermal durability without any structural changes for 2 hours at 300°C, which is much better than commercially available organic imprinting materials. Thus, these nano-imprinted sub-wavelength periodic structures using our original hybrid materials have great potentials for several applications to micro- and nano-photonic devices.

6462B-46, Poster Session

Polarization hologram

M. Okada, Nalux Co., Ltd. (Japan)

Since a sub-wavelength grating does not diffract light due to its period smaller enough than wavelength, it can be treated as uniform material having a certain refractive index. This index can be determined from grating structure, refractive index of material forming the grating, and polarization direction of light transmitting the grating.

Making use of this property and making two-layer structure of resin (lower refractive index) and coating material (higher index) has allowed us to achieve an optical design of polarization hologram whose grating height is low and which is given less impact by changing wavelength in use or incident angle into the substrate.

This hologram mainly functions with two wavelengths for DVD and CD and can be used in order to diffract returning light to LD and reduce noise.

6462B-47, Poster Session

Three-dimensional diffractive micro- and nano-optical elements fabricated by electron-beam lithography

I. B. Divliansky, E. G. Johnson, College of Optics & Photonics/ Univ. of Central Florida

The broad development of the micro- and nano-technologies in the past few years increased the need of techniques capable of fabricating sub-micron structures with arbitrary surface profiles. Out of the several fabrication approaches (HEBS lithography, laser writing, etc.) the electron beam writing stands out as the one capable of the highest resolution, superior alignment accuracy and very small surface roughness. These characteristics make the technique greatly applicable in the fields of photonics and micro-opto-electro-mechanical-systems (MOEMS).

Electron-beam writing is generally associated with binary writing in polymers achieved via exposing the resist with constant dose at the desired locations. If dose variation is implemented during the process of writing, the electron-beam resist accumulates different rates of exposure. This transforms into different thicknesses developed and correspondingly to three-dimensional profile of the final structure.

Here we describe the specificity of fabricating 3D diffractive micro- and nano-optical elements using Leica EBPG 5000+ electron beam system. Parameters like speed of writing, dose accumulation, degree of beam spot overlaps, etc. affect greatly the electron-beam resist properties and the desired 3D profile. We present data that can be used to better understand the different dependencies and therefore achieve better profile and surface roughness management. The results can be useful in future developments in the areas of integrated photonic circuits and MOEMS.

6462B-48, Poster Session

Implementation of far-field phase-shift lithography using diffractive optical elements

W. Hsu, Y. Su, National Taipei Univ. of Technology (Taiwan)

Phase-shift lithography (PSL) provides a promising means to the fabrication of features beyond the diffraction limit. In PSL, a phase shift of pi radians is prescribed on the edge of different regions on a phase-shift mask (PSM), and a fine feature in the photoresist layer can be generated by being exposed to the near-field diffractive light behind the PSM. Here, we present a method to implement a light pattern in the optical far field which is analog to the near-field pattern of PSM by using a free-space system and a phase-only diffractive optical element (DOE).

In this method, a free-space confocal system was adopted in which the output disturbance was Fourier transform of the input disturbance produced by a DOE. The phase-shift pattern was encoded onto the phase-only DOE using an IFTA algorithm with dummy-area method because more degrees of freedom were needed. The designed DOE consisted of 128-by-128 pixels, and so was the target image. The central 16-by-16-pixel square of the target image was the signal region of amplitude 1, which was surrounded by a 0-amplitude region, and the region outside them was the dummy area. The phase of the central square was separated and specified by 0 and pi, respectively, to create a phase-shift pattern. This far-field pattern resembled to the near-field pattern of PSM which can be used to create micro-features.

The 0-pi phase pattern was not the only solution provided by the far-field PSL. We also present some DOE designs generating smoothly-variant phase-shift patterns which can solve the intractable closed-loop problems.

6462B-49, Poster Session

Simplified fabrication process of 3-D photonic crystal optical transmission filter

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No abstract available

6462B-50, Poster Session

Diffractive optical elements fabricated by precise pressing of glass

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Diffractive optical elements (DOEs) are becoming key elements laser optics, sensor optics and lighting applications. DOEs have the advantage to combine several optical functions needed for miniaturizing of optics. They are used to diffract and shape light into the area of interest. Glass DOEs made by SCHOTT are planar optical phase elements with highly accurate shape and efficiency. The new established fabrication process allows mass production of glass DOEs. Detailed results of developments in micro-optics and diffractive optical elements, design, fabrication and their applications are presented in the oral presentation.

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6463-01, Session 1

Receptor free nanomechanical sensing

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Molecular adsorption-induced nanomechanical motion of a cantilever beam has been demonstrated as the basis for many chemical and biological sensors. Chemical selectivity of such sensors depends on immobilized receptors. Receptor-analyte interactions do not very often show high selectivity, which leads to a high false positive rate. Receptor free techniques that can provide very high sensitivity, therefore, are very attractive. A receptor free technique for molecular recognition can be developed using the extreme high temperature sensitivity of a bi-material cantilever. A bi-materail cantilever with adsorbed molecules undergoes bending when exposed to mid infrared (IR) waves when the molecules adsorb the IR light. Differential bending of the cantilever as a function of illuminating IR wavelength resembles an IR absorption spectrum of the adsorbed molecules. We have obtained sensitivity in the sub nanogram level for explosives, and biowarfare agents. The sensitivity could be further improved by optimizing the cantilever properties. Recent results and attempts towards developing a small portable unit will be discussed. We will also address the fundamental issues involved in generating a mechanical photothermal spectrum.

6463-02, Session 1

New techniques for detecting and monitoring corrosion using nanostructures

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Many metal containing devices and structures must function in corrosive atmospheres that can cause them to deteriorate over time. Corrosion may take the form of metal oxides or may be compounds formed by exposure to the effluent of industrial manufacturing processes.

The electronic process measurement and control industry estimates that approximately one-third of all warranty repair work can be attributable to corrosion. Accordingly, the ability to accurately monitor corrosion and take appropriate measures to avoid, deter, or prevent it can be of utmost importance to the industry.

One method and apparatus for monitoring corrosion utilizes a piezoelectric crystal as a corrosion monitor. The crystal is coated with one of several corrodible metals, and the coated crystal is attached to an oscillator before placement in a potentially corrosive atmosphere. As the metal corrodes, the frequency of vibration of the coated crystal decreases. The frequency reading is then converted to a corresponding corrosion film thickness. This monitoring method and apparatus are generally suitable for measuring and detecting certain degrees of corrosion, however, in some instances more precise measurements of corrosion are desired.

This paper will describe a corrosion monitor based on a microcantilever device coated with a reactive metal. Information will be provided on the development of a working microcantilever-based corrosion sensor.

6463-03, Session 1

Hybrid approach to MEMS reliability assessment

J. L. Zunino III, U.S. Army Armament Research, Development and Engineering Ctr.; D. R. Skelton, U.S. Army Research, Development and Engineering Command; W. Han, R. J. Pryputniewicz, Worcester Polytechnic Institute

Recent advances in MEMS technology have led to development of a multitude of new devices. However applications of these devices are hampered by challenges posed by limited understanding of their reliability particularly the impacts of long-term storage. Current trend in micro/nanosystems is to produce ever smaller, lighter, and more capable devices in greater quantities and at a lower cost than ever before. In addition, the finished products have to operate at very low power and in very adverse conditions while assuring durable and reliable performance. Some of the new devices are being developed to function at high operational speeds, others to make accurate measurements of operating conditions in specific processes. Regardless of their application, the devices have to be reliable while in use. MEMS reliability, however, is application specific and, usually, has to be developed on a case by case basis. This paper presents a hybrid methodology particularly suitable for quantitative studies of various aspects in MEMS reliability assessment. The presentation is illustrated with selected examples representing a study of reliability of specific MEMS. By quantitatively characterizing performance of MEMS, under different operating conditions, we can make specific suggestions for their improvements. Then, using the hybrid methodology, we can verify the effect of these improvements. In this way, we can develop better understanding of functional characteristics of MEMS sensors, which will ensure that these sensors are operated at maximum performance, are durable, and are reliable.

6463-04, Session 2

Metal contact reliability of RF MEMS switches

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It is well-recognized that MEMS switches, compared to their more traditional solid state counterparts, have several important advantages for wireless communications. These include superior linearity, low insertion loss and high isolation. Indeed, many potential applications have been investigated such as Tx/Rx antenna switching, frequency band selection, tunable matching networks for PA and antenna, tunable filters, and antenna reconfiguration. However, none of these applications have been materialized in high volume products to a large extent because of reliability concerns, particularly those related to the metal contacts. The subject of the metal contact in a switch was studied extensively in the history of developing miniaturized switches, such as the Reed switches for telecommunication applications. While such studies are highly relevant, they do not address the issues encountered in the sub 100 μN, low contact force regime in which most MEMS switches operate. It was observed that at such low contact forces, even a partial monolayer of surface contaminants could raise the contact resistance dramatically, because the metal tip could not penetrate the contamination layer. Significant work was done to develop wafer cleaning processes and storage techniques to maintain the cleanliness. When pure gold was used as the contact material, significant stiction problems occurred when clean switches were cycled in N2 environment. It was also observed that significant tip deformation occurred after several millions of switching cycles. Harder alloys, while more resistant to deformation and stiction, could introduce additional problems of surface oxidation and organic polymerization. Metal contact reliability is also very much influenced by MEMS packaging. Several hermetic packaging technologies were developed and their effectiveness in protecting the switch contacts from contamination was examined.

6463-05, Session 2

Effects of V additions on the mechanical behavior of Au thin films for MEMS contact switches

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MEMS contact switches with Au contacts fail mainly due to issues associated with the relatively low hardness of Au. Alloying of the contacting thin films as a means to improve the wear properties at a negligible expense of electrical contact resistance is the focus of this paper.

Three film classes are compared: pure Au, Au-V solid solution, and Au-VOx dispersions. Au-V thin films in the 1-10 at% composition range were fabricated by co-sputtering and tested for fundamental contact mechanical properties such as stiction and wear. Au films with VOx dispersions were fabricated using reactive co-sputter deposition to further improve hardness and wear properties. Thin film composition was determined by RBS and XPS while the hardness was derived from nanoindentation. The contact phenomena in clean ball-on-plane contacts were studied in a custom designed low-force test configuration under varied hot-switching conditions. The degradation of micrometallic contacts in slow testing as well as Highly Accelerated Life Tests was examined electrically and also under SEM and AFM to probe origins of failure. The oxide particle dispersion strengthened films showed different contact properties and life-times than solid solution films.

6463-06, Session 2

Mechanics of thin film adhesion-delamination subjected to residual stress and interfacial adhesion: application to MEMS-RF-switch

M. F. Wong, K. T. Wan, Univ. of Missouri/Rolla

Thin film delamination is an important phenomenon in micro-electromechanical systems (MEMS). A typical radio frequency micro-switch (MEMS-RF-switch) comprises a rectangular beam (bridge) suspended above an underlying dielectric pad. The bridge of a dormant switch keeps its “on”-state. When an applied electrostatic potential is applied to the pad, the bridge is pulled into contact with the pad, leading to “off”-state. Once the electrostatic force is removed, the bridge is released and returns to its up-state. However, the presence of intrinsic surface forces such as stray charges, van der Waals, and water meniscus will hinder the switch operation. Besides, the bridge is also subject to pre-stress as a result of thermal mismatch during fabrication or heating due to operation. Delamination of the bridge is thus influenced by a coupled interfacial adhesion and residual stress. The mechanics of thin film delamination thus plays a significant role in designing and fabricating MEMS-switch.

A 1-D linear model is constructed. A rectangular beam clamped at both ends is adhered to a punch substrate. An external tensile force is applied to the punch to cause an interfacial delamination along the film-substrate interface. The constitutive relation or mechanical response is derived from rigorous solid-mechanics modeling based on bending and stretching deformation of the bridge. A simple energy balance will also be derived to trace the delamination trajectory. The model will further be extended to a 2-D axisymmetric membrane clamped at the perimeter. The classical von Karman equation will be adopted to derive the film deformation profile and the delamination mechanics. The coupling between adhesion and residual stress, and their manifestation in the delamination procedure will be discussed.

Some preliminary studies show the presence of a “pull-off” event in the 2-D configuration when the membrane snaps from the substrate once the punch displacement exceeds a certain threshold and the contact circle reduces to a non-zero critical value. Such “pull-off” parameters depend on the relative ratio of the adhesion energy and residual stress. It is interesting to note that 1-D counterpart does not possess a “pull-off” event, in that, the adhered membrane will reduce to a line contact before complete detachment.

Experiments based on the above 1-D and 2-D model will be conducted in a model film and punch materials to verify the theoretical framework. The adhesion energy will be varied by different combination of film and substrate and the corresponding dissimilar interfaces, while the residual stress will be introduced by thermal mismatch. Measurement of the pull-off forces and delamination trajectory allow one to deduce the adhesion energy and residuals stress.

Both the theoretical model and experimental data have significant impacts in the operation and life-span of a MEMS-RF-switch and other similar devices involving moveable beams and membranes. In particular, the model will help to gauge the optimal and feasible bridge thickness and bridge-gap separation. Trends and graphs presented in this work present important design parameters.

Experiment has carried out base on the assumption of the theory. Force, displacement of the substrate, interfacial contact area, adhesion energy, and tensile residual stress will be measured and compared with the theory.

6463-08, Session 3

Fatigue of silicon structural films for MEMS applications

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Fatigue failure, which is observed in micron-scale silicon structural films but not in bulk silicon, can severely impact the reliability of microelectromechanical system devices. Despite several studies into the fatigue behavior of these films, the exact mechanism is not as yet known. We have determined numerous data sets of stress-lifetime results for fatigue resonator devices from the MUMPs and SUMMIT processes in different environments. The fatigue data show similar trends for all types of devices in ambient air, i.e., shorter lifetimes in higher relative humidity environments and no fatigue failure in vacuo, even at a high number of loading cycles (greater than 109) and high applied stresses. Transmission electron microscopy of the native oxide scales in all these type of films show four to six-fold oxide thickening at stress concentrations after high-cyclic fatigue cycling, but understandably there is thickening in vacuo. Specifically, fatigue failure (and oxide thickening) is observed both in silicon films with ~4 nm initial post-release oxide thickness as well as in devices with ~20 nm thick films. This behavior is explained in terms of a ‘reaction layer’ fatigue mechanism, where moisture-assisted subcritical cracking of the thickened oxide layer occurs until the crack reaches a critical length inside the oxide to induce catastrophic failure of the device.

6463-09, Session 3

A novel technique for extraction of material properties through measurement of pull-in voltage and off-capacitance of beams

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The mechanical properties of the structural layer play important role in the design and optimization of MEMS structures. The pull-in measurement is a popular technique used to measure the mechanical properties of the material, but its success depends on the accurate measurement of the gap (g) between the beam and the ground plane and its uniformity. In this paper we propose a novel technique to measure the material properties of a structural material, which does not require accurate knowledge of the value of ‘g’. This method requires the measurement of the off-Capacitance (Coff) in addition to pull-in voltage (Vpi), which can in fact be measured easily in the same set-up. In the conventional method, a large number of beams with different lengths (L) are fabricated simultaneously. The slope of Vpi versus (1/L or 1/L2) characteristics depends on the Young’s modulus, which can be extracted provided the values of other parameters are known. In our method, we plot (Coff3)(Vpi2)(L4)/(A3) versus (1/A) for beams under bending dominating condition and (Coff3)(Vpi2)(L2)/(A3) versus (1/A) for beams under stress dominating con-

dition, where A is the area of a beam. The plots are extrapolated to intersect the y-axis. The value of the intercept can be used to extract the values of Young's modulus and residual stress, without any definite knowledge of the value of 'g'. In this paper, we have shown with the help of simulations that the material properties can be extracted very accurately even when the gap (g) is very nonuniform.

6463-10, Session 3

Cyclic thin film flexible strain sensor testing

H. C. Lim, J. F. Federici, New Jersey Institute of Technology; J. L. Zunino III, U.S. Army Armament Research, Development and Engineering Ctr.

Testing and failure measurement of the flexible thin film strain/pressure sensor is a critical indicator for the U.S Army's field sensing application. This accelerated lifetime aging test would characterize the existing flexible strain sensor with repeated application of pressure load. The active element of the sensor under test is composed of n-type doped a-Si:H piezo-resistive layer, with metallic conduction pads and traces. The sensor further is encapsulated and passivated with a layer of SiNx top coat. A basic experimental setup with DAQ system is devised to document the sensor's mean time between failures under standard laboratory conditions. A full Wheatstone bridge configuration is used to eliminate any temperature and environmental variation during the experiment. The test setup is also damped out of any random vibrations on a tuned damping optical table. Of the typical industrial cyclic testing run of 10x106 duty cycles, the sensor survived a total of 6.091x106 cycles before sensor stopped to responses effectively and fails. The deterioration might be due to cracks formation on the piezo-resistance semiconductor layers, delamination of the thin film layers and conduction metal.

6463-11, Session 3

Self-sensing and actuation of CNF and Ni nanowire/polymer composites using electromicromechanical test

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Self-sensing and actuation of CNF and Ni nanowire/various polymer composites were investigated using electro-micromechanical technique. Self-sensing of CNF with different aspect ratio and Ni nanowire with different diameter/polymer composites were evaluated and compared as function s of loading/unloading, temperature, and humidity. Thermal treated electrospun PVDF nanofiber web showed higher mechanical properties than the untreated case due to increased crystallization, whereas load sensing decreased for heat treated case. Electrospun PVDF nanofiber web showed the sensing effect on loding, emperature, and humidity. Actuated strain of CNF and Ni nanowire/PVDF and cellulose actuator was also investigated with different frequency, amplitudes.Nanocomposites using CNF, Ni nanowire, and electrospun PVDF nanofiber web can be applicable practically for multifunctional smart structural materials. Acknowledgement: this work was financially supported from Yunhak Project by Korea Research Institute of Standards and Science (KRISS).

6463-12, Session 3

Critical comparison of metrology techniques for MEMS

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MEMS Technology has become more ubiquitous in recent years but still metrology for MEMS materials has lagged in terms of standardization and common industry usage. MEMS metrology encompasses a very wide range of test methods for various kinds of functional and manufacturing characteristics of these devices but in this article we only refer to test techniques for extraction of mechanical properties essential to the product development process. These include methods such as test structures and other methods for measuring elastic modulus, residual stress and stress gradients, biaxial modulus, pull-in voltage, capacitance etc. as well as properties important to device reliability such as creep, fatigue and wear.

Metrology for MEMS materials has always included attempts by researchers and engineers to miniaturize existing macro level test methods like the uniaxial tensile test, hardness test, bulge test etc. but historically another approach has always existed in parallel. Novel on-wafer or on-chip test structures are continuously being developed in the hope of achieving stream-lined in-situ tests that don't require the "destructive" nature of the former group of test methods. The hope is that in-situ methods would eventually be standardized to the point where they, in the mask layout phase, could be "dropped onto" wafer as in-line process control monitors (PCMs). Today, we're still far away from realizing this dream in the sense that the ASTM standards list does not include a single unique test structure for material property extraction. The focus of this current article is to critically compare the various techniques that have been developed so far and contrast their viability and potential as candidates for standardization either in-situ or ex-situ.

6463-13, Session 4

MEMS reliability assessment program - progress to date

J. L. Zunino III, U.S. Army Armament Research, Development and Engineering Ctr.; D. R. Skelton, U.S. Army Research, Development and Engineering Command

As the Army transforms into a more lethal, lighter and agile force, the technologies that support these systems must decrease in size while increasing in intelligence. Micro-electromechanical systems (MEMS) are one such technology that the Army and DOD will rely on heavily to achieve these objectives. Current and future military applications of MEMS devices include safety and arming devices, fuzing devices, various guidance systems, sensors/detectors, inertial measurement units, tracking devices, radio frequency devices, wireless RFIDs and network systems, GPS's, radar systems, mobile base systems, satellites, missiles and the like.

The MEMs devices within these systems will be required to last as long as the lifetime of the weapon systems in which they are embedded which may be decades. MEMS devices are also required to function properly after extended periods of inactivity while in storage. Even though the reliance on MEMS devices has been increasing, there have been limited studies performed to determine their reliability and failure mechanisms. Accordingly, the US Army Corrosion Office at Picatinny, NJ manages the MEMS Reliability Assessment Program to address this issue.

The goals of the MEMS Reliability Assessment Program are to 1) Establish the reliability of MEMS devices including the impact of transportation, long term storage, operating environment, packaging & interconnection issues; 2) Analyze the compatibility of MEMs devices with energetic and other hazardous materials found in military items; 3) Identify failure mechanisms and failure rates; 4) Develop accelerated test protocols for assessing the reliability of MEMS; 5) Develop reliability models for these devices; 6) Identify a standardizing body, standard terminology, definitions, and categories for MEMS devices; 7) Determine potential test methodologies for assessing these mechanisms.

Current ongoing efforts in support of the program include: 1) an assessment of the Long-term storage performance and standards requirements, 2) initiation of ESS testing for the identification of failure mechanisms of selected devices, 3) drafting of a joint test protocol for assessment of the corrosion potential of MEMs devices, 4) assessment of applicability of reliability software packages for use with MEMs devices and 5) development of test guidelines and test capabilities for the assessment of MEMs reliability.

The MEMS assessment generated under this program will benefit the MEMS user community by filling the information gap that currently exists for reliability. With the rapid growth of the MEMS industry it is crucial to consider the reliability of this emerging technology and its applications in the early stages of its development.

6463-14, Session 4

Development of a model for predicting dry stiction in microelectromechanical systems (MEMS)

A. Hariri, J. Zu, R. Ben Mrad, Univ. of Toronto (Canada)

Adhesion between micro parts, also referred to as stiction, is a major failure mode in MEMS. Undesirable stiction, which results from contact between surfaces, can severely compromise the reliability of MEMS. In this paper, a model is developed to predict the dry stiction between uncharged micro parts in MEMS. In dry stiction the interacting surfaces are assumed to be either hydrophobic or placed in dry environment. In this condition the van der Waals (vdW) and asperity deformation forces are dominant. Here, a model is developed for the vdW force between rough micro surfaces and the new model is combined with a newly developed multiple asperity point model for the elastic/plastic deformation of rough surfaces in contact to solve for the equilibrium condition of the forces. This, in turn, will yield the equilibrium distance between micro surfaces, using which the apparent work of adhesion can be found. The result of the theory is compared with the available experimental data from literature. The developed model can be easily used for design purpose. If the topographic data and material constants are known, the desirable adhesion parameters can be quickly found from the model.

6463-15, Session 6

Optical MEMS: designing for reliability

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The inter-disciplinary nature of MEMS makes its design a highly involved process. In Optical MEMS the addition of optical parameters only increases the complexity. It is almost impossible for a designer to know where to start given the number of variables in the design process. For the design process to yield a device that will meet the required specifications over its entire lifetime, reliability issues must be included in the design process. This paper develops a method that can be used to create a step-by-step design process involving reliability issues at every stage. The process begins by listing out the constants and constraints of the design. The constraints could be due to physical parameters, MEMS fabrication processes, optical reasons, reliability issues, etc. They affect the design in different ways, for example, two fibres cannot be brought closer than 250mm which will affect the optical design and the overall dimensions of the device. Taking all such constraints into account, an optical design process is outlined. The effect of individual errors are studied on a key parameter like insertion loss. This gives the designer invaluable information about which parameters the design is more sensitive to. This will help in deciding the manufacturing tolerances required in the different stages. Using all of this data, an “ideal design” is developed. A Monte Carlo analysis is carried out on that design to show the effect of errors occurring simultaneously. The paper concludes with a flow chart of a suggested design process to be used when designing optical MEMS devices.

6463-16, Session 6

Process engineering and failure analysis of MEMS and MOEMS

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Process engineering and failure analysis of MEMS and MOEMS requires dynamical characterization of both their in-plane and out of plane response to an excitation.

Light interaction with a sample modifies both intensity and phase of the illuminating wave. Any available supports for image recording are sensitive only to intensity. Denis Gabor1 invented in 1948 a way to encode the phase as an intensity variation: the “hologram”. Digital Holographic Microscopy (DHM) implements digitally this powerful principle. With the present power of computers and the developments of digital cameras, holograms can be numerically interpreted within a tenth of second to provide simultaneously: (1) the phase information, which reveals object surface with vertical resolution at the nanometer scale along the optical axis, and (2) intensity images, as obtained by conventional optical microscope. Both images are defined with a diffraction limited resolution in the transverse (0xy) plane and are “reconstructed” from the hologram in real time. The strength of DHM as implemented in the frame of this paper lies in particular on the use of the so-called off-axis configuration2, which enables to capture the whole information, by a single image acquisition, within a few microseconds.

These important features make out of DHM a unique and very efficient tool for dynamical characterization of in-plane and out-of-plane response as:

The extremely short acquisition time makes DHM systems insensitive to vibrations. These instruments can operate without vibration insulation means, making them a cost effective solution for an implementation in clean rooms and on production lines.

Standard camera used in conjunction with a stroboscopic synchronization of acquisition with the micro system movements, enables presently characterization up to excitation frequencies of 100 kHz. Fast acquisition cameras and reconstruction of the holograms in a second step is an alternative for non periodic movement analysis.

The optical set up enable to measure through cover glass for analysis of micro systems in vacuum.

This presentation explains the basics of the technology and illustrates examples of failure analysis and process engineering of MEMS and MOEMS by DHM.

The development of the technology has been supported by Swiss government through CTI grants TopNano 21 #6101.3 and NanoMicro #6606.2 and #7152.1. Systems are commercialized by Lyncée Tec SA (www.lynceetec.com).

6463-17, Session 6

Performance and reliability test of MEMS optical scanners

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Very different and specific customized measurement techniques for MEMS scanners and characterisation of newly developed devices or the evaluation of simulation models have been reported so far. However, a development of test methods leading to reproducible and comprehensible results and being suitable to apply in the fabrication and before packaging procedure is in the beginning. The main concern of this paper is to report and discuss suitable measurement techniques and to compare and verify this methods on different scanners for examples.

Measurement of resonant frequencies in an early production state provides information about geometry properties and enables selection of scanner chips with characteristics which do not meet the specification and the cost for packaging of this bad dies is saved. A parameter adaptation procedure on base of a finite element model, order reduction methods and parameter fitting provides the required information.

The application of a tilt angle measuring set up containing a position sensitive semiconductor device and a laser diode and of a laser Doppler interferometer is analysed and benefits and drawbacks are discussed. A Scanning Laser Doppler Interferometer is used for rapid measurement of frequency response functions at a large number of locations at the scanner for visualizing of the motion and for a structural modal analysis based on measured data. Measuring the deformation of scanners at resonant frequency, a phase shift interferometer with stroboscopic illumination has been utilized. Peak to peak deformation of the mirror in the range of several 10nm is clearly resolved meanwhile the scanner resonates to an angle of ±5 degrees mechanical deflection.

6463-18, Session 6

White-light interferometric profile measurement system using spectral coherence

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White light interferometry (WLI) has played an important role in nanoscale 3-D profile measurement technology. To meet the demands of cost-effective, accurate, and fast measurement, the research and applications for WLI are widely spreading. Our objective is to build up a 3-D microstructure profile measurement system based on white-light interferometry technique, for micro-mechatronic, micro-optical, and/or semi-conductor devices. This paper briefly reviews related WLI theory and then the principle of spectral coherence is applied to improve the system design. Specifically, proper spectral filters can be employed to extend the coherence length of the light source (i.e., that of the filtered light source) to the order of several ten micrometers. In this paper, Michelson interference experiments are performed with filtered and unfiltered white light sources, to show the feasibility of the concept of spectral coherence. The Michelson interferometer is adopted due to its convenience to fabricate and its acceptable tolerance to noise. For signal processing, a parallel process technique is used to efficiently process the light and electronic signal. Finally, in the system integration, an opto-mechatronic technique is devised to establish the 3-D micro-structure profile measurement system. In addition to measuring the surfaces of micro-mechanical and micro-optical elements, this technique can be applied to do the real-time measurement because of its shorter measurement time.

6463-20, Session 7

Charging effects in spatial light modulators based on micromirrors

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This paper describes charging effects on spatial light modulators. These light modulators consist of up to one million mirrors that can be addressed individually and are operated at a frame rate of up to 2kHz. They are used for DUV mask writing were they have to meet very high requirements with respect to accuracy.

In order to be usable in a mask-writing tool, the chips have to be able to work under DUV light and main-tain their performance with high accuracy over a long time. Charging effects are a problem frequently en-countered with MEMS, especially when they are operated in an analog mode.

In this paper, the issue of charging effects in SLMs used for microlithography, their causes and methods of their elimination, by means of addressing methods as well as technological changes, will be discussed. The first method deals with the way charges can accumulate within the actor, it is a simple method that requires no technological changes but cannot always be implemented. The second involves the removal of the mate-rials within the actor where charges can accumulate. Both methods reduce the charging to a level below the detection limit.

6463-21, Session 7

On the reliability of thermopneumatic actuators with silicon membranes

A. K. Henning, Aquarian Microsystems

The reliability of microvalves has received little attention. Some work has been performed on thermopneumatically actuated microvalves, and on flow control systems created from them [2-6]. In this work, the details of the coupled mechanical and thermodynamic system which constitutes a thermopneumatic actuator [1] are used to understand new observations of a rare failure mode in such actuators. The failure mode is related to cavitation of a vapor bubble in the actuator cavity, which can occur when the thermopneumatic liquid shrinks more than the actuator membrane, combined with the surface tension between the membrane and the liquid, can tolerate. The sudden nature of the resultant bubble formation causes the mechanical membrane to oscillate. If more than one normal mode is excited by the cavitation event, then energy can be traded between the modes, and in rare instances the oscillation of the membrane can create stress which exceeds the fracture limit of the single-crystal silicon which constitutes the membrane.

6463-22, Session 7

Reliability of MEMS materials in liquid environments

T. P. Kuehn, S. M. Ali, S. C. Mantell, E. K. Longmire, Univ. of Minnesota

As one of the most common MEMS structural materials, single crystal silicon has gathered a large amount of the attention in this area of research. Other materials such as silicon nitride, gold, and titanium are all commonly used as either structural layers or adhesion seed layers. It is desired to focus on the reliability of these materials in both air and liquid environments. Similar studies have been done recently where the microcantilever is subjected to dynamic actuation via an oscillating magnetic field. In this study, however, actuation will be induced by a piezoelectric stack. This will eliminate the need for magnetic layers to be deposited on the microcantilevers, ensuring only the material of interest is being studied. Silicon nitride cantilevers are dynamically actuated for many cycles (>10^8) by a piezoelectric actuator. Position data is obtained by reflecting a laser beam off the cantilever tip and onto a position sensing photo-diode array. Previous tests of silicon at similar stress levels have shown no indication of structural fatigue failure due to the high tensile strength of silicon. The tensile strength of silicon nitride is actually higher than that of silicon, so fatigue failure is not expected in these tests as well. Regardless, changes in resonant frequency are expected in liquid environments. In a saline solution, for example, it is expected that the resonant frequency will decrease markedly. This is due to the deposition of sodium, chloride, magnesium, and other ions found in saline. Tests in air show no effect outside measurement limits. Sufficient changes in the resonant frequency can represent an operational failure whereby measurement accuracy is reduced depending on the application (mass sensors, etc).

6463-23, Session 8

Wafer capping of MEMS with fab-friendly metals

J. Martin, Analog Devices, Inc.

Inertial MEMS sensors are normally sealed in hermetic enclosures. Some are in ceramic or metal packages. Others are capped with a silicon wafer after the fab process is completed. These capped products use a screen printed glass frit to seal the devices prior to wafer singulation and plastic packaging. Glass frit is attractive because it is cost-effective, requires reasonably low temperatures and readily accomodates interconnect topography. Unfortunately, it also limits reliability, product size, cost and performance. Screen printed glass frit does not meet IC contamination standards. This affects cost as well as reliability and yield because in-fab

capping processes cannot be used. The dielectric nature of glass is also a shortcoming because EMI shielding requires electrical connection to the caps. Bond wires are one solution, but the wires increase package thickness. Glass frit seals are 150 to 300 microns wide so they constrain die shrink efforts, particularly in MEMS-only die. These quality, cost and performance considerations underline the advantages of narrow metal seals. Wafer bond processes based on gold alloys and a variety of solders have been reported in the literature. They generally involve deep trap metals so they are not suitable for use in an IC fab. This paper will describe a MEMS wafer capping process that uses metal seal technology that is compatible with IC fabrication.

6463-24, Session 8

Simple measurement technique for resonance frequency of micromachined cantilevers

S. Bhat, E. Bhattacharya, Indian Institute of Technology Madras (India)

This paper discusses a simple electrical measurement technique to determine resonance frequency of surface micromachined cantilever beams that is also suitable for packaged devices. Measurements are done on oxide anchored doped polysilicon beams. With a DC bias applied between the beam and the substrate, the beam bends towards the substrate due to electrostatic force. At a particular DC bias called Pull-in voltage, the electrostatic force exceeds the mechanical restoring force and the beam collapses on the substrate. If the beam is driven by an AC signal riding on the DC bias, the beam starts vibrating. When the drive frequency matches the natural frequency of the beam, the oscillation amplitude is maximum. In this measurement the DC bias is fixed at a value lower than the pull-in voltage. A small AC bias is then applied such that the sum of the DC and the maximum amplitude of the AC is less than the pull-in voltage. The frequency of the AC is then swept and at resonance, because of maximum displacement, the beam is pulled in which is detected by a current flowing between the beam and the substrate. By iteratively adjusting the DC bias it is possible to make sure that pull-in occurs only due to resonance and the frequency setting at this point gives the natural frequency of the beam. Measured values for different beam lengths were compared with optical and Doppler vibrometry results and gave an excellent match.

6463-25, Session 8

Analytical model of a single-stage compliant mechanism with a flexible lever arm

P. A. Hassanpour, W. L. Cleghorn, Univ. of Toronto (Canada); E. Esmailzadeh, Univ. of Ontario Institute of Technology (Canada); J. K. Mills, Univ. of Toronto (Canada)

Compliant micromechanisms are employed in the design of MEMS to amplify force or displacement. Models, which have been developed for a compliant mechanism, generally assume that its lever arm is rigid and does not experience deformation during the operation. In most cases, this assumption is acceptable since the lever arms are designed wide enough so that they undergo minimal deformity when transferring force or displacement from input to output; however, in some cases, the lever arm not only is the mechanical interface between its input and output, but it also couples them electrically and/or thermally. Therefore, it may be desirable to design the lever arm as thin as possible to reduce the coupling between the input and output systems. Consequently, the assumption of a rigid arm is no longer valid for calculating the amplification factor. In this paper, the assumption of the rigidity of the lever arm is relaxed to develop an analytical model for a compliant mechanism having a flexible lever arm. The results obtained using the flexible arm model, in contrast with the rigid arm model, shows very good agreement with the finite element model. For wide levers, the results of the flexible arm and the finite element models approach to those of rigid arm model. These results show that the amplification factor of a flexible lever arm is less than a rigid one. The reason is that the flexible lever arm absorbs a fraction of input energy in the form of elastic strain energy. Without significant loss of accuracy, this model can replace the finite element model to improve the computation time in the optimization procedure to achieve higher amplification factor and lower electrical/thermal coupling.

6463-26, Session 8

A fast model-order reduction algorithm for microelectromechanical devices

R. Zhang, G. A. Jullien, Univ. of Calgary (Canada)

A fast model-order reduction algorithm is proposed for microelectromechanical devices. The proposed technique can reduce the computational cost and memory requirement. As an example, experimental studies are presented for multiple-mode linear-drive resonator, and the predicted results are obtained in a very good agreement with previous publications.

6463-27, Session 8

Development of integrated wireless SAW microsensors for pressure-temperature monitoring and ID tag applications

K. Lee, W. Wang, S. S. Yang, Ajou Univ. (South Korea)

For the first time, 440MHz range wireless SAW microsensors integrated with pressure/temperature sensors and ID tag were fabricated and then wirelessly characterized using network analyzer. Two piezoelectric substrates (41o YX LiNbO3) were bonded with conductive silver paste, in which ~150μm air gap was structured (Fig. 1(a)). The pressure sensor was placed on the top plate, whereas the RFID tag and temperature sensor were located in the bottom substrate. An antenna with 440MHz central frequency was fabricated and wire-bonded to the electrode pads for wireless characterization. The IDTs (Interdigital Transducers) were placed on both top/bottom substrates, and had identical dimension and structure, and were electrically connected each other with 140μm height metal poles. A SPUDT (single phase unidirectional transducer), multi-acoustic tracks, optimal device dimension, shorted grating reflector were employed to obtain sharp reflection peaks, small signal attenuation, large readout distance, and high sensitivity of sensors. To find optimal design parameters, a coupling of modes (COM) modeling and finite element methods (FEMs) were performed prior to fabrication[1]. Table 1 shows the simulated results in case of 41o YX-LiNbO3 substrate, aluminum IDT with 10 and 50 finger pairs, 0.5mm aperture size, and various type reflectors. Based on the extracted optimal design parameters, the SAW device was fabricated. In wireless device testing using the network analyzer, eight sharp peaks from ID reflectors, three peaks from temperature sensor, and three peaks from pressure sensor were observed in a row in time domain. All the reflected peaks were well matched with the predicted values from the simulation. Peaks showed small signal attenuation and few spurious peaks because (1) all the device parameters had good impedance matching with the propagating SAW; (2) the employment of SPUDT avoids bidirectional SAW flow and stimulates nearly all SAWs to one side propagation; and (3) the use of two acoustic tracks minimizes multiple reflections from reflectors. With a 10mW RF power from the network analyzer, a ~1 meter readout distance was observed. Depending on external RF power, frequency, and antenna gain, the readout distance can be further enlarged[2].

Conference 6464: MEMS/MOEMS Components and Their Applications IV Special Focus Topics: Transducers at the Micro-Nano Interface

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6464-01, Session 1

Nanoelectronic technology for bioscience

A. N. Cleland, Univ. of California/Santa Barbara

I will describe our development of an all-electronic biosensing technology, an approach that uses radiofrequency signals to penetrate the ionic double layer that typically shields biologically relevant solutions from electronic sensors. We have demonstrated a radiofrequency version of a Coulter counter, and more recently have been able to demonstrate micron-scale labels for cells, that can be used to identify and digitally encode cell type based on the cell's surface epitopes. The labels are read out electronically in a microfluidic system, and have applications in cell counting and sorting. We have also developed a nanoscale version of the sensor electronics that should allow molecular scale sensing, and are attempting to develop an electronic version of the ELISA sandwich assay. This talk will summarize our progress in these areas.

6464-02, Session 1

Drosophila as an unconventional substrate for microfabrication

A. J. Shum, B. A. Parviz, Univ. of Washington

We report on direct solid-state microfabrication on fruit flies (Drosophila) yielding live insects incorporating metal microstructures. From an engineering vantage point, a fruit fly is considered a multi-functional mm-scale robot. Construction of such a sophisticated robot is beyond the capabilities of the MEMS technology today. We demonstrate how some of the inherently parallel microfabrication techniques, such as metal evaporation under vacuum, can be performed on Drosophila. This demonstration paves the way for the massively-parallel manipulation and alteration of the structure of mm-scale insects in a fashion similar to MEMS processing, leading to the integration of inorganic microstructures with the nature-built robots.

We performed a systematic study of the resilience of adult flies to vacuum exposure. Our data shows a marked dependence on time in vacuum for fly survival and establishes that adult flies can be subjected to 55 mTorr vacuum for as long as one hour with a measurable chance of survival. This finding is significant since it shows that many microfabrication steps performed under vacuum conditions can be applied to flies, producing viable insects after completion.

As a model process, we demonstrated thin film metal evaporation on flies. We placed a collection of flies in a container consisting of a solid and a mesh side. We positioned the container in a thermal evaporator and evaporated ~93 nm of indium at 1 mTorr. After the completion of the procedure up to 30% of the flies regained consciousness. Repetition of this procedure consistently produced indium coated live flies.

6464-03, Session 1

Integrated biophotonic hybridization sensor based on chitosan-mediated biomolecule assembly

V. Badilita, M. Powers, S. T. Koev, H. Yi, G. Payne, R. Ghodssi, Univ. of Maryland/College Park

This paper presents an integrated biophotonic sensor that uses polysaccharide chitosan to assemble biomolecules on microfabricated device surfaces. Chitosan can be electrodeposited onto readily addressable locations due to its pH-dependent solubility transition, allowing excellent spatial and temporal resolution of biomolecule placement. At the same time, chitosan is rich in primary amine groups that allow for biomolecule assembly by various chemical/biochemical means. We demonstrate in this paper single-stranded probe DNA assembly and optical detection of hybridization events with fluorescently tagged target DNA through sidewall chitosan electrodeposition/conjugation and integrated optical fibers.

The biophotonic sensor consists of SU-8 polymer optical waveguides and microfluidic channels defined on a Pyrex substrate. A key element in the device design is the successful vertical patterning of the waveguides facets with transparent indium tin oxide (ITO) electrodes. Chitosan is electrodeposited on these electrodes and probe DNA molecules are attached for hybridization with fluorescently-tagged target DNA. The device is top-down illuminated and the waveguides collect emitted light from the biomolecules for fluorescence analysis. The waveguides are coupled to optical fibers, which are connected to a benchtop spectrum analyzer.

There are several advantages of this device: i) the large collection efficiency of the emitted light compared to the evanescent coupling techniques due to the fact that the analyte is immobilized on the waveguide facet; ii) the integrated optical sensing through sidewall allows multifaceted, high throughput analysis on minimal sample volumes within single microfluidic channel; iii) versatility - the device can be adapted to sense proteins, enzymes and other optically active biocomponents.

6464-04, Session 1

Self assembled monolayer and protein adsorption studies on micromachined quartz crystal balances

P. Kao, A. Goyal, D. L. Allara, S. A. Tadigadapa, The Pennsylvania State Univ.

Micromachined quartz crystal microbalance have been fabricated in array format for protein adsorption studies. In a 100 μm thick polished AT-cut quartz substrate, 1 mm diameter circular features were etched to a depth of 40 μm using an SF6 + Ar based chemistry in an inductively coupled plasma reactive ion etcher. RMS surface roughness of better than 2 nm was obtained after the 40 μm thick etch. Figure 1 shows the fabricated resonator array packaged in a modified ceramic dual-in-line package. The 3 x 3 array consisting of 60 μm thick resonators were measured to have a fundamental resonance at 27.7 MHz and the third overtone of 83.1 MHz. Q-factor of ~1000 in liquid loading conditions were measured using an Agilent 4294A impedance analyzer. The absolute mass sensitivity of the fabricated device operating at 83.1 MHz is expected to 31.8 fg/Hz which represents an improvement of nearly 578,000 times that of a conventional macroQCM.

SAMS and Protein adsorption studies have been carried using the fabricated QCM array. The packaged device was thoroughly cleaned using ethanol followed by exposure to UV in ozone ambient. The cleaning procedure has been separately demonstrated to be effective in achieving good SAMS growth. The device was allowed to stabilize against drift by running an experiment in ethanol for 2-hours. After drying the ethanol, a 1 mM solution of 1-hexadecanthiol (CH3(CH2)15SH) in ethanol, was prepared prior to the experiment and added onto the resonator surface. Fig. 2 shows the change in the frequency of the resonator upon the growth of hexadecane thiol SAMS on the resonator surface. Upon completion of the SAMS growth, the SAMS solution was dried and resonator surface was gently cleaned using ethanol. Bovine serum albumin (BSA) protein solution in phosphate buffer solutions (PBS) was subsequently added on the resonator surface. Fig. 3 shows the observed frequency change upon the addition of the protein solution. A frequency change of ~12.23 kHz

was observed for the protein adsorption as opposed to the 3.65 kHz frequency change for SAMS growth was observed. This paper will present the adsorption isotherms for SAMS and proteins obtained using the micromachined quartz resonator array.

6464-05, Session 3

Nanomechanical cantilever arrays for low-power and low-voltage embedded nonvolatile memory applications

C. G. Smith, Univ. of Cambridge (United Kingdom); R. Van Kampen, J. Pop, Cavendish Kinetics B.V. (Netherlands); D. Lacey, M. Renault, Cavendish Kinetics Inc.

A new non-volatile memory technology for embedded memory applications is described. The technology uses one cantilever per cell with two stable states to store information. The two stable states are either stuck down to a landing electrode or not. Because the cantilever and landing electrode is made from conducting material, each cantilever can be read in a straight forward manner by measuring the contact resistance between the two. The cantilever stays in the 'on' state due to the short range attractive forces at the contact. Using standard CMOS processing equipment and materials the cantilevers are designed to switch at the native voltages found in a standard micro-controller, making this technology an attractive alternative to other forms of embedded non-volatile memory and it also reduces the memory block area by eliminating the requirement for charge pumps.

With scaling of the cantilever geometries the switching speed is reduced to 100ns and below making it very much faster to program and erase compared to FLASH and SONOS devices. The high activation energies associated with adhesion ensure that the technology is reliable over a wide temperature range. In this paper we discuss how the cantilevers are encapsulated in a wafer scale CMOS process and how the resulting micro-cavities are qualified. We will discuss how advanced CMOS processing techniques can be used for aggressively scaling cantilever dimensions for 45nm applications and below.

6464-06, Session 3

Nanoelectromechanical systems as single electron switches and field emitters

R. H. Blick, Univ. of Wisconsin/Madison

Nano-electromechanical systems (NEMS) have been shown to accurately regulate the flow of electric current. We present the concept and demonstrate experimental operation of nano-electromechanical single-electron transistors. The devices are fabricated from silicon forming a nanopillar situated between source and drain contacts. The advantage of this concept is its straightforward manufacturing. The devices operate at room temperature and at frequencies in the range of up to 500 MHz. Recently we found field emission in these NEMS electron shuttles, being key to a number of applications such as flat panel displays, etc. A theoretical model of the operation of this device is given, explaining qualitatively the obtained experimental data.

6464-07, Session 3

Electrically insulated scanning thermal microscopy

N. Duarte, S. A. Tadigadapa, The Pennsylvania State Univ.

Scanning thermal microscopy (SThM) has been used to map the thermal profiles of microstructures with multiple end goals including failure analysis[1] and thermal management of microchips[2]. Overcoming the resolution limitations of IR imaging, SThM uses either a thermocouple or a thermistor on the tip of an AFM cantilever to obtain thermal images limited only by the size of the tip[3] (Figure 1). However, to the best knowledge of the authors, up until the work presented here this measurement method has had limited applications due to the electrically exposed nature of the SThM tip. In this work we have coated a commercially purchased Wollaston wire thermal AFM tip with a 90 nm layer of SiO2. In this work we compare the thermal map of a heated structure measured with a plain Wollaston wire thermal AFM tip to one measured with our insulated Wollaston wire tip and report the improvements for micro and nanoscale thermography applications.

6464-08, Session 3

Electrical and optical properties of supported n-graphene layer films

P. Joshi, A. Gupta, P. C. Eklund, S. A. Tadigadapa, The Pennsylvania State Univ.

Graphite is a quasi two-dimensional (2D) electronic material exhibiting very high in-plane electron and hole mobilities. It has been recently possible to produce ultra-thin graphene films by mechanical transfer from bulk graphite which are referred to as n (1, 2...)-graphene layer films (or nGL). Interesting electrical properties such as gate modulation of in-plane current, oscillatory magneto-transport and unusual half integer quantum Hall effect have been reported experimentally. Raman scattering on these ultra-thin nGLs significantly differ from the graphite. We will report detailed Raman scattering and electrical transport measurements on these nGL layers in this paper.

6464-09, Session 3

Micromachined silicon grids for direct TEM and Raman characterization of CVD grown carbon nanotubes

Y. Choi, A. Ural, Univ. of Florida

Transmission electron microscopy (TEM) and micro-Raman spectroscopy are key techniques in the structural characterization of carbon nanotubes. For device applications, carbon nanotubes are typically grown by chemical vapor deposition (CVD) on silicon substrates. However, TEM requires very thin samples, which are electron transparent. Therefore, for TEM analysis, CVD grown nanotubes are typically deposited on commercial TEM grids by post-processing. This procedure has two problems: It can damage the nanotubes, and it does not work reliably if the nanotube density is too low.

The ability to do TEM directly on as-grown nanotubes lying on the silicon substrate would solve these two problems. In this talk, for this purpose, we have fabricated micromachined TEM grids from silicon substrates. Subsequently, we have grown nanotubes on these micromachined TEM grids by CVD, and characterized the nanotubes by TEM, micro-Raman spectroscopy, scanning electron microscopy (SEM), and atomic force microscopy (AFM). Since the nanotubes grown on the micromachined substrates are completely suspended over the width of the open slits, these substrates form a natural TEM grid for direct imaging of CVD-grown nanotubes. Furthermore, the signal from the substrate is significantly reduced during micro-Raman spectroscopy, resulting in a better signal-to-noise ratio. In addition, the silicon membranes are strong enough to support AFM and SEM characterization. As a result, these substrates provide a low cost, mass producible, efficient, and reliable platform for direct TEM, Raman, AFM, and SEM analysis of as-grown nanotubes or other nanomaterials on the same substrate, eliminating the need for any post-processing after CVD growth.

6464-10, Session 4

Mechanical properties of ZnO nanowires

M. A. Haque, Penn State Univ.

Nanowires are one-dimensional solids that exhibit superior physical properties. In this paper, we report experimental investigations on the mechanical properties of ZnO nanowires. We present a MEMS test-bed for

mechanical characterization of nanowires that exploits post-buckling deformation mechanics to achieve very high force and displacement resolution. The small size of the test-bed allows for in-situ experimentation inside analytical chambers, such as SEM and TEM. We present microscale version of pick-and-place as a generic specimen preparation and manipulation technique for experimentation on individual nanostructures. We performed experiments on ZnO nanowires inside a scanning electron microscope (SEM) and estimated the Young's modulus to be about 21 GPa and the fracture strain to vary from 5 % to 15 %.

6464-11, Session 4

MEMS-based testing stage to study electrical and mechanical properties of nanocrystalline metal films

J. Han, J. Rajagopalan, T. Saif, Univ. of Illinois at Urbana-Champaign

The increased use of nanocrystalline metal films as interconnects in integrated circuits has necessitated their thermo-electro-mechanical characterization, as these films experience elevated temperatures and thermal stresses during device operation. Also, the superior mechanical properties of nanocrystalline materials, compared to their bulk counterparts, has spurred interest in the deformation mechanisms operating at this scale. We have developed a MEMS-based testing stage that can quantitatively characterize both the electrical and mechanical properties of nanocrystalline metal films. This stage, which is SEM and TEM compatible, is a modified version of an earlier MEMS-based tensile testing stage (Haque, M.A. and Saif, M.T.A., Proc. Soc. Exp. Mech., Vol. 49, pp. 123-128, 2002). This modified stage requires a simpler fabrication procedure, involving fewer lithography and etching steps, and has higher yield compared to the earlier version. It allows for 4-point electrical resistance measurements, and in situ tensile testing in SEM and TEM of freestanding nano-scale metal films. The stage was used to perform a tensile test on a 100 nm thick aluminum film and electrical resistance measurements on a 110 nm thick aluminum film, the results of which are described. A compact heating stage is also being developed so that electrical and mechanical characterization at elevated temperatures can be performed in situ in SEM and TEM.

6464-12, Session 4

All-optical micromechanical chemical sensors

T. H. Stievater, W. S. Rabinovich, M. S. Ferraro, N. A. Papanicolaou, J. B. Boos, R. A. McGill, J. L. Stepnowski, Naval Research Lab.

We describe experimental results from micromechanical resonators coated with chemoselective polymers that detect chemical vapors using all-optical interrogation. Detected chemicals include volatile organic compounds and explosives. The shift in the resonant frequency of a gold microbeam is read-out using photothermal actuation and microcavity interferometry. Response times of less than 5 seconds are achieved for vapor concentrations as low as 5 ppb using optical powers of about one mW. An analysis of the the measured frequency noise in these sensors shows that the noise is dominated by thermal-mechanical amplitude noise at the fundamental flexural mode. We have therefore reached the ultimate limit of detection (LOD) in our sensor for a given drive amplitude. All-optical interrogation of passive, lightweight micromechanical chemical sensors enables remote read-out over retroreflecting free-space links or fiber-optic networks.

6464-13, Session 4

Integrated nanomechanical motion detection by evanescent light-wave coupling

I. De Vlaminck, J. Roels, D. Taillaert, Univ. Gent (Belgium) and IMEC (Belgium); D. Van Thourhout, Univ. Gent (Belgium); L. Lagae, IMEC (Belgium); R. Baets, Univ. Gent (Belgium); G. Borghs, IMEC (Belgium)

The properties of micro- and nanomechanical resonators are attractive for application in signal processing and sensor technology [1]. The development of sensitive and broadband motion detection techniques is of prime importance for all these applications [2].

In this work a motion detection technique based on the evanescent wave coupling between a photonic waveguide and a nanomechanical resonator is introduced. The mechanical resonator and the main waveguide are both freestanding and doubly-clamped. Any relative displacement results in a change in optical coupling, providing a means of detecting motions.

This technique has a number of advantages. It offers a means of integrating nanomechanical sensors in a photonic circuitry. Furthermore, high vibration amplitude resolution can be obtained because of the high displacement sensitivity of the coupling, the high optical power applicable and the low optical losses achievable.

High quality photonic single-mode waveguides were fabricated in Silicon On Insulator and defined by Deep Ultraviolet lithography [3]. In and out-of-plane vibration modes of the mechanical resonator and the main waveguide were actuated capacitively and were detected at ambient conditions with high sensitivity.

We used a calculation method based on frequency-domain eigenmode expansion to analyze the sensitivity of optical coupling to relative displacements.

An assessment of the displacement sensitivity and attainable amplitude resolution will be provided along with a comparison with other displacement detection techniques for nanomechanical resonators.

[1] I. De Vlaminck et al., APL. 88, 063112 (2006)

[2] K.L. Ekinci, Small 1, 786 (2005).

[3] W. Bogaerts, et al., Optics Express, 12(8), 1583 (2004)

6464-14, Session 4

Experimental study of fluid damping in microdevices with flow ranging from continuum to molecular regime

A. K. Pandey, R. Pratap, Indian Institute of Science (India); F. S. Chau, National Univ. of Singapore (Singapore)

High quality factor of dynamic structures at micro and nano scale is exploited in various applications of MEMS and NEMS. The quality factor of such devices can be very high in vacuum. However, when vacuum is not desirable or not possible, the tiny dynamic structures must vibrate in air or some other gas at pressure levels that can vary from atmospheric to low vacuum. The interaction of the surrounding fluid with the vibrating structure leads to dissipation, thus bringing down the quality factor. Depending on the ambient fluid pressure or the gap between the vibrating and the fixed structure, the fluid motion can range from continuum flow to molecular flow giving a wide range of dissipation. The relevant fluid flow characteristics are determined by Knudsen number which is the ratio of the mean free path of the gas molecule to the characteristic flow length of the device. This number is very small for continuum flow and reasonably big for molecular flow. In this paper, we study the effect of fluid pressure on the quality factor by carrying out experiments on a MEMS device that consists of a double gimbaled torsional mirror. Such devices are commonly used in optical cross-connects and switches. Although, we only vary fluid pressure to make the Knudsen number go through the entire range of continuum flow, slip flow, transition flow, and molecular flow, the same can also be done by reducing the characteristic flow lengths in a device from micrometers to nanometers. Thus the result presented here will hold good for micro-scale to nano-scale devices for damping due to the surrounding fluid flow. In our study, we experimentally determine the quality factor of the MEMS torsional mirror at different air pressure ranging from 760 torr to 0.001 torr. The variation of this pressure over six orders of magnitude ensures required rarefaction to range over all flow conditions. The main result-variation of quality factor with pressure-is discussed over all flow regimes. The result indicates that the quality factor,

Q, follows a power law, Q proportional to P(-r), with different values of exponent r in different flow regimes. While the observed variation in the continuum regime and the molecular regime can be explained with existing theories, the variation in the transition regime is still an open problem.

6464-15, Session 5

Measuring biological mass with microchannel resonators

K. Babcock, Affinity Biosensors; S. R. Manalis, Massachusetts Institute of Technology

A novel MEMS-based biosensor known as the suspended microchannel resonator (SMR) allows the most sensitive mass measurements of biological samples in fluid. Evolving from prototypes created at MIT, a recent generation of commercial-grade SMR sensors have ample resolution to "weigh" individual cells and detect molecular targets at low surface concentration. Significant applications of SMR may include medical diagnostics, biomolecular research, biodefense, and food safety. This talk will describe the SMR concept and results to date, overview emerging applications, and comment on the role of micro- vs. nano- scales in the context of biological sensing.

6464-16, Session 5

Development of amorphous SiC for MEMS-based microbridges

J. B. Summers, Case Western Reserve Univ.; M. C. Scardelletti, NASA Glenn Research Ctr.; C. A. Zorman, Case Western Reserve Univ.

SiC is an attractive material for MEMS and NEMS applications due to its outstanding mechanical, chemical and electrical properties. The preponderance of work in the development of SiC for these application areas has focused on SiC thin films deposited by APCVD and LPCVD at substrate temperatures ranging from 800 degrees Celsius to 1350 degrees Celsius. Recently, interest in fabricating SiC-based devices on temperature-sensitive substrates has motivated the development of PECVD-based processes for hydrogen-terminated, amorphous SiC (a-SiC:H) with properties suitable for micromachining. The PECVD approach has permitted the lowering of substrate temperatures during the deposition process to below 400 degrees Celsius, thus enabling the incorporation of buried metal electrode structures and the use of non-conventional sacrificial layers (i.e., polyimide) and furthering the development of SiC micromechanical structures with integrated microelectronics. For applications requiring doubly-clamped microbridges, SiC is particularly attractive for its chemical inertness, anti-stiction properties and mechanical stiffness. This paper reports our effort to develop a PECVD process for submicron-thick a-SiC:H films specifically designed for microbridge applications. We find that for the range of pressures, powers, and precursor flow rates studied, the as-deposited films exhibit a compressive residual stress that can be converted to a tensile stress by a thermal anneal at 400 degrees Celsius. Bulk micromachined membranes and surface micromachined doubly-clamped bridges could readily be fabricated from the annealed films. The extended paper will detail recipe development, film characterization, finite element modeling and testing of bridge-based actuators.

6464-17, Session 5

Fabrication of comb-drive micro-actuators based on UV lithography of SU-8 and electroless plating technique

W. Dai, W. Wang, Louisiana State Univ.

We reported the fabrication and metallization of high aspect ratio polymer comb drive microactuators. The fabrication process combined multi-step and multi-layer UV lithography of SU-8 on silicon substrate with copper electroless plating to metallize UV modified SU-8 comb drive. After the comb drive microstructure was produced, metal film needs to be coated to form two electrically separated electrodes. We have developed a novel electroless plating technique to coat metal on cured SU-8 surface after SU-8 was modified by optimal UV radiation and chemical immersion. Our experiments found that UV exposure dosage and illumination direction played significant rules in selective electroless plating of metal films on cured SU-8 polymer. The metal film on both the top and sidewall surfaces of microstructures can be achieved while the silicon substrate was not plated.

6464-18, Session 5

On-chip integration of a microfluidic valve and pump for sample acquisition and movement

S. S. Sridharamurthy, L. Dong, H. Jiang, Univ. of Wisconsin/ Madison

We report on the on-chip integration of a valve and pump for acquiring microfluidic samples and moving them through micro-channels. The valve employs temperature sensitive hydrogels [1] which are controlled by micro-heaters. The pump is a nickel rotor actuated magnetically by an external rotating magnet. The valve is fabricated as a string of hydrogel cylinders spaced within microfluidic channels. The hydrogel cylinders are initially in the expanded state and hence block fluid flow. Upon application of heat, the hydrogels lose water and contract in size allowing fluid to flow through them. The pump brings about a recirculating movement of the fluid within the microchannel due to the rotation of the nickel rotor. The fabrication is based on liquid phase photopolymerization (LP3) [2] which is compatible with microsystems technology [3, 4]. The pump is fabricated by electroplating a Ni rotor on a glass substrate having Cu as seed layer. The electroplating mold is formed by LP3 using an isobornyl acrylate based polymer ((poly)IBA). Next, microfluidic channels are photo-defined using LP3 and ((poly)IBA). The valve is fabricated using LP3 and temperature sensitive hydrogels. The valve showed a response time of ~45 s and the characterization of the pump is in progress.

6464-20, Session 5

Design and microfabrication of integrated fiber bundle couplers with imbedded microlens arrays

R. Yang, S. A. Soper, W. Wang, Louisiana State Univ.

This paper describes the microfabrication of pre-aligned fiber bundle couplers using UV lithography of SU-8. The fiber bundle coupler includes an array of out-of-plane refractive microlenses and fiberport collimator arrays. With the optical axis of each pixel parallel with the substrate, the each pixel of the microlens array can be pre-aligned with the corresponding pixels of fiberport collimator arrays in the mask design. The out-of-plane polymer microlens array is pre-aligned with the fiber collimator arrays with no additional adjustment and assembly required, therefore dramatically reduce the fabrication cost and improve the alignment quality and coupling efficiency.

In this improved design, two symmetrical microlenses were used to obtain better match between the numerical apertures of the fiber and the microlens pair. The symmetrical microlens pair also helps to reduce the optical aberration for higher focal pads quality. This new version of the fiber bundle coupler has been successfully fabricated. The prototypes are currently under test and the results will be presented in the SPIE MOEMS and MEMS.

6464-21, Session 6

IR detectors with adaptive responsivity and wavelength

W. Song, J. J. Talghader, Univ. of Minnesota

One of the most successful commercial micromachined technologies is the microbolometer array. These are used heavily by the military and law

enforcement for night vision, but also applications in medical, scientific, and other fields. To date, microbolometers and other thermal detectors have been limited to seeing objects near room temperature in a single wavelength band, but recent advances in interface heat transfer and optical cavity design promise to change that.

Commercial microbolometers are designed for high sensitivity so that they can observe objects with small differences in temperature or emissivity; however, when such devices are confronted with a very large signal, they are unable to process the full dynamic range and can be damaged either temporarily or permanently. This is not merely an electronics issue but also a thermal one that results from excessive heating of the device. Recent work in our group has shown that extended dynamic range in thermal detectors can be achieved by electrostatically bringing a portion of the detector support structure in contact with the substrate. The exact amount of heat transfer can be controlled by adjusting the contact area and pressure. The thermal conductance and responsivity of devices fabricated in our lab can be switched more than an order of magnitude.

Microbolometers have traditionally been limited to broadband detection. However, only small changes to the structure of a microbolometer are necessary to create a wavelength tunable device in the LWIR. If the microbolometer is made to be moderately reflective and is combined with a highly reflective bottom mirror, then light at a single wavelength can be coupled into the microbolometer while other wavelengths are rejected. The resonant width depends on cavity design and can be microns or nanometers depending on the needs of the cavity. Further the device can be switched to a broadband detection mode to preserve standard bolometer function. Our group has demonstrated resonance tuning from 8.7 to 11.1μm with applied voltages from 0 to 42 V and FWHM of around 1.5μm in narrow-band mode and 2.83μm in broad-band mode.

6464-22, Session 6

LVD micromirror for rapid reference scanning in optical coherence tomography

A. Jain, X. Feng, H. Xie, Univ. of Florida

This paper reports a MEMS micromirror that uses a large-vertical-displacement (LVD) microactuator to generate large piston motion. This single-crystal silicon LVD micromirror has been fabricated using a DRIE CMOS-MEMS micromachining process, and uses two sets of electrothermal bimorph actuators to generate out-of-plane piston motion. The LVD micromirror can be used for rapid axial scanning in the reference arm of an optical coherence tomography (OCT) system. OCT is a noninvasive, high-resolution imaging technology that can be used for early cancer detection.

The dynamic response of the LVD micromirror has been characterized using a laser Doppler vibrometer, and the micromirror exhibits resonant peaks at 1.18 and 2.62 kHz. A vertical displacement of 26 microns was obtained by this piston-motion micromirror at an AC actuation voltage of 3.3 Vpp at 50 Hz. It was also observed that the piston motion range increases with decreasing frequency; and a maximum vertical displacement of 36 microns is obtained at a frequency of 3 Hz. We believe that this frequency dependence is directly related to the thermal time constant of the device. More detailed thermomechanical modeling is being developed for full understanding of this dynamic behavior and optimizing the device design. The large piston-motion range makes this device very suitable for use in interferometry and optical delay lines.

6464-23, Session 6

Process development, fabrication, and characterization of high-finesse micromachined optical Fabry-Perot microcavities

M. W. Pruessner, T. H. Stievater, W. S. Rabinovich, Naval Research Lab.

We present the development of a cryogenic dry etch process using SF6/O2 for silicon micromachining. Unlike the Bosch process, in which etch and passivation steps alternate, the cryogenic process performs both etch and passivation concurrently. Passivation occurs via the formation of a thin SiOxFy layer on the sidewalls, which protects the surface during etching. Because the formation of SiOxFy is temperature dependent, etching is performed at T~-100 degrees Celsius.

Our process enables sub-micron trenches with high aspect ratio, high verticality, and low sidewall roughness. Etch depths approaching 10um with etch rates of 4um/minute are possible using a single 380nm thick electron beam resist mask. We studied the effect of various process parameters (substrate temperature, O2 flow, chamber pressure, RF forward power) on the trench quality (verticality, linewidth, and sidewall roughness). The optimized process is performed at 7mTorr chamber pressure and T=-110 degrees Celsius temperature to achieve adequate passivation, high aspect-ratio (>10:1), low sidewall roughness (1-10nm), and high sidewall verticality (89.5 degrees<alpha<90 degrees).

To test the quality of our etch and to ascertain the suitability of this process for MEMS, MOEMS, and photonics applications, we fabricate a silicon-on-insulator (SOI) Fabry-Perot cavity with integrated rib waveguides. The Fabry-Perot cavity utilizes deeply-etched (~4.5um) silicon/air distributed Bragg reflectors (DBR's), which enable high mirror reflectivity with small footprint. Measurements indicate high Q-factors (Q>10,000), high finesse (F=196), and sharp resonance full-width-half-maximum (FWHM=0.15nm). From the FWHM, we extract a mirror reflectance R=98.5%, which confirms the high quality of our silicon micromachining process. Fabrication, device characterization and experimental results are presented.

6464-24, Session 6

Silicon/porous silicon composite membrane for high-sensitivity pressure sensor

S. L. Narayanan, E. Bhattacharya, Indian Institute of Technology Madras (India)

In this paper we discuss the fabrication of a bulk micromachined pressure sensor with improved sensitivity by converting a part of the silicon membrane depth into porous silicon (PS). PS is formed by electrochemical etching of silicon in HF based electrolytes and the porosity and depth of the layer can be controlled with the formation parameters. Due to low Young's Modulus of PS, the membrane deflection is more and the sensitivity is found to be higher than that obtained with single crystalline silicon membrane, the magnitude of the increase depending upon the depth and porosity of the PS layer. KOH etching was done to realize 14μm thick membranes on p-type <100> wafers of 1-10 Ohm-cm resistivity with various aspect ratios of the membrane. PS was formed on the KOH etched surface of the membrane with different porosities and depths. Two-step oxidation was done to prevent the PS structure from collapsing and to provide isolation of the piezoresistors. Polysilicon layer was deposited by LPCVD and patterned to form the piezoresistors with aluminium metal contacts to form a wheatstone bridge. Testing at wafer level was carried out for 0 bar and 1 bar pressure with input voltage of 1V. Improvements in sensitivity of up to a factor of 10 were seen as compared to only silicon membranes. Simulation of Si/PS membrane was also done using Coventorware and the sensitivity was calculated analytically by extracting the longitudinal and transverse stress estimated from the simulation results.

6464-25, Session 6

μMicrophone piezorestitive type

A. H. Heredia-Jimenez, M. Gonzalez-Perez, L. Castro, Univ. Popular Autonoma del estado de Puebla (Mexico)

The fabrication of a sensors of pressure for acoustic waves detection using a Amorphous silicon-germanium alloys (a-Si1-xGex:H) thin film is presented for the first time. This thin film (170 nm) was deposited on a silicon nitride membrane sustained by a frame made of micromachined crystalline silicon in order to improve changing electrical resistance due to applied mechanical stress, generated by acoustics waves.

Electrical connectivity to the element was achieved by means of aluminum contact pads.

The 150 nm thick silicon nitride film was deposited by LPCVD. The c-Si wafer was micro machined using a KOH solution at 80 degrees Celsius for 5 hours. An AMP 3300 PECVD system from Applied Materials was used to deposit the amorphous films, with the substrate held at 270 degrees Celsius. This 170 nm-thick a-Si film was deposited at 0.6 Torr by decomposing a SiH4-GeH4 nmixture at a 750-scc/min flux. The deposition rate was 1.3 A/s for an RF power of 300 W operating at 110 KHz. Finally, aluminum was deposited and patterned to form contact pads.

The resultant figures of merit, measured at room temperature, were: electrical conductivity of 1.513X10-3 (Ohm-cm)-1, the electrical resistance 20k-Ohms, the dimensions of the diaphragm of the microphone is of 300μmx200μm, and the device is sensitive to pressure variations as small as 0.5 mPa.

6464-26, Session 6

Stereolithography as a meso-structure for input force reduction to a capacitive force MEMS sensor

H. K. Chu, W. L. Cleghorn, J. K. Mills, Univ. of Toronto (Canada)

This paper presents the design of a packaging cover incorporated with the function of a meso-structure for input force reduction using stereolithography. This packaging cover will be installed on top of a standard ceramic pin grid array (PGA) package where the MEMS force sensor will be wire-bonded on, and the complete sensor will be used in the engine compartment of a vehicle. The purpose of the cover is to transform the macroscopic input force imparted by a technician into a grasping action on the sensor. The macroscopic input force is estimated to be 60N at maximum. To prevent potential damage on the MEMS sensor, the cover will have to convert the force to a grasping force in the milli-Newton scale. Since the sensor is to be operated under the harsh environment of the compartment, transverse comb-drive capacitors are selected as the force sensing technique. The capacitive MEMS sensor will be fabricated using PolyMUMPs surface micromachining. To ensure linearity, the displacement of the comb drive is limited to 1um for a net capacitance change of 0.042pF. Strain energy and Castigliano's Theorem are used to model the proposed cover design and the sensor. It is found that for a 60N of input force, the design is capable of generating a grasping force of 0.15N without the sensor and 0.01N with the sensor. Design analysis, and results from the Finite Element Method (FEM) simulation and the experiments of the cover design as well as the sensor will be presented in this paper.

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6465-01, Session 1

Methods and instruments for continuous-flow PCR on a chip

C. Gaertner, R. Klemm, H. Becker, Microfluidic ChipShop GmbH (Germany)

No abstract available

6465-02, Session 1

Microdevice for rapid separation of particulate-ladden fluids for use in micro total-analysis systems

I. Gregoratto, C. J. McNeil, M. W. Reeks, Univ. of Newcastle Upon Tyne (United Kingdom)

A novel micro-device which is capable of rapidly fractionating large (millilitre) volumes of particulate-laden fluids and is easy to integrate into Lab-on-Chip systems has been developed. The device is simple to control by use of an off-chip syringe pump and, unlike many other types of micro-scale separating devices it is not prone to blockage or mechanical failure.

The device was designed for enriching the ratio of bacteria cells to red blood cells in millilitre volume samples of dilute human blood from patients suspected of suffering from bacteraemia. The device exploits small inertial and hydrodynamic differences between dissimilar particle sizes, which arise as the sample is rapidly pumped through the spiral micro-channel by an external syringe pump. At the exit of the device, a carefully fabricated bifurcation is used to split the flow into its different components.

A CFD package (Fluent 6.1) was used to model the fluid flow, determine the displacement of the particles through the micro-channel and optimize its geometry. In particular, the channel dimensions and the bifurcation location were found to have a large influence on the effectiveness of the separation achieved by the device. In order to contain the Dean Vortices at the extreme edges and still achieve adequate separation, the device geometry and pressure drop across the device was investigated and optimized.

Due to the presence of the Dean Vortices and their tendency to induce mixing, the maximum achievable fractionation with the current device design is an enrichment of approximately 6:1 with a flow rate of 1ml/min.

Devices with greater aspect ratios (under development) and slight modifications to the exit geometry should lead to vast improvements (several hundred-fold) in separation. A device with these changes, in combination with a suitable filter chamber may be used as a sample preparation module in uTAS systems.

6465-03, Session 1

Thermal gradient PCR in a continuous-flow microchip

N. D. Crews, C. Wittwer, B. K. Gale, The Univ. of Utah

A new category of continuous-flow PCR microchips has been developed. These chips operate by cycling a PCR sample within a spatial temperature gradient, thus allowing for zero-second thermal residence times. Continuous-flow PCR (CF-PCR) platforms excel at generating heating and cooling rates that are both precise and ultra-fast. The thermal gradient PCR chips now combine these advantages with the transitory temperature protocols which are currently used by the fastest commercial PCR equipment. The evolution from the traditional CF-PCR design to the thermal gradient system is a simplification, since thermal gradients are a natural effect of heat dissipation. Thus, the appropriate temperature distribution for PCR can be generated by as few as one heater held at a steady state temperature. Prior to optimization, a thermal gradient chip of this new type was used to perform a 22-cycle amplification of a 75-bp segment of exon 11 of the cystic fibrosis gene in less than seven minutes. The thermal gradient chips are fabricated using mature glass etching protocols and a proprietary glass-to-glass fusion bonding process. Since a thermal gradient of more than 3°C/mm was generated across the chip, each complete PCR cycle requires approximately 2cm of channel length. Therefore, the entire serpentine channel (~0.5m) can be fabricated on a 25mm x 75mm x 1.1mm glass blank. Samples of a PCR mixture were amplified on both the thermal gradient chips and commercial PCR equipment. Gel electrophoresis was used to compare the products. Visual inspection of fluorescent images of the stained gel shows that the amplicon from both sources was 75-bp in length and of comparable final DNA concentration.

6465-04, Session 1

A complete, self-contained, optical biochip with live-cell imaging capability

I. A. Pope, P. R. Barber, K. Skouridou, B. Vojnovic, Gray Cancer Institute (United Kingdom); A. D. Goater, Univ. of Wales, Bangor (United Kingdom); D. J. Morris, J. P. H. Burt, Prifysgol Cymru Bangor (United Kingdom); D. R. Matthews, H. D. Summers, K. L. Njoh, S. Chappell, R. J. Errington, P. Smith, Cardiff Univ. (United Kingdom)

The development of microfluidic arrays opens up many potential lab-on-a-chip applications such as drug screening, bioreactor optimisation and quantitative cell biology. Whilst significant work has been done on the development of microfluidic arrays, efforts have tended to be concentrated solely on the development of the array itself. Little work has been done towards cutting the ties between the microfluidic device and the laboratory; i.e. the reliance on conventional incubators and microscopy techniques for imaging purposes.

Our approach has been to develop a complete and self contained, compact biochip, comparable in size to a mobile phone, which is controlled via a laptop computer and is readily portable. The biochip incorporates microfluidics, environmental control (maintaining cells at a steady 37oC or arresting them at 4°C) and live-cell imaging. Imaging is achieved using a novel modality, developed in house, which is not based on conventional microscope optics. Using this imaging technique in conjunction with custom image analysis software it is possible to locate and track cells over extended time periods.

We will describe our complete, self-contained biochip, demonstrating progress towards 'lab-on-a-chip' capabilities and present on the results of several assays performed on the device, such as wound healing, cell mitosis and cell tracking through a microfluidic system.

6465-05, Session 2

Digital microfluidics platform for lab-on-a-chip applications

Y. Fouillet, Lab. d'Electronique de Technologie de l'Information (France)

No abstract available

6465-06, Session 2

Diffusion dynamics in microfluidic dye lasers

S. Balslev, N. A. Mortensen, A. Kristensen, Danmarks Tekniske Univ. (Denmark)

Miniaturized dye lasers are considered as efficient light sources for integration on lab-on-a-chip micro-systems. However, dye bleaching resulting in limited life-time and requirements for external fluidic handling apparatus could limit the application of such devices in lab-on-a-chip technology. We propose a solution to this based on diffusion. On average, the random walk of a dye molecule dissolved in Ethylene Glycol transports the molecule 0.5 mm in five minutes, which is enough to replenish bleached dye in a miniaturized dye laser.

Through experiments, we show the special bleaching dynamics that occur in a microfluidic channel, and propose simple methods for modelling the dynamics.

6465-07, Session 2

A novel electrolysis-bubble-actuated micropump

C. Cheng, C. Liu, National Tsing Hua Univ. (Taiwan)

A novel electrolysis-bubble-actuated micropump based on the roughness gradient design on the hydrophobic surface of the lateral breather. The micropump is implemented by means of electrolysis, surface tension effect and the periodic electrolysis-bubble generation. The advantages of this proposed micropump design not only achieve a net pumping flow but also resolve the main problem existing in most electrolytic bubble actuators for the issue of degassing the insoluble gases out of microchannels. This micropump with a simple circuit control and without moving parts is suitable for the development of low power-consumption and compact micropumps. Experimental results successfully demonstrate the pumping function of our micropump to continuously push liquid forward based on our gradient roughness design of hydrophobic surface and the periodic generation of an electrolytic bubble in a microchannel. Furthermore, experimental results also show that the liquid displacement and pumping rate could be easily and accurately controlled by adjusting the applied voltage with specific operating frequency. Under the applied voltage of 15 volts at 4.5 Hz, a maximum pumping rate of 114 nl/min is achieved for our micropump#1 with a microchannel cross section of 100μm × 20μm. In this paper, we describe the theoretical analysis, design, micromachining process, and operating principles, as well as the experimental demonstration of this micropump.

6465-08, Session 2

Using a CD-like microfluidic platform for uniform calcium alginate micro-drug carrier generation

Y. Lin, National Cheng Kung Univ. (Taiwan)

The manipulation of monodisperse Ca-alginate microparticles using a microfluidic chip fabricated by the optical disc process and a reaction of external gelation is presented. Ca-alginate is currently gaining a great deal of attention for medical applications as well as for the controlled release of drugs. To date, the production of Ca-alginate beads has been accomplished mainly by using external gelation (dripping method). The approach in manipulation of Ca-alginate microspheres will provide many potential uses for pharmaceutical applications.

Our strategy is based on the sheath (focusing) effect to form uniform water-in-oil (w/o) emulsions in the cross-junction microchannel. These fine emulsions, consisting of 1.5% w/v Na-alginate are dripped into 1.0% w/v calcium carbonate to accomplish Ca-alginate microspheres in an efficient manner. The mechanism is that calcium carbonate to release the calcium ions, and these calcium ions are then crosslinking with the Na-alginate to produce Ca-alginate microspheres.

We have demonstrated that one can control the size of Ca-alginate microparticles from 20 μm to 50 μm in diameter with a variation less than 5% by altering the relative sheath/sample flow rate ratio. For a given 1.000 μL/min of the dispersed phase flow (sample flow), the emulsion size decreased as the average velocity of the continuous phase (oil flow) increased, and the opposite tendency was observed in the decreased sample flow under the constant flow rate of the continuous phase.

6465-09, Session 2

Set-up of a biological monitoring module realized in LTCC technology

W. Smetana, B. Balluch, L. Musiejovsky, Technische Univ. Wien (Austria); E. Gaubitzer, M. Edetsberger, G. Köhler, Univ. Wien (Austria)

LTCC-technology originally developed for the realization of electronic circuits has been considered as an appropriate approach to realize a compact temperature controlled monitoring module for biological reactions with low sample consumption. The module comprises a spherical reactor cell where continous mixing of the reagent fluids is provided. Besides the mixing chamber the module is equipped with pH-, oxygen-, temperature- and iodide sensitive sensors for reaction monitoring as well as with SMA-connectors for glass fibers required for absorption or fluorescence spectroscopy analyses. Temperature controll is provided by pumping a thermal fluid through embedded ducts. A network of micro-channels with cross section dimensions varying from 200 μm x 200 μm up to 2 mm x 2 mm are connecting the different measuring sections within the ceramic module. A standard LTCC-processing technology cannot be applied for the realization of such a complex device, since finally 135 ceramic layers each of 325 μm thickness (unfired) have to be structured by laser machining, laminated and fired. Special attention has to be paid on the lamination of the ceramic tapes since the module contains a large number of cavities and channels (the reactor cell has a cavity volume of 1 cm3). It was therefore mandatory to find an appropriate sacrificial substance for filling the cavities which should evaporate during the burn out phase of the sintering process. Critical processing steps and parameters which are important to be considered will be demonstrated and the performance of the module unit and its special functionalities will be highlighted.

6465-10, Session 3

Assembly and testing of microparticle and microcapsule ‘smart tattoo’ materials

M. J. McShane, Texas A&M Univ.

No abstract available

6465-11, Session 3

An integrated microsystem for multiplex processing of encoded silicon microbeads

M. G. Loughran, Tyndall National Institute (Ireland)

A novel integrated microsystem for multiplex processing of encoded microbeads on a single microchip is presented (Figure 1a). Conventional bio-analysis of proteins & DNA requires a combination of different techniques including: accurate delivery of reagents, mixing, then reaction at controlled temperature to yield a detectable product [1]. Hoffmann previously confirmed microbeads can be injected into a network of microchannels and transported to different reaction sites [2]. However this new multiplex microsystem enhances logical bio-assay development due to the integration of a compact optical detection system with customized analysis software in an enclosed microfluidic environment (Figure 1b).

Multiplex transport, systematic identification, reaction chamber processing, analysis and sorting of encoded microbeads in an enclosed microchip has not yet been achieved by other research groups. Standard laboratory bio-assays require intervention at several stages to manipulate samples. Furthermore, ultra sensitive quantification with a colorimetric or

fluorescent label is required to obtain the necessary results. This process is time consuming and labour intensive. Complete integration of the different bio-assay components on a single multiplex assay platform provides distinct advantages of reduced sample volume, rapid analysis and low cost.

Figure 2 shows time-controlled, multiplex injection of encoded microbeads in the microfluidic channel. Figure 3a illustrates in situ microbead functionalisation in a reaction chamber of the processing unit. Multiple fluorescence measurements of complimentary hybridised DNA at the surface of the encoded microbead, confirms the ability to select a specific DNA sequence from a 4 x 4 DNA library (Figure 3b).

6465-12, Session 3

Lasing droplets in a microfabricated channel

M. M. Tanyeri, R. M. Perron, I. M. Kennedy, Univ. of California/ Davis

Optical resonances are observed in microdroplets produced in a microfabricated device; 50 micron diameter water droplets containing fluorescent dye (Rhodamine 6G or Fluorescein) are injected into low-refractive index oil in a T-junction configuration. Frequency doubled Nd:YAG (532 nm) laser light or Argon ion (488 nm) laser light is delivered through a multimode fiber into the outlet channel where the microdroplets are ejected. The optical resonance spectrum from the microdroplet is acquired through collection optics and a spectrophotometer. Droplet images and spectrum clearly demonstrate the successful coupling of fluorescent dye emission into the Morphology Dependent Resonances (MDRs) in the microdroplet. The refractive index difference between the microdroplets and the surrounding laser liquid medium allows the microdroplet to be an efficient microcavity through total internal reflection. These optical resonances can be used as an ultrasensitive detection mechanism for chemical and biological sensing.

6465-13, Session 3

Hybrid microfluidic systems - combining a polymer microfluidic toolbox with biosensors

C. Gaertner, S. Kirsch, B. Anton, H. Becker, Microfluidic ChipShop GmbH (Germany)

No abstract available

6465-14, Session 4

Nanoparticle analysis using microscale field flow fractionation

B. K. Gale, The Univ. of Utah

No abstract available

6465-15, Session 4

Three-dimensional integrated circuits for lab-on-chip dielectrophoresis of nanometer scale particles

S. J. Dickerson, D. M. Chiarulli, S. P. Levitan, A. J. Noyola, Univ. of Pittsburgh

In this paper, we present a mixed-technology micro-system for electronically manipulating and optically detecting virus-scale particles in fluids. Dielectrophoresis has been shown to be a viable technique for contactless manipulation and trapping of objects that are on the nanometer scale. However, most implementations use electrode geometries that are on the micron scale. By using two features of “3D chip-stacking” technology, we are able to create time multiplexed electrode arrays that have a spacing of less than 250 nm. The 3D integrated circuits are fabricated by transferring and interconnecting conventional silicon wafers in a vertically tiered fashion. In our implementation, the top-most tier is upside down and the active devices are located at the top of the circuit stack, with the associated substrate material removed. This places these devices in close proximity to a fluid channel etched into the top of the stack. Therefore, we can construct an array of 200 nm electrodes with a pitch of approximately 450 nm, 650 nm below the fluid channel. An electrode array with such a fine pitch yields a high degree of selectivity when manipulating submicron size particles. Using 3D CMOS technology also provides the ability to densely integrate digital control circuitry for the electrodes using the additional levels of the chip stack. We show simulations of the system with a physical model of a Kaposi’s sarcoma-associated herpes virus, which has a radius of approximately 125 nm, being dielectrophoretically sorted into striped patterns. These striped patterns of trapped nanometer scale particles create an effective diffraction grating which can then be sensed with macroscale optical techniques.

6465-16, Session 4

Integration of red VCSEL in a versatile microchip for encoding and subsequent detection of encoded beads

M. G. Loughran, Tyndall National Institute (Ireland)

The integration of optical excitation and detection in a microfluidic platform is another step towards the final Lab-on-a-chip concept. This work presents a microfluidic system made of polymer material with integrated miniaturized LASER source (red VCSEL). The light emitted by the VCSEL is detected by a photodiode. The concept was demonstrated by reading barcodes from silicon microbeads with encoded through holes.

The microfluidic system consists of two processed polymer chips that are bonded together. The substrate contains cavities to accommodate VCSEL components. The second polymer chip (superstrate) contains the microfluidic channel network. The photodiode detector is easily mounted on top of the superstrate. As shown in Figure 2, polymer chip substrates and master templates for hot embossing were fabricated by rapid prototyping technology. Fabricated masters are then moulded into thermoplastic polycarbonate (PC) substrate by hot embossing. Generated polymer sheets with embossed structures were diced into polymer chips and subsequently bonded together using a customised procedure. Figure 3 shows a complimentary moulded cavity which accommodates the VCSEL.

Illumination of an optically encoded microbead with a VCSEL light source is shown in Figure 4b. The VCSEL is operated with a power of 7 mW. As the bead flows under the VCSEL, the light is modulated by the bar code and subsequently detected by the photodiode. Signal measurements in Figure 4c confirm that different light levels can be analyzed by customized Labview software.

6465-18, Session 5

Nanoimprinting for micro- and nano-fluidics

J. Pong, Nanonex Corp.

No abstract available

6465-19, Session 5

Creation of embedded channels in SU-8 using two distinct exposure wavelengths

G. H. Chapman, D. K. Poon, J. M. Dykes, J. T. K. Tsui, C. Choo, Y. Tu, J. Wang, Simon Fraser Univ. (Canada)

SU-8 is a thick epoxy-based negative photoresist that is frequently used with binary photomasks to create high aspect ratio, straight-walled MEMS structures. It is a high gamma resist where its thickness can be set by exceeding the exposure threshold of the resist at short wavelengths. Short wavelength light at 350 nm or lower is highly absorptive and can be used

to form surface coverings on the SU-8. The surface covering thickness is controlled by reaching the exposure threshold of the high gamma SU-8, which is determined by exposure wavelength and dosage. Using a dual wavelength exposure technique, embedded micro-channels within SU-8 were created with just one photomask. The technique uses first a 365 nm wavelength exposure and a photomask to define the vertical sidewalls of the SU-8 micro-channels. A flood exposure is then carried out at 254 nm. Because 254 nm light can only penetrate the top few microns of SU-8, a thin membrane of hardened SU-8 is created on top of the SU-8 resist that acts as the channel encapsulation layer. Micro-channels 10-500 μm in width and up to 10000 μm in length with 5-20 μm surface coverings have been successfully fabricated. Further research is being conducted towards producing micro-channels of various dimensions in SU-8 as well as towards improving the smoothness and accuracy of the 3D structures. Work is also being done to explore the effect of exposure wavelength and time on the thickness of the hardened SU-8 skin and its application on creating embedded SU-8 micro-channels.

6465-20, Session 5

Two-photon polymerization for fabrication of biomedical devices

A. Ovsianikov II, Laser Zentrum Hannover e.V. (Germany); A. Doraiswamy, R. Narayan, Univ. of North Carolina; B. N. Chichkov, Laser Zentrum Hannover e.V. (Germany)

Development of novel biomedical devices depends vitally on the progress in the microfabrication technologies. Two-photon polymerization (2PP) is a novel technology which allows the fabrication of complex three-dimensional microstructures and nanostructures. The number of applications of this technology is rapidly increasing, including the fabrication of three-dimensional photonic crystals, medical devices, and tissue scaffolds.

In this contribution, we discuss current and potential applications of 2PP for microstructuring of biomedical devices. An important application sector for these devices is drug delivery. While in general this sector is still dominated by oral administration of drugs, precise dosing, safety, and convenience are being addressed by other forms of drug delivery that are developed today. Properties of micro-needle arrays (Figure 1) with various geometries fabricated by means of the 2PP technique will be discussed in this presentation. These devices provide a unique approach for transdermal delivery of nucleic acid- and protein-based pharmacologic agents. The application of microneedle arrays may overcome many issues associated with intravenous drug administration, including pain to the patient, trauma at the injection site, and difficulty in providing sustained release of a pharmacologic agent.

2PP is a fast and flexible technology, allowing the rapid fabrication of microneedle arrays, with various geometries. The effect of microneedle geometry (e.g., tip sharpness and aspect ratio) on skin penetration and flow properties is examined. In addition, the biocompatibility of three different classes of materials compatible with 2PP is studied using various cell types. Our results indicate that microneedles created using 2PP technique are suitable for in vivo use, and for integration with the next generation of MEMS- and NEMS-based drug delivery devices.

6465-21, Session 5

Mechanically assembled polymer interconnects with dead volume analysis for microfluidic systems

S. Jaffer, O. A. Lui, B. L. Gray, Simon Fraser Univ. (Canada)

For microfluidic systems, both SU-8 and silicon have proven to be effective materials for mechanical and microfluidic interconnect of discrete components (Gray et al., 2004). We now demonstrate microassembly of interconnect structures fabricated in the polymer polydimethylsiloxane (PDMS) with PDMS, SU-8, and silicon holes. PDMS cylindrical posts join with silicon holes with less force compared to SU-8 and silicon posts to silicon holes. In addition to interconnect fabrication and demonstration of substrate-to-substrate attachment, we also analyze fluidic properties of the interconnects via ANSYS simulation to predict whether pressure drop will result in disassembly and to estimate dead volume due to fluid flow. Pressures due to simulated fluid flow at 1 mL/min were determined to be 383.6Pa at the interconnect interface, which is insignificant compared to previously simulated SU 8 and silicon disassembly forces (Gray and Jaffer, 2005). Worst-case interconnect dead volume is simulated using ANSYS and Matlab to determine regions of dead volume and is compared to estimates using common linear approximations. This analysis shows differences in sudden expansions and sudden contractions in dead volume estimates.

6465-22, Session 6

Concepts for micropneumatic and microhydraulic logic gates

A. K. Henning, Aquarian Microsystems

A qualitative analogy between electronic MOSFETs and pneumatic microvalves has recently been suggested [1]. The suggested analogy leads naturally to the notion of a logic element, based on the flow of a compressible (electrically neutral) gas. Neither the notion of a pneumatic logic element [2], nor the flow vs. pressure behavior of a pneumatic microvalve [3], is new. Nonetheless, the extension of the MOSFET-microvalve analogy, to encompass a micro-pneumatic or micro-hydraulic logic element in microvalve form, and the exciting prospects for such elements (for instance, to facilitate microflow or microfluidic arrays, or to enable non-electronic computation in environments hazardous to electronics), warrant substantial further investigation.

Previously, we proposed novel microvalve structures, amenable to bulk micromachining, which effected fully complementary behavior in the switching of pneumatic signals from a PHI pressure state to a PLO state, and vice versa [4]. Using our quantitative relations for the flow of compressible gases in microvalves [5], we described mathematically the static behavior of these micro-pneumatic logic gates, and derived the transfer characteristic for switching between pneumatic states.

In this work, we extend the steady-state description to encompass a mathematical treatment of the transient response of micro-pneumatic logic gates. Following the suggestion of [6], we also apply the full transient model to scaled versions of a micro-pneumatic ring oscillator, in order to illustrate the performance which these devices may afford. Note that, as with MOSFETs, the ultimate speed of these devices is limited by the speed of sound of the compressible gas.

Equations 1 relate the pneumatic boundary conditions, mechanical behavior of a microvalve membrane, and the microvalve flow model [5]. Though not elaborated in this work, the sonic and subsonic flow equations have close analogies to, respectively, the saturation and linear equations for electron flow in MOSFETs.

Additional portions of this work will demonstrate how micro-hydraulic logic (involving incompressible fluids instead of compressible gases) is facilitated using identical microvalve structures, but with replacement of the fixed volume at the pressure node between inverter stages (Vn in Equations 2), by a volume which varies with the node pressure.

6465-23, Session 6

Squeeze film damping with a vibrating plate: implications and measurements for microfluidics

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We present results with a MEMS (Micro-Electromechanical System) technology that upon immersion within a fluid determines the density and viscosity in about 10 s. The working equations for this device were derived from knowledge of the added mass felt by an oscillating object as described by Landau and Liftshitz. The operational principal involves the influence of the fluid on the resonance frequency and quality factor of a vibrating plate oscillating normal to its plane. One of the challenges of

incorporating such sensors into microfluidic channels is to minimize the squeeze film damping that arises when a body is translated in close proximity to a fixed surface in a fluid. To that end we present results concerning the influence of a rigid wall (that simulates a microfluidic channel) on the resonance properties of a cantilever plate. These results show the vibrating plate needs to be separated from the channel walls by approximately one plate width to avoid large systematic errors.

6465-24, Session 6

Visualization of turbid two-fluid flows inside microfluidic conduits

Y. Ahn, W. Jung, Z. Chen, Univ. of California/Irvine

Frequency domain optical coherence tomography (OCT) with phase-resolved algorithm is presented to perform high-resolution (8 micrometers), cross-sectional imaging of structure and velocity in turbid gas-liquid slug flow inside a microtube and liquid-liquid flow inside a barrier embedded Kenics micromixer.

Slug flow, the most common flow regime in microfluidic gas-liquid two-phase flow, consists of trails of bubbles separated by liquid slugs flowing concurrently and provides significant radial heat and mass transfer. Since interfacial transports are proportional to the interfacial area between two phases, interfacial area concentration defined by interfacial area per unit mixture volume is an important parameter in a biochip with turbid biofluids. All the en face image techniques like light microscopy experience errors in the interfacial area concentration resulting from light refraction and have overlapping depth information from the layers within a laser sheet or a depth of focus of the objective lens. OCT, however, can provide accurate interfacial area concentration in a microtube because it is a cross-sectional imaging technique which dispenses with the refraction correction in the radial direction. Simultaneously, OCT can measure bubble velocity and velocity field inside liquid slugs. The radial liquid velocity was quantified without refraction correction. Two toroidal vortices per liquid slug were visualized which is the essential mechanism for radial heat and mass transfers.

The barrier embedded Kenics micromixer is a high performance chaotic mixer with complex three-dimensional geometry where one cannot visualize mixing phenomena with other techniques. OCT can image a three-dimensional mixing pattern and velocity field simultaneously.

6465-25, Session 6

Numerical simulation of transient nonlinear behaviors of electric-sensitive hydrogel membrane under an external electric field

Z. Yuan, Univ. of Florida and National Univ.of Singapore (Singapore); L. Yin, H. Jiang, Univ. of Florida

A multi-physics model is developed in this paper to predict the transient nonlinear behavior of electric-sensitive hydrogel membrane based on a multi-phasic mixture theory. In the developed model involving chemo-electro-mechanics, the transient convection-diffusion equations for ionic concentrations incorporate the migration and diffusion terms, the Poisson equation is employed to compute the distribution of electric potential directly and the transient hydrogel deformation is implemented easily by the continuity and momentum equations. To solve the present mathematical model consisting of transient nonlinear partial differential governing equations, a true meshfree, implicit numerical scheme is conducted for solution of convection-diffusion problem and hydrogel deformation iteratively. The employed meshless finite point method uses the point collocation technique for discretization of partial differential boundary values and initial value problems. The transient responds of electric-sensitive hydrogels including the membrane deformation, ionic concentrations and electric potentials interior and exterior the membranes are numerically simulated. And the parameters having important influence on the transient hydrogel deformation are also investigated.

6465-26, Session 6

Stochastic time-of-flight flow rate measurement for microfluidic applications

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We have developed a thermal time-of-flight liquid flow rate measurement based on injection of a pseudo-random sequence of thermal tracers in a microfluidic flow stream, followed by downstream detection of the temperature variation. The cross correlation function between the injected sequence and the detected signal displays a peak corresponding to the time-of-flight, which in turn provides a sensitive measure of flow rate. We have demonstrated the technique by using integrated MEMS silicon structures suspended across a microfluidic channel for both heating and detection. The encapsulation technique we use involves 3-layer glass-silicon-glass bonding. We are capable of measuring flow rate over more than three decades with an accuracy of a few percent (the exact measurement range scales with geometry, in our case corresponding to 5 - 10,000 microliters / minute). By comparison with other existing techniques for microfluidic flow metering (anemometric, coriolis), our method offers the advantage of being largely independent of physical fluid properties. In addition, the suspended MEMS heaters we fabricate can also be used as regular anemometer probes, extending the measurement possibilities to gas flow.

6465-28, Poster Session

Specific immobilization of human immunoglobulin G on gold-coated silicon microcantilever array

S. K. Vashist, R. S. Dahiya, Univ. of Genoa (Italy)

We demonstrate a procedure for immobilizing human immunoglobulin G (IgG) on an array of gold-coated silicon microcantilevers. The procedure employs protein A for the specific immobilization of human IgG on the gold surface. Protein A binds specifically to the gold-coated upper surface of the silicon microcantilever and has no interaction with silicon. It binds to the constant Fc regions of IgG keeping the antigen binding sites on the variable Fab region free to bind to antigens. The immobilization densities of protein A and human IgG were 112 ng/cm2 and 629 ng/cm2 as determined by 3, 3', 4, 4'-tetramethyl benzidine (TMB) substrate assay. The uniformness of the biomolecular coatings was determined by atomic force microscopy (AFM). Surface plasmon resonance (SPR) was used to determine the optimum concentration of human IgG suitable for the immobilization procedure and to cross-validate the immobilization density of functional human IgG molecules immobilized on the gold surface.

6465-29, Poster Session

A simple planar micromixer with low-pressure drop for disposable lab-on-a-chip (LOC) systems

A. A. S. Bhagat, E. T. K. Peterson, I. Papautsky, Univ. of Cincinnati

In this paper, we report on a new passive microfluidic mixer with low pressure drop for disposable lab-on-a-chip (LOC) systems, capable of mixing at short distances for low Reynolds number (Re) flows. The micromixer consists of alternating triangular features, protruding into the center of the channel to alternately force one fluid stream into the other. This alternating action of the two fluids results in mixing. The effects of the triangular sidewall geometry on mixing were fully investigated, including notch length (L), notch width (W), and spacing between consecutive notches (S), using CFD-ACE+ simulation software. Modeling results were experimentally confirmed by fabricating devices in polydimethylsiloxane (PDMS). The channels are 200 μm wide with a height of 55 μm. The opti-

mized design containing 100 μm x 25 μm (L x W) notches spaced at 25 μm yielded >90% mixing at ~6.5 mm from the channel inlets at Re = 0.1. The mixer design described herein has a number of critical advantages: 1) efficient mixing of low Re flows which are characteristic of LOC systems, 2) low pressure drop which permits cascading and easier integration with other LOC components, and 3) planar 2-D design which simplifies fabrication and integration with existing LOC technologies.

6465-30, Poster Session

Structural and electrical properties of conducting polymeric-aligned nanofibers via electrospinning

J. H. Lee, Univ. at Albany

Recently, conductive polymer nanofibers have attracted much attention for use in diverse applications. Electrospinning is one method to prepare such nanofibers using various polymeric materials. Under standard deposition conditions, these fibers can be randomly arranged on a collection electrode forming a mesh network structure. Although the disordered fibers are still interesting for various applications, aligned 2-D and stacked 3-D layers of fibers can be of critical importance when applied to devices such as bio-sensors, drug release architectures, tissue engineering, and microelectronics. In the present work, we report fabrication of polymeric composite aligned nanofibers made up of polypyrrole (PPy) with polymethyl-methacrylate (PMMA) and with poly(ethylene oxide) (PEO). Historically, PPy has been widely investigated because of its high electrical conductivity, biocompatibility, and electrochemical activity. However, it has been observed that pure PPy electrospun nanofibers are difficult to fabricate. Therefore, to improve the structural and electrical properties, composite materials containing a conducting polymer alloyed with a non-conducting polymer have been proposed. A series of aligned composite nanofibers using pure PMMA, pure PEO and their composite with conducting polymer PPy in acetone and NN-Dimethyl formamide (DMF) were produced. Structural properties of these fibers were analyzed using scanning electron microscopy (SEM) and electrical conductivity was measured using the two-point method on a patterned silicon wafer. The diameters of PMMA + PPy fibers were found to be approximately 200 nm and the diameters of PEO + PPy fibers were approximately 100 nm. Details of these initial experiments along with a discussion of applications will be presented.

6465-32, Poster Session

Optimization of COC hot embossing with soft PDMS tools

K. Zhou, I. Papautsky, Univ. of Cincinnati

In this paper, we use Taguchi optimization method to investigate a COC (cyclic olefin copolymer) hot embossing process using soft PDMS tools.

A test pattern made up of 6 x 6 square arrays of microchannels varying from 10μm to 100μm in width and 10μm to 100μm at center-to-center spacing was employed. The PDMS embossing tool was fabricated by casting PDMS on a silicon master with the test pattern fabricated in AZP4620 photoresist. Taguchi method was utilized to optimize the hot embossing process using PDMS tool. Temperature, embossing force and hold time were selected as the control factors, each set in a wide range with four levels. These levels and range were selected based on our prior work with hot embossing of COC. L16 (45) orthogonal array was used to accommodate these three parameters at four levels. Height and width of the embossed channels were defined as quality characteristic. A fast and effective method was utilized to characterize the profile of channels by simply inspecting PDMS negative replica of the channels. After calculating the signal-to-noise(S/N) ratio, analysis of variance (ANOVA) was performed to estimate error variance and to determine the relative importance of the factors.

The microchannels of 20μm width were the smallest feature size pattern that could be analyzed by Taguchi method. For microchannels of 10μm width, Taguchi method could not be performed due to too many infeasible data at low temperature 150°C and 160°C. However, for microchannels of other feature sizes, channels could be fabricated in all runs except only one extreme condition. Here, we performed Taguchi optimization analysis for the microchannels of 20μm width at 20μm center-to-center spacing; the suggested hot embossing parameters were temperature at 170° C, embossing force with 3.0 kN, and hold time for 12 min. The result indicated that temperature was of most significance and could significantly affect the replication fidelity. The optimized embossing proicess can now be used to replicate microfluidic devices having both small (~20μm) and large (~100μm) features with confidence.

6465-33, Poster Session

A simple passive micromixer using recombinant multiple flow streams

J. S. Shim, I. Nikcevic, M. J. Rust, A. A. S. Bhagat, I. Papautsky, Univ. of Cincinnati

The design and fabrication of a passive microfluidic mixer is reported in this work. The past two decades have seen significant growth in research on devices and systems for manipulating very small volumes of fluids, an area called microfluidics. One of the most important components for microfluidic systems is the micromixer, which is needed in sample preparation for many chemical reactions. However, the major drawback of micromixers is the challenge of achieving mixing in short distances with small pressure drop as required for Lab-on-a-chip (LOC) devices.

In this work, two design concepts were used to maximize mixing within the minimum channel length and pressure drop. To increase mixing efficiency, multiple flow streams were generated at different velocities through the use of asymmetric obstacles in the fluid flow path. When the streams are later recombined, the difference in velocity between streams creates vortices, thus improving mixing. Additionally, the design was optimized to maintain high velocity throughout the length of the device. Diamond-shaped obstacles were chosen to split the flow into several streams, which are then guided back into contact after the obstacle. To keep pressure drop low, the channel cross-sectional area was maintained equal to the input cross-sectional area, and this was held constant throughout the device. Thus the fluid is never forced through a very narrow channel cross-section, which would create a large pressure drop. The proposed design was modeled using computational fluid dynamics (CFD) software. CFD-GEOM was used to create the channel geometry and CFD-ACE+ was used to simulate the flow at Reynold's Number (Re) = 0.01, 0.1, 1, 10 and 100. The effects of channel width, channel length, location of obstructions, and Re were investigated. The micromixer was fabricated in PDMS using SU-8 lithography. PDMS molds were bonded to 3" 1" glass wafer using O2 plasma. The width of the channel inlet and channel cross-section was 200 μm and the depth of the PDMS channel was 50 μm. The mixing performance of the device was tested using two liquids: DI water and 0.1 μM fluorescein in DI water.

The results from simulations showed that decreasing channel width to create nozzles or reduced diffusion distances increased mixing efficiency. However, this advantage is offset by increased pressure drop, which should be avoided due to collapse of PDMS channels. Simulated data showed that the designed micromixer achieved 90 % mixing at a channel length of 4.35 mm with pressure drop of 584 Pa at Re = 1, while experimental data for Re = 0.1 showed 90% mixing at 7 mm. Experimental results have shown 96.32 % mixing at Re = 0.1, 74.08 % mixing at Re = 1, 87.39 % at Re = 10 at a channel length of 1 cm, indicating that there is a difference in simulation results and experimental results. The observed differences between simulation and experimental results are likely due the use of lower resolution meshing conditions in the CFD software.

6465-34, Poster Session

A recyclable real-time DNA computing system based on surface plasmon resonance

T. Chang, C. Lin, National Taiwan Univ. (Taiwan); C. Lin, National Sun Yat-Sen Univ. (Taiwan); C. Yang, I-Shou Univ. (Taiwan)

This study proposes a real-time and reusable microfluidic DNA computing platform for solving satisfiability (SAT) problem based on surface plasmon resonance (SPR). In this work, we immobilized three different sequences of 18-mer ssDNA with thiol terminal on the gold surface in different microfluidic channels to direct nucleotides of complementary sequences to the surface-bound ssDNA probes of specific sites for hybridization under constant temperature (26°C). We also conjugate antibody (human IgG, about 150kD) to complementary ssDNA chemically to amplify the hybridization signal and to distinguish Boolean value of true and false . In the other words, once a surface is patterned with the appropriate probe sequences, sequence-specific hybridization will sort out the target conjugates and direct them to the appropriate spots on the surface. In order to keep the SPR measurement stable, DNA annealing and denaturing is manipulated by changing salt concentration (by adding 0.05M NaOH to denature DNA) of the reaction solution rather than changing reaction temperature.

The SAT problem is a decision problem considered in complexity theory. An instance of the problem is a Boolean expression written using only AND, OR, NOT, variables, and parentheses. The SAT question is: given the expression, is there some assignment of TRUE and FALSE values to the variables that will make the entire expression true? The kind of problem is difficult for computers, but it is much simple for the DNA computer that can compute in parallel.

In this study, we demonstrate a multi-channel microfuidic DNA computation system to solving 3 variables (X,Y,Z) Boolean SAT formula with reusability, sensitivity (the concentration of complementary ssDNA is about1nM) and specificity using protein-ssDNA conjugates to link to DNA SAM surface under the constant temperature, and the whole processes can be done in 1hour.

6465-35, Poster Session

Initial investigation of SU-8 photopolymer as a material for noninvasive endothelial cell research platforms

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This paper presents a preliminary study of the micromachining polymer material SU-8 for the non-invasive functional study and shape control of vascular endothelial cells (ECs), the cells lining the inner surfaces of blood vessels. We have previously demonstrated a silicon and glass modular microinstrument platform that allowed for a wide range of EC functional response studies. However, we expect SU-8 to provide a more versatile fabrication technology and material for microchannel fabrication and instrumentation. SU-8 is an epoxy-based negative photoresist that has gained interest in recent years in the fabrication of low-cost microfluidic, medical, and other MEMS devices. SU-8 is a transparent material that can be fabricated at very high aspect ratios (>20) by simple spin-on and photopatterning. Thus, it is easily compatible with CMOS and sensors, making it a good material for the fabrication of passive channels on active devices without the need for substrate-to-substrate bonding. In this paper, SU-8 microchannels were fabricated on glass slides for straightforward optical observation and biological sampling. Channel widths were from 50 to 210 micrometers, length varied from 100 to 2100 micrometers, with depth fixed at 100 micrometers. We plated bovine aortic ECs (BAECs) in the microchannels and used image analysis to determine cellular elongation. Similarly, to silicon-on-glass microchannels, the cells become more elongated as the width of the microchannel decreases. Initial results indicate cells plate both in the microchannels and on the SU-8 surface. This finding has implications for SU-8 as a mechanical structure for channel instrumentation.

6465-36, Poster Session

Numerical simulations and analysis of a micropump actuated by traveling plane waves

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Traveling plane-wave deformations on a solid thin film immersed in a fluid can create viscous propulsion in the direction opposite to propagation direction of the waves. The mechanism is used by micro-organisms for propulsion. Here, we modeled and analyzed the characteristics of a micropump that incorporates a traveling plane-wave actuator. As, typically, peristaltic pumps use one-sided interaction with the fluid, the traveling plane-wave actuator utilizes both sides to move the fluid when inserted in a channel parallel to its axis. Our numerical model incorporates direct coupling between solid deforming boundaries and the fluid by means of a deforming mesh according to Arbitrary Lagrangian Eulerian implementation, and the 2D Stokes equations to solve for the flow in the channel created by the traveling-wave actuator. A commercial finite-element package COMSOL is used for simulations. Analysis is carried out with nondimensional quantities. For a given topology, the nondimensional flow rate's (channel Reynolds number) dependence on the nondimensional amplitude, wave-length, and the frequency of the oscillations is investigated. As the channel Reynolds number grows quadratically with the amplitude, its dependence is only linear with the wave-length and the frequency at constant group velocity. Efficiency of the micropump is calculated for both restrained and unrestrained flows. The characteristic pressure difference vs. flow rate curve of the pump is obtained for the former.

6465-37, Poster Session

Fabrication and characterization of SiO2 microcantilever for high sensitive moisture sensor

Q. Chen, Louisiana Tech Univ.

This paper reports a novel design and fabrication of SiO2 microcantilever for high sensitive moisture sensor. In order to fabricate the device, the new process using isotropic combined with anisotropic dry etching to release the SiO2 microcantilever beam by ICP (Inductively Coupled Plasma) is developed and investigated. This new processing not only obtains the high etching rate about 9.1 μm per minute, but also provides a good profile controllability, and a flexibility of device design. To compare the SiO2 and Si cantilever beam, the results of simulation and theoretical analysis are given. The results predict the SiO2 cantilever can achieve a higher sensitivity than the Si cantilever. The SiO2 cantilever beams with 1 μm thickness, 100 μm width, and 250 μm length were fabricated and tested by exposing it to aminoethanethiol solution of low concentration. The experimental data support the prediction derived from the simulation results. The moisture sensor was made of coating a sensing polymer mixture on the beam surface and tested in the moisture vapor. The experimental results demonstrate that the moisture sensitivity of this sensor is better than one percentage of relative humidity.

6465-38, Poster Session

Water-soluble (MUA-coated) quantum dots: physicochemical characterization and application

Y. Lin, National Cheng Kung Univ. (Taiwan)

This paper describes the physicochemical characterization and application of quantum dots (CdSe/ZnS, QDs) whose surface were hydrophilic modified by mercaptoundecanoic acid (MUA). The stability kinetics of MUA-coated QDs (MUA-QDs) in aqueous solution was studied as a function of MUA-QDs concentration, type of light exposed, pH conditions

and temperatures. The results show that the optimum concentration range of MUA-QDs is 0.5 to 1 mg/mL. We find that no obvious difference of fluorescence intensity was detected in MUA-QDs stored respectively at 4°C, 24°C and 44°C (8-hour). When they were exposed to UV light (312 nm) for 8 hr, their fluorescence intensity was shown serious decay. Moreover, the results show that the pH of maximum stability of MUA-QDs in buffer solutions was 8. Finally, MUA-QDs had been endocytosis into H9c2 cells, a permanent cell line derived from rat cardiac tissue, for cell imaging applications, the results provide the benefit to apply MUA-QDs in medical areas.

6465-39, Poster Session

Fabrication of a microfluidic system with integrated electrochemical pump and valves

D. E. Lee, S. A. Soper, W. Wang, Louisiana State Univ.

No abstract available

6465-44, Poster Session

Cross-polarization scheme for fluorescence detection for biochip and biomedical applications

A. Pais, A. Banerjee, E. T. K. Peterson, H. Mu, I. Papautsky, D. J. Klotzkin, Univ. of Cincinnati

No abstract available

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6466-01, Session 1

Miniaturized FTIR-spectrometer based on an optical MEMS translatory actuator

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We present a MOEMS based miniaturized Fourier-transform infrared (FTIR) spectrometer capable to perform time resolved measurements from NIR to MIR. To enhance the performance of the FTIR-spectrometer an optimized MOEMS translatory actuator was designed and fabricated. The MOEMS device is manufactured in a CMOS compatible process using SOI technology. It consists of a metallized actuator plate with an area of 7 mm2 acting as mirror. The springs are designed such that they can perform a pantograph-like movement allowing for large displacements of the mirror plate. The actuator uses an in-plane comb-electrode drive. As a result, a translatory amplitude of 200 μm, corresponding to an optical path length modulation of 400 μm is achieved with comparatively low voltages (> 40 V) at an ambient pressure below 500 Pa. The actuator operates at a resonant frequency of 500 Hz. Consequently this yields an acquisition time of 2 ms per spectrum. Based on a Michelson setup the infrared optical bench of the presented FTIR system is designed to account for the mirror aperture and the desired spectral bandwidth of 2 to 11 μm. The integrated signal processing electronics has to cope with a bandwidth of 8 MHz as a result of the mirror motion. A digital signal processor manages system control and data processing. The high acquisition rate and integration level of the system makes it appropriate for applications like process control and surveillance of fast reactions. First results of transmission and absorbance measurements are shown. Furthermore, the influence of ambient pressure on oscillation amplitude and possibilities for a MOEMS vacuum packaging are discussed to further increase oscillation amplitude and thus spectral resolution.

6466-02, Session 1

Uniform tilt-angle micromirror array for multi-object spectroscopy

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We report on micromirror arrays being developed for the use as reflective slit mask in Multi Object Spectrographs. The micromirrors are etched in bulk single crystal silicon whereas the cantilever type suspension is realized by surface micromachining. One micromirror element is 100x200 μm2 in size. The micromirrors are actuated electrostatically by electrodes located on a second chip. The use of silicon on insulator (SOI) wafers for both mirror and electrode chip ensures thermal compatibility for cryogenic operation. A system of multiple landing beams has been developed, which passively locks the mirror at a well defined tilt angle when actuated. The tilt angle obtained is 20 degrees at a pull-in voltage of 90V. Measurements with an optical profiler showed that the tilt angle of the actuated and locked mirror is stable with a precision of one arc minute over a range of 15V. This locking system makes the tilt angle merely independent from process variations across the wafer and thus provides uniform tilt angle over the whole array. The precision on tilt angle from mirror to mirror measured is one arc minute. The surface quality of the mirrors in actuated state is better than 10nm peak-to-valley and the local roughness is around 1nm RMS.

6466-03, Session 1

Using MEMS technology for cost effective recycling of plastics

Y. Geller, M. Ramani, Polychromix, Inc.

Polychromix has introduced a line of compact, portable, low-cost NIR systems, namely the Digital Transform Spectroscopy (DTS[TM]) Spectrometers and Phazir[TM]. They deliver outstanding value in the manufacture, analysis and recycling processes involving plastics, petrochemical, food/ agriculture and pharmaceutical products.

The portability of Phazir and DTS spectrometers allows characterization and content analysis of various plastics to be performed either on site or in the lab. In the plastics industry, for instance, materials need to be sorted before the proper chemical process can be applied to them for either manufacture or recycling. Using the DTS or Phazir, in-line or factory inspections can take place on site with minimal training.

Currently, many such applications go unanswered for want of a low-cost spectrometer that can be used in-field. For instance, often it is impractical for the sample to be brought to the spectrometer (e.g. incoming inspection for large vats of unprocessed plastics received at the incoming sort center), or alternatively, sample identification must be conducted immediately and accurately (e.g. differentiation between Nylon 6 and Nylon 66 as various carpet fabrics are being recycled). Using Micro-Electro-Mechanical-Systems (MEMS) technology, a new breed of portable, high-performance NIR devices is now commercially available at unprecedented low cost for just such applications.

The use of DTS and Phazir NIR spectrometers, based on MEMS technology, yields a compact device that can easily be used in hand-held applications. As the MEMS engine is an electrostatic device, power consumption is kept to a minimum, allowing DTS spectrometers to use a battery pack to power all functional and processing electronics for many hours without the need to recharge the device. Also, with the use of new composite materials and manufacturing processes, the devices are light enough to be carried and used extensively in the field. Devices are manufactured with a small footprint to deliver a broad range of field and laboratory applications as well as to promote their integration into process control.

6466-04, Session 1

Investigation and characterization of high-efficient NIR-scanning gratings used in NIR microspectrometer

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Spectroscopy in the infrared region is today an important application to measure, control and investigate liquids or gases in industrial, medical or environmental applications. We have developed a small, transportable NIR-spectrometer with a size of only 120 x 80 x 80 mm3, and a MOEMS-scanning-grating chip as main element. The scanning-grating chip is resonantly driven by a pulsed voltage of only 36V, has a size of 3 x 3 mm2 and reaches maximum deflection angles of +/- 11°. The NIR-micro-spectrometer works in a spectral range of 900 - 2500 nm with a resolution of less than 10 nm using only one single InGaAs-diode as detector. One entire spectral measurement is done within 6 milliseconds, calculated by a digital signal processor, which is included in the spectrometer. Results can be either displayed by special computer software or directly by a graphical user interface. In this paper, we will focus on the properties of the

different grating structures, which can be applied to the mirror surface, and their spectral efficiency in the first diffraction order. Furthermore the characterization of the fabrication process and its consequence on the spectrometer properties will be discussed, as well as the characterization of the scanning grating chip itself (frequency, movement, static deformation...). Characteristic measurement results of an argon calibration lamp, which shows the performance of the NIR-micro-spectrometer, will be presented as well.

6466-05, Session 1

Tunable infrared detector with integrated micromachined Fabry-Perot filter

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This paper deals with design, fabrication and test results of a tunable pyroelectric detector with an integrated micromachined Fabry-Perot filter for gas analysis in the Mid-Wave Infrared. The new approach is based on a Fabry-Perot interferometer with an electrostatic tuned air cavity. The movable reflector of 2 x 2 mm2 is located in the center surrounded by the driving electrodes and suspended by diagonally arranged springs located in the corners of the outer frame. Various types of spring configurations have been fabricated to determine an optimum solution. Alternating quarter-wave layers of low refractive index silicon dioxide and high refractive index polycrystalline silicon build up distributed Bragg reflectors. Two types of FPI filters have been fabricated for a tuning range of 3...4.1 mm and for 3.9...5 μm respectively. The spectral bandwidth of the filters is about 80...100 nm and the peak transmittance about 75...50 %. Depending on the type of spring a high tuning range of 1100 nm is achieved by applying a voltage of 27 V or 60 V.. The tunable filter is arranged on top of a current mode pyroelectric detector. A low noise, low power CMOS op-amp with a 100 GW feedback resistor and a very low 40 fF feedback capacity converts the pyroelectric current into a high signal voltage. The pyroelectric and the compensating chips and the input of TIA are completely shielded in order to avoid capacitive coupling from the electrostatic driving circuitry. Both the tunable filter and the detector are packaged in a TO-8 housing with a broad bandpass filter.

6466-06, Session 1

An indium phosphide-based near-infrared MOEMS microspectrometer for agri-food and environmental monitoring

M. Garrigues, J. Leclercq, R. Gil-Sobraques, École Centrale de Lyon (France); O. Parillaud, A. Marceaux, Alcatel Research & Innovation (France); M. Crochon, J. Roger, Cemagref (France); O. Amore, B. Vilotitch, Datalink Instruments (France)

The general aim of this project is to realize optical microsystems for NIR spectroscopy (1.5 μm to 2 μm) using the InP/InGaAs material system. We have designed an integrated microspectrometer based on a long-wavelength strained InGaAs quantum well RCE photodiode combined with a wavelength tunability function (MEMS concept). The weak absorption of the QWs is enhanced by embedding the quantum wells into a micromachined tunable vertical resonant resonator that consists of multiple InP/air-gap alternate layers that form both the DBR reflectors and the electrostatically tunable air-gap cavity. The devices are fabricated using a specific MOEMS process based on selective wet etching of an InP/InGaAs epitaxial layer stack grown by MOVPE.. The small size and low cost of these microsystems pave the way to promising industrial applications, such as non-invasive biological analysis, on-line industrial process analysis and hyperspectral imaging.

The paper will first focus on critical design and process issues in order to accommodate residual stresses in the suspended membranes while preserving a suitable tuning range. We will then present a specific design optimized for the monitoring of sugar concentration in water. The selected spectral range for this analysis is comprised between 1650 nm and 1750 nm. The spectral selectivity is about 5 nm. Internal wavelength calibration and baseline correction is achieved by specific signal processing. Due to the reduction of the active layer thickness combined with low defect density of the pseudomorphic strain compensated QWs, extremely low room temperature dark current densities can be achieved.

6466-07, Session 2

MEMS compatible illumination and imaging micro-optical systems

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The development of new MOEMS demands for cooperation between researchers in micromechanics, optoelectronics and microoptics at a very early state. Additionally, microoptical technologies being compatible with structured silicon have to be developed. The microoptics for two silicon based microsystems will be described in the paper. First, a very small scanning laser projector with a volume of less than 2 cm(c)^3, which operates with a directly modulated red semiconductor laser collimated with a microlens, is shown. The laser radiation illuminates a 2D-MEMS scanning mirror. The optical design is optimized for high resolution (VGA). Thermomechanical stability is realized by design and using a structured ceramics motherboard.

Secondly, an ultrathin CMOS-camera having an insect inspired imaging system has been realized. It is the first experimental realization of an artificial compound eye. Micro-optical design principles and technology is used. The overall thickness of the imaging system is only 320 μm, the diagonal field of view is 21°, and the f-number is 2.6. The monolithic device consists of an UV-replicated microlens array upon a thin silica substrate with a pinhole array in a metal layer on the back side. The pitch of the pinholes differs from that of the lens array to provide individual viewing angle for each channel. The imaging chip is directly glued to a CMOS sensor with adapted pitch. The whole camera is less than 1mm thick. New packaging methods for these systems are under development.

6466-08, Session 2

The iMoD display: considerations and challenges in fabricating MOEMS on large area glass substrates

C. Chui, Exponent Failure Analysis

No abstract available

6466-09, Session 2

Ultra-compact laser projection systems based on two-dimensional resonant microscanning mirrors

M. Scholles, Fraunhofer-Institut für Photonische Mikrosysteme (Germany); A. H. Bräuer, Fraunhofer-Institut für Optik und Feinmechanik (Germany); K. Frommhagen, C. Gerwig, H. K. Lakner, H. Schenk, M. Schwarzenberg, Fraunhofer-Institut für Photonische Mikrosysteme (Germany)

Recently, there has been substantial progress in the development of ultra-compact image projection systems with dimensions clearly below the size of products based on DMD[TM] technology. This has been enabled by the availability of electrically modulated laser sources for all three elementary colors and a two-dimensional resonant micro scanning mirror as MOEMS device for light deflection. The laser beam formed by collimator optics is directed onto the micro scanning mirror. Then, the reflected

beam describes a highly complicated Lissajous figure on the projection screen with flare angles of up to 20 degrees. By driving the mirror and electrically modulating the intensity of the laser beam in a synchronous manner, projection of images can be achieved. In this contribution we will present the theoretical background of the projection system as well as the latest achievements in system design.

Both monochrome and full color systems are currently available. The latter use a separate laser bank as RGB light source, which is coupled with the projection head comprising the micro-optics and the micro scanning mirror via Glass Optical Fiber. For monochrome red systems, the laser diode can be integrated into the projection head as well, whose volume could be reduced to 15mm x 7 mm x 5mm. All systems have VGA (640 x 480 pixels) resolution and operate with 8 bit color depth per pixel and 50 frames per second. This degree of miniaturization makes laser projection systems attractive for integration into mobile devices and overcomes limitations of display size in such appliances.

6466-10, Session 2

Electrostatic 1D microscanner with vertical combs for HD resolution display

J. Cho, Y. Park, Y. Ko, S. Kang, S. Chung, Y. Cho, S. Chang, J. Lee, J. Sunu, SAMSUNG Advanced Institute of Technology (South Korea)

Optical scanners are widely used for laser printing, optical communication, display and so on. Due to its high speed scanning capability with small form-factor, low-cost, low-power consumption and light-weight, developments of the optical micro scanner has been carried out by many researchers [1-5]. Recently laser scanning display using micro scanning mirror is being developed as one of the key component of the future projection displays. In the previous work, a laser scanning video image was demonstrated using the one-dimensionally tilting (1D) horizontal scanning mirror combined with a galvanometric scanner [5]. At that time, we introduced the eye-type scanning mirror for horizontal scanning, of which resonant frequency is about 24.5 kHz and mechanical scanning angle of ±8° with mirror diameter of 1mm.

6466-11, Session 3

High-performance silicon scanning mirror for laser printing

W. O. Davis, D. Brown, Microvision, Inc.; M. Helsel, North Seattle Community College; R. Sprague, G. Gibson, Microvision, Inc.; A. Yalcinkaya, H. Ürey, Koç Univ. (Turkey)

This paper describes the design, fabrication, and characterization of a MEMS scanning mirror suitable for replacing the polygon mirrors currently used for high-speed consumer laser printing. It has reflector dimensions of 8mm X 0.75mm, and achieves 80 degree total optical scan angle at a scanning frequency of 5kHz. This level of performance enables the placement of approximately 14,000 individually resolvable dots per line at a line rate of 10,000 per second, a record-setting speed and resolution combination for a MEMS scanner. The scanning mirror is formed in a simple microfabrication process by gold reflector deposition and patterning, and through-wafer deep reactive-ion etching. The scanner is actuated by off-the-shelf piezo-ceramic stacks mounted to the silicon structure in a steel package. Antiphase linear displacements of the piezo stacks generate an angular displacement at the base of the scanning mirror's torsion bar suspension. Under a resonant condition, this angular displacement is amplified according to the scanning mirror's frequency response characteristics. The paper describes an analysis of the scanning mirror design in the form of a derivation of the equations of motion for the scanner and actuator assembly. Lumped-parameter constants are derived by hand calculations and finite element analysis. Device characteristics predicted by the mathematical model are compared to measurements.

6466-12, Session 3

Fracture strength of silicon-on-insulator torsional springs in MEMS micromirrors

S. Hsu, A. Wolter, W. Owe, H. Schenk, Fraunhofer-Institut für Photonische Mikrosysteme (Germany)

This paper discusses the fracture strength study of torsional springs in MEMS microscanners, which are fabricated in silicon-on-insulator (SOI) with deep-reactive-ion-etch (DRIE) process. High performance microscanners are of particular interest for scanning laser projection displays. To produce high resolution images, scanners are required to rotate with large actuation angles (>10 degrees mechanical angle) at designated resonant frequencies. While the designs are pushed closer to material limits, it is essential to acquire knowledge of single-crystal-silicon's fracture strength. We have designed samples for fracture strength tests, which reach a failure angle (> 20 degrees) with a low driving voltage (> 50 volts) under vacuum. The tests are performed with real-time optical feedback to ensure resonance operations. A voltage ramp is applied to scanners until fractures occur; the ramp-rate and starting angle are chosen such that failures occur within thirty minutes of operation. Torsional stresses at fracture are calculated from failure angles via an ANSYS model. In preliminary tests, the average fracture angle from twenty samples is 32.8 degrees, which indicates a fracture stress of 2.82 GPa for springs with a cross-section of 14x30 um and a length of 240 um. Because fracture angles scatter around a mean value, Weibull statistics is used to treat the characteristic behaviors of the tested samples to better interpret the test results. With a conservative stress tolerance of less than 2 GPa, we can achieve a SVGA microscanner design with a 1 mm diameter, a 32 KHz resonance frequency, and a 13 degrees single-side mechanical angle.

6466-25, Session 3

Electro-optomechanical cantilever-based logic gates

G. P. Rehder, M. I. Alayo Chavez, H. B. Medina, M. N. P. Carreño, Univ. de São Paulo (Brazil)

In this work we describe the fabrication and characterization of micro-opto-electro-mechanical AND, OR and XOR logic gates based in a combination of optical and micro-electro-mechanical devices. These structures consist of silicon oxynitride-based optical waveguides, through which a light beam of 633-nm can be conducted [1], and mobile thermo-electro actuated cantilevers, which form part of the waveguide and can work as ON-OFF switches for the laser. These switches are combined to form AND, OR and XOR gates, allowing the laser light to pass when activated electrically or blocking the laser light otherwise. The cantilevers are fabricated by freeing regions of the waveguide, which is done by front side micromachining the silicon wafer used as substrate. Also, they are actuated electrically through the heating of a metallic resistance positioned in the device, where the applied current heats the cantilevers and, due to the difference in thermal expansion coefficients of the constituent materials, it is possible to produce a controlled motion proportional to the heating current [2]. Therefore, the switches can be electrically polarized in on/off cycles allowing or blocking the light through the waveguide, similar to logic "1's" and "0's". The electro-opto-mechanical logic gates function by inserting light through the waveguide and controlling electrically the cantilever-based ON-OFF switches to obtain an optical logic output.

[1] M.I. Alayo, D. Criado, M.N.P. Carreño, I. Pereyra, Materials Science and Engineering B 112 (2004) 154.

[2] G. Rehder and M.N.P. Carreño, Journal of Non-Crystalline Solids, 352 (2006) 1822.

6466-13, Session 4

Liquid-based variable-focus lenses for zoom cameras

S. Kuiper, B. H. W. Hendriks, Philips Research Labs. (Netherlands)

The interface between two immiscible liquids can be used as a lens. Changing the curvature of this interface by electrowetting leads to a variable-focus lens. We demonstrated that such a lens can very well be used for focusing purposes in miniature cameras, for instance in camera phones. The optical design of such a camera is simple, even when a high-quality picture is required.

Zoom cameras can be made by placing two variable-focus lenses in series. The design for such a camera is much more complicated than for an autofocus camera and demands more from the individual lenses with respect to range in curvature. Liquids with high refractive index differences are required to obtain a reasonable zoom factor and the abbe numbers must fulfil special and rare requirements to make the system achromatic.

The presentation will be focused on the differences between autofocus and zoom cameras and on the solutions we found to make a zoom camera. Furthermore, photos and movies made with our first demonstrator will be shown.

6466-14, Session 4

Dual-axes confocal microscopy with a MEMS scanner for reflectance and fluorescence imaging

H. Ra, W. Piyawattanametha, Y. Taguchi, D. Lee, O. D. Solgaard, Stanford Univ.

We present a two-dimensional (2-D) MEMS scanner that enables dual-axes confocal microscopy. Dual-axes confocal microscopy provides high resolution in both transverse and axial dimensions, while being well-suited for miniaturization into endoscopes for in vivo imaging. The MEMS device performs two-dimensional raster scanning of the beam to acquire an image. Its small dimensions make post-objective scanning and miniaturization of the scan head possible, and its optically flat mirror surfaces lead to high quality images.

The 2-D scanner has a gimbal structure with two connected mirror surfaces, in order to accommodate the illumination and collection beam. It is fabricated from double silicon-on-insulator (SOI) wafers and is electrostatically actuated by self-aligned vertical combdrives for large scanning angles. The overall scanner is designed to be integrated in a 5-mm-diameter endoscope. The die size of the MEMS chip is 3.2 mm x 2.9 mm, and the peak-to-valley surface deformation is less than 0.1 μm. Maximum optical deflections of ± 4.8 degrees and ± 5.5 degrees are achieved for the outer and inner axes, respectively. The torsional resonant frequencies are at 500 Hz and 2.9 kHz for the outer and inner axes, respectively.

Reflectance and fluorescence imaging with the MEMS mirror is demonstrated in a breadboard setup with a dual-axes configuration. Large field of view images are acquired at 8 frames per second. The transverse resolution is 3.9 μm and 6.7 μm for the horizontal and vertical dimensions, respectively. For fluorescence imaging, a metallized mirror is used to increase the photon collection efficiency.

6466-15, Session 4

High-speed three-dimensional endoscopic OCT using MEMS technology

Z. Chen, W. Jung, Univ. of California/Irvine; D. T. McCormick, Univ. of California/Berkeley; N. C. Tien, Case Western Reserve Univ.

Optical coherence tomography (OCT) is a noninvasive medical imaging modality for cross-sectional imaging of biological tissue with micrometer scale resolution. Conventional OCT endoscopic probes suffer from low scanning speed, non-uniform coupling, and are limited to 1-D scan. The recent development of Fourier domain OCT (FD-OCT) has significantly increased OCT imaging speed. High speed 2-D and 3-D OCT imaging require scanning probes with performance parameters that cannot be met with conventional OCT probes.

We present a three-dimensional (3-D) endoscopic OCT system based on a dual axis scanning microelectromechanical system (MEMS) mirror. The MEMS scanning actuators are monolithic, single crystal silicon (SCS), 2-dimensional, gimbal-less, vertical comb-driven structures. The devices are designed and realized in a self-aligned DRIE fabrication process on SOI. The mirrors are fabricated in a separate SOI process and later bonded to the actuator. This design approach allows the mirror and the actuator to be independently optimized. In addition, the MEMS and optical designers have a much broader design space when making trade-offs between mirror size and speed. The apertures are metalized, low-inertia, SCS structures with a thinned mirror plate (2-5μm), thick stiffening trusses (~20μm) and a tall standoff pedestal (~120μm). A variety of scanners with mirror size up to 2.0 mm have been developed. Both axes were capable of scanning greater than 20° with scanning speeds of several kHz and excellent linearity. The endoscopic MEMS probe was integrated with an OCT system and volume images were obtained at a rate of 3 frames/s by means of 2-axis lateral scanning combined with an axial scan.

6466-16, Session 4

A new microlaser camera

C. Drabe, T. Klose, A. Wolter, H. Schenk, Fraunhofer-Institut für Photonische Mikrosysteme (Germany); R. A. James, Microvision, Inc.

A new two-dimensional and resonantly driven scanning micro mirror has been simulated, fabricated and characterized. Features are a small chip size of 3000μm x 2300μm with a frame oscillating at frequencies in the range of 1 kHz carrying a mirror of 500 μm diameter oscillating at frequencies in the range of 16 kHz. The characteristic mechanical amplitudes are 21 degrees and 28 degrees respectively. Voltages of 60 V and 140 V were necessary to accomplish this. Much higher amplitudes have been achieved on the mirror axis without breaking the torsion bars. Initial difficulties in realizing the high amplitudes have been overcome by improving the geometry of the suspension. The initial design is presented as well as the measurement results of the initial and improved amplitudes. The device was used to develop a micro laser camera with high depth of focus. Pictures taken with the system are presented revealing the excellent resolution.

6466-17, Session 4

Update on MEMS-based scanned beam imager

R. A. James, G. Gibson, W. O. Davis, F. Metting, Microvision, Inc.; C. Drabe, Fraunhofer-Institut für Photonische Mikrosysteme (Germany)

In 2004, Microvision presented “Scanned Beam Medical Imager” as an introduction of our MEMS-based, full color scanned beam imaging system. This presentation will provide an update of the technological advancements since 2004. This includes the development of functional prototypes of a Micro Laser Camera. These prototypes are much smaller than previous prototypes and use a design architecture that is easily scalable. Performance has been significantly enhanced by imaging at much larger field of views and at faster refresh rates. Real-time image processing capabilities have been developed to enhance the image quality and functionality over a wide range of operating conditions. Actual images of various objects will be presented.

6466-18, Session 4

Artificial compound eye on a curved basis by laser beam writing

J. W. Duparré, D. Radtke, A. Tünnermann, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany)

Comparing our up-to-date demonstrated artificial compound eye concepts with their natural archetypes the following conclusions can be drawn: The major difference at this stage of development is the planar arrangement of the artificial systems compared to the curved geometry of the natural ones. This is the consequence of our today's limitation to planar lithographic patterning technologies. The advantages of a curved basis compared to a planar one are obvious: The immanence of a large field of view, avoiding of off-axis aberrations, and avoiding of declining illumination with increasing field angle due to the cos^4-law. In order to overcome these limitations we generated microlens arrays and pinhole arrays on curved concetrical surfaces with the difference of radius of curvature of the surfaces matching the microlenses focal length by a special type of laser beam writer. However, up-to-date the fabrication of the corresponding photo detector array on a curved surface with only some mm or cm radius of curvature appears to be difficult. This is why we use conventional relay optics to image the pinhole plane of the curved artificial apposition compound eye objective onto a conventional CCD-camera. The optical design of the compound eye as well as its fabrication by laser beam writing of photoresist-pedestals on a curved surface and subsequent reflow and replication steps are discussed. The final characterization is demonstrated by the evaluation of the obtained compound eye images with respect to resolution, sensitivity and field of view.

6466-19, Session 6

Chip-scale reconfigurable-optical add/drop multiplexer for wavelength routing in telecommunications

J. A. Kubby, Univ. of California/Santa Cruz; J. Chen, J. C. Diehl, K. Feinberg, K. A. German, P. Gulvin, L. Herko, N. Jia, P. Lin, X. Liu, J. Ma, J. Meyers, P. J. Nystrom, Y. R. Wang, Xerox Corp.

This presentation will review the design, development and testing of a chip-scale Reconfigurable-Optical Add/Drop Multiplexer (R-OADM) for wavelength routing in metro-area telecommunications. Arrayed waveguide gratings for multiplexing and de-multiplexing of wavelength division multiplexed signals are integrated with micro-electro-mechanical optical waveguide switches to form a complete optical system on a chip that can be batch fabricated using standard silicon processing.

6466-20, Session 6

Fabrication of micromechanical and micro-optical systems by two-photon polymerization

C. Reinhardt, A. Ovsianikov II, S. Passinger, B. N. Chichkov, Laser Zentrum Hannover e.V. (Germany)

The recently developed two-photon polymerisation technique is used for the fabrication of two- and three-dimensional structures in photosensitive organic-inorganic hybrid materials with a resolution down to 100nm. In this contribution we present applications of this powerful technology for the realization of micromechanical systems and micro- and nano-optical components. We will demonstrate results on the fabrication of complex movable three-dimensional micromechanical parts and microfluidic components which cannot be realized by any other technology. This approach of structuring photosensitive materials also provides the unique possibility for the generation of single and arrays of microoptical components like arbitrary shaped microlenses, microprisms, and 3D-photonic crystals with high optical quality.

6466-22, Session 6

Investigation of a seesaw structure for elevating the micro-optical device by CMOS-MEMS process

C. Tsai, S. Tsai, Y. Huang, Ming Hsin Univ. of Science and Technology (Taiwan)

The paper proposed a novel seesaw structure for elevating the micro optical device by the driving force of micro array thermal actuator, MATA. The effects of elevating structure, lateral connection arm structure, immobile structure and width of vertical connection arm on the maximum displacements and the variation of surface flatness of the elevated micro mirror surface varied with operation voltage are investigated. The out plane motion of micro mirror results in the constraint of the displacement in plane when the operation voltage is applied on MATAs' electrodes of elevating structure. The motion behavior of the elevated micro mirror is stimulated and analyzed to get the maximum displacement and inclined angle of the device. The results demonstrate a pair of {1 x 2} parallel type MATA for the elevating structure, simple beam for the lateral connection arm structure, single MATA for the immobile structure and 10μm for width of vertical connection arm are the optimum design for the micro optical device. The maximum displacement and inclined angle of the proposed micro optical device are 34.7μm and 10° with high quality of surface flatness, respectively. The device is fabricated by Taiwan Semiconductor Manufacture Cooperation, TSMC 0.35μm 2P4M mixed signal model, based upon CMOS-MEMS process and its performance analysis will be shown in the paper.

6466-23, Session 6

Long-term stability of chip-scale atomic clock physics packages

S. Knappe, V. P. Gerginov, V. Shah, H. G. Robinson, L. W. Hollberg, J. E. Kitching, National Institute of Standards and Technology

We present measurements regarding the long-term stability of chip-scale atomic clock (CSAC) physics packages. The tight requirements for the temperature stability of vapor cell and laser in these packages currently limit their frequency stability after 100-1000 seconds. Even with advanced MEMS packaging techniques such as vacuum sealing or thermal insulation, it seems difficult to maintain the required stabilities in small, low-power setups over a large range of ambient temperatures. In order to make CSACs useful devices for portable applications in the area of navigation and communication this problem needs to be addressed.

We present an advanced CSAC setup to relax these requirements and discuss its performance in a microfabricated CSAC physics package. Fabrication of the individual MEMS parts, as well as assembly into a small optical system will be discussed.

6466-24, Session 6

Six-axis complaint mechanisms for manipulation of microscale fiber optics components

S. Chen, M. L. Culpepper, Massachusetts Institute of Technology; S. C. Jordan, Physik Instrumente LP

There is a growing need for multi-axis precision motion control and in growing number of micro optical applications including active alignment of fiber-optic elements, micro-endoscopic scanner, and machine elements for micro-scale machinery. Meanwhile, other applications such as micro-mirrors and micro-optical-resonators will require both multi-axis nano/micro-positioners and extremely flat mirror surfaces.

In this paper, we report/summarize a design concept, prototype device, and dynamic control methods for achieving high-speed six-axis positioning using a micro-scale robotic manipulator with integrated micro-actua-

tors. This manipulator, the Micro-HexFlex, is designed to have the requisite range and force needed to perform useful six-axis alignment/manipulation for small optical elements including but not limited to semiconductor waveguide, diode laser, GRIN lens/prisms, single mode fiber...etc.

Micro-HexFlex of different sizes, including 1mm, 1.2mm, 1.5mm, and 3mm in diameter, were made. They are designed to have a ~4x4x4 μm3 minimum wok volume and ~150 μN force output to compensate the potential ~3μm misalignment from the passive alignment components, for example the extensively used V-grooves. We have experimentally characterized a 3mm MiHx. The quasi-static performance of this prototype shows a maximum range of 7 x 13 x 8 μm and 0.9 x 0.8 x 1.4 degrees. Enhanced dynamic performance of Micro-HexFlex via Input Shaping[TM] and Hyperbit control[R] have also been demonstrated. The results confirm MiHx can be precisely controlled within 10nm at 100 Hz or higher frequencies. The device was manufactured using deep reactive ion etching (DRIE) at a cost of less than $2 dollars per device.

6466-26, Poster Session

Investigation of motion behavior for the opposite connection micro-optical devices by CMOS-MEMS process

C. Tsai, Y. Huang, S. Tsai, Ming Hsin Univ. of Science and Technology (Taiwan)

The motion behaviors of the elevation for a pair of micro mirrors connected in opposite are investigated. The driving force of micro array thermal actuator, MATA, is applied for elevating the micro mirrors. The device design shall be followed Taiwan Semiconductor Manufacture Cooperation, TSMC, 0.35μm 2P4M mixed signal model process design rule. The optimum number of springs and type of MATA are selected by the simulation results. Simple double springs for connecting two mirrors and two pairs of parallel type MATAs for elevating the micro mirrors are the optimum design. The out plane motion of two connected mirrors results in the constraint of the displacement in plane when the operation voltage is applied on MATAs' electrodes. The effects of the position layer of connection springs on the maximum displacements and the surface flatness of the elevated micro mirror surface varied with operation voltage are investigated. The results demonstrate the position of double springs for connecting two micro mirrors is at metal 3, the maximum displacement of elevated micro mirror is the largest. On the other hand, the variation of surface flatness of the elevated micro mirror is relatively significant on the edges where are without any constricted. However, the variation of surface flatness is between 0.2μm and 0.4μm based upon the "U" supporting structure layer at the bottom of mirror in thickness of metal 3. Nevertheless, the variation of surface flatness is improved to below 0.1μm when the thickness of supporting structure layer is increasing by the thickness of metal 2 due to the high rigidity. When the operation voltage is 7V and the size of single micro mirror is 200μm x 200μm with a 'U' supporting structure in thickness of metal 3 and metal 2 layers, the maximum displacement and inclined angle of the proposed micro optical device are 37.4 μm and 10.7o, respectively. The device is fabricated by based upon TSMC CMOS-MEMS process and its performance analysis will be shown in the paper.

6466-27, Poster Session

Improved homogenization of fly's eye condenser setups under coherent illumination using chirped microlens arrays

F. C. Wippermann, P. Dannberg, A. H. Bräuer, Fraunhofer-Institut Angewandte Optik und Feinmechanik (Germany); S. Sinzinger, Technische Univ. Ilmenau (Germany)

Fly's eye condensers are commonly used for the beam shaping of an arbitrary input intensity distribution into that of a top hat. The setup usually consists of a Fourier lens and two identical regular microlens arrays - often referred to as tandem lens array - where the second one is placed in the first microlens' focal plane. The periodic structure of the regular arrays acts as a grating and consequently the output intensity distribution is modulated by equidistantly located sharp intensity peaks.

In a chirped array, the inflexibility of a regular structure has been overcome. Hence, an array can be formed which is non-periodic and consequently the equidistantly located intensity peaks can be suppressed. A far field speckle pattern results with more densely and irregularly located intensity peaks leading to an improved homogeneity of the intensity distribution. In contrast to stochastic arrays, chirped arrays consist of individually shaped lenses defined by a parametric description of the cells optical function which can be derived completely from analytical functions. This gives the opportunity to build up tandem array setups enabling to achieve far field intensity distribution with an envelope of a top hat.

We propose a new concept of a fly's eye condenser incorporating a chirped tandem microlens array for the generation of a top hat far field intensity distribution with improved homogenization under coherent illumination. Consideration for the design of the irregular micro lens arrays and measurements of far field intensity distributions obtained from first prototypes generated by reflow of photoresist are presented.

6466-28, Poster Session

Novel modeling approach for multidisciplinary microdomains

M. Motiee, A. Khajepour, R. R. Mansour, Univ. of Waterloo (Canada)

Planar MEMS are microscopic mechanical devices generally made of silicon or polysilicon layers that are relatively thin. Most batch fabricated MEMS systems require on-chip movement of microstructures. The desired attributes of an on-chip actuator are small chip footprint, large deflection and an electrical requirement compatible with today's CMOS circuitry. MEMS actuators are typically used for either one time deployment of structures for automatic assembly or constant periodic actuation as in case of micro optic scanners. Electro-thermal actuators rely on the joule heating resulting small mechanical expansion of a conductor when a current is passed through it.

In the literature, an extensive research is done on modeling of thermal actuators but the modeling is limited to developing and solving the exact equations of a particular system with limited number of elements. Developing a new finite element formulation is necessary to solve a general multi-disciplinary domain with arbitrary arrangement of boundary conditions and large number of nodes and elements.

This paper, presents a new finite element formulation for automated modeling of multi-disciplinary domains. The electro-thermo-mechanical domain is explained and an algorithmic approach for sequential analysis of an arbitrary ground structure with multi-disciplinary boundaries is developed and implemented using the finite element method.

To solve a specified domain with defined electrical, thermal and mechanical boundary conditions, the constitutive equations of the system in all three domains are derived and discretized into finite number of nodes and elements. The equation of continuity of current is solved by modified nodal analysis method, MNA and the Galerkin's integration is used to integrate the thermoelstic equations over the domain. Thermal effects are included in the formulation in the form of dilatational strains. Moreover, in this paper the phenomena of heat transfer in micro scale for conduction, convection and radiation are studied. Results show that the micro scale heat transfer takes place by conduction, as opposed to convection.

The above automated algorithm is implemented in Matlab and its results are compared and verified with exact solutions and experimental results of the hot arm thermal actuator and Chevron actuator. The agreement of results verifies the application of proposed finite element formulation to the analysis of electro-thermo-mechanical domains.

This new finite element formulation provides a fast and reliable tool to analyze electro-thermoelastic devices. It also enables topology and hot arm placement optimization in thermal actuators.

Conference 6467: MEMS Adaptive Optics

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6467-01, Session 1

MEMS development for astronomical instrumentation at the Lick Observatory Laboratory for Adaptive Optics

D. T. Gavel, Univ. of California/Santa Cruz

The Lick Observatory has been a pioneer in the development of innovative technology for astronomy particularly the development of adaptive optics and laser guidestar systems. The UCO/Lick Observatory Laboratory for Adaptive Optics (LAO) is actively pursuing development of new device technologies and techniques that will enable the next generation of adaptive optics systems for astronomy. The LAO has been developing, in coordination with industry, MEMS deformable mirrors for high speed high precision wavefront control. In this paper we will present the status of the development process and the goals for the future.

6467-02, Session 1

Retinal imaging of mice with an adaptive optics laser scanning opthalmascope

D. P. Biss, R. H. Webb, Schepens Eye Research Institute; Y. Zhou, T. G. Bifano, Boston Univ.; C. P. Lin, Massachusetts General Hospital

Medical research of disease progression often relies upon mouse models, which may involve sacrificing animals at different stages of the disease to be able to study effects over time. This requires statistical studies of disease with large numbers of animals and only provides periodic snapshots of the disease. In vivo retinal imaging is a powerful tool that allows one to follow a single animal over time, but aberrations in the mouse eye limit the best possible resolution that can be obtained.

Adaptive optics has been successful in correcting phase aberrations introduced by the atmosphere in astronomical imaging. This technique has recently been extended to opthalmic imaging in humans. We are using adaptive optics to correct for aberrations introduced by the mouse eye in hopes of achieving cellular resolution retinal images of live mice. In addition to the use of a wavefront sensor to drive the adaptive optic element, we explore the use of image data to correct for wavefront aberrations introduced by the mouse eye. Image data in the form of the confocal detection pinhole intensity are used as the feedback mechanism to control the MEMS deformable mirror in the adaptive optics system. Experimental results are shown.

6467-03, Session 1

Improving two-photon microscope depth penetration with a deformable mirror

J. Mertz, A. Leray, Boston Univ.

Two-photon excitation fluorescence (TPEF) microscopy is a powerful technique to image deep biological living tissue [1]. Given that the TPEF is generated by ballistic (unscattered) light, this technique can provide high resolution images even within scattering media. Recently, it has been shown that the imaging depth in TPEF microscopy is limited to 1000μm in living brain tissue due to the out-of-focus fluorescence background generated at superficial tissue layers [2]. This limitation arises when the surface background fluorescence begins to dominate the deep signal fluorescence generated at the laser focus where the ballistic power has been weakened by scattering.

We present here a simple technique to reduce this out-of-focus TPEF background in scattering tissue. Our technique is based on the use of a deformable mirror to control the phase profile of the near-infrared femtosecond laser beam in the back aperture of the focusing objective. We present a heuristic description of our technique which we corroborate with experimental results. Images of labeled mitral cells in a mouse olfactory bulb are compared with standard TPEF microscopy images, demonstrating significant out of focus TPEF background rejection and better image quality with our technique.

1. W. Denk, J.H. Strickler and W. W. Webb, Science 248 (4951), 73-76 (1990).

2. P. Theer, M. T. Hasan and W. Denk, Optics Letters 28 (12), 1022-1024 (2003).

6467-04, Session 1

Adaptive optics two-photon fluorescence microscopy

Y. Zhou, T. G. Bifano, Boston Univ.; C. P. Lin, Massachusetts General Hospital

Multi-photon fluorescence microscopy has been wildly used in studying cell biology. In recent research, a two-photon fluorescence microscopy (TPFM) was used for vivo imaging of bone marrow environment located at mouse skull. Current technology has been enable one to imaging deep into tissue up to 200micron, which reaches to about half the depth of whole bone marrow, however the full image of bone marrow is desired. The shorter wavelength fluorescence light emission relies on absorption of two photons with longer wavelength simultaneously by a molecule, in other words, the excited fluorescence light is proportional to the quadratic value of average input light intensity. Spherical aberration introduced by tissue is the primary factor limiting necessary light intensity level for fluorescence excitation in deeper tissue imaging. We have developed an adaptive optics two-photon fluorescence microscopy that uses a deformable mirror and real time control system to correct the aberrations of the tissue and improve imaging depth in bone marrow. A MEMS deformable mirror (DM) from Boston University is the enabling component for this system, used as the wavefront corrector. A gradient decent technique is used to control the MEMS DM for real time aberration correction. We are being able to correcting aberration up to 7th order Zernike polynomial, that includes first and second order spherical aberrations.

6467-05, Session 1

Adaptive scanning optical microscope (ASOM): large field of view and high-resolution imaging using a MEMS deformable mirror

B. M. Potsaid, J. T. Wen, Rensselaer Polytechnic Institute

In microrobotic applications and biomedical imaging, the small field of view associated with high resolution microscope systems poses a significant challenge in practice. This paper describes an optical microscope design, called the Adaptive Scanning Optical Microscope (ASOM), which uses a MEMS deformable mirror working with a specially designed scanning lens to achieve a greatly expanded field of view. Most adaptive optics systems (e.g. telescopes and ophthalmology instruments) are designed to exhibit diffraction limited performance under nominal operating conditions and only use the adaptive optics element to compensate for an external time varying disturbance to the wavefront. In contrast to this approach, the deformable mirror in the ASOM is an integral component in the optical system and the static (glass) optical elements have been specifically designed to match the shape correcting capabilities of the deformable mirror. Using a high speed steering mirror coordinated with the deformable mirror actuation voltages, the ASOM operates by scanning over the workspace to achieve diffraction limited imaging over a region approximately two orders of magnitude larger in area than a traditional microscope design. With the rapid scanning capabilities allowed by the

high speed steering mirror and by acquiring a complete n by n pixel image during each exposure, the imaging principle of the ASOM offers certain advantages over a moving stage or confocal based approach. After describing the design and operating principle of the ASOM, we present our latest results associated with both microrobotic and biological applications to highlight the advantages of this new microscope design.

6467-06, Session 1

MEMS membrane mirrors for focus adjustment and aberration correction in endoscopic confocal and OCT imaging instruments

D. L. Dickensheets, Montana State Univ./Bozeman

Optical coherence tomography (OCT) and confocal microscopy are two optical imaging techniques that can deliver cellular and sub-cellular resolution images of human tissues. Recent efforts to realize OCT and confocal microscopy in an endoscopic instrument are driven by the potentially huge clinical impact that real-time interactive imaging of body tissues at the cellular level would have, potentially obviating the need for excisional biopsy in order to diagnose disease. The optical fiber confocal microscope and the fiber-based OCT instrument both rely on beam scanning, and miniature MEMS mirror scanners have been developed to meet this need. In addition to scanning the beam, these instruments must also incorporate a means to adjust the focus of the beam, and this paper will consider the use of deformable membrane mirrors to accomplish both focus control and aberration compensation while meeting the small size limitations of the endoscopic platform. In particular, the distinct optical requirements for large NA imaging typical of confocal microscopy and small NA imaging typical of OCT are developed, and appropriate application of MEMS deformable membrane mirror technology is discussed. Examples of the use of MEMS mirrors for dynamic focus tracking in time-domain OCT and for focus adjustment and correction of spherical aberration in confocal microscopy are presented. The need for large stroke mirrors is emphasized, and recent progress to operate electrostatic membrane mirrors beyond the static “snap-down” limit is presented. Finally, possible synergies between deformable membrane mirrors and other emerging technologies such as variable liquid lenses are assessed.

6467-07, Session 1

Latest developments in adaptive optics: optical coherence tomography

R. J. Zawadzki, Univ. of California/Davis

Adaptive Optics - Optical Coherence Tomography (AO-OCT) demonstrates a promising improvement in lateral resolution for retinal imaging compared to standard clinical OCT. Increased lateral resolution combined with the high axial resolution offered by OCT provides the narrowest to date three dimensional Point Spread Function (PSF) (on the order of ~ 3x3x6 μm3). This is more than 10 times smaller that that offered by any other (non OCT) in vivo retinal imaging techniques including Adaptive Optics - Scanning Laser Ophthalmoscope (AO-SLO) and AO fundus camera. Due to high volumetric resolution of (AO-OCT systems it is possible to acquire images of 3D cellular structures in the living retina. The development of AO-OCT instrumentation at UC Davis will be presented, including its subsystem development (i.e., 3D Fourier domain OCT technology and AO wavefront correcting system). Some of the limitations of AO-OCT instruments, including speed, speckle, chromatic aberration and laser safety will be discussed. Image processing methods and data visualization (including 2D and 3D representations) techniques developed in our group will also be described. Finally, results showing microscopic retinal structures of healthy and diseased eyes as well as directions for future AO-OCT system developments and applications will be presented.

6467-08, Session 2

MEMS adaptive optics, the NRL program: an update

S. R. Restaino, J. R. Andrews, Naval Research Lab.; T. Martinez, Air Force Research Lab.; C. C. Wilcox, Naval Research Lab.

The Naval Prototype Optical Interferometer (NPOI) is the longest baseline at visible wavelengths interferometer in the world. The astronomical capabilities of such an instrument are being exploited and recent results will be presented. NPOI is also the largest optical telescope belonging to the US Department of Defense with a maximum baseline of 435 meter has a resolution that is approximately 181 times the resolution attainable by the Hubble Space Telescope (HST) and 118 times the resolution attainable by the Advanced Electro-Optical System (AEOS). It is also the only optical interferometer capable of recombining up to six apertures simultaneously. The NPOI is a sparse aperture and its sensitivity is limited by the size of the unit aperture, currently that size is 0.5 meters. In order to increase the overall sensitivity of the instrument a program was started to manufacture larger, 1.4 meter, ultra-light telescopes. The lightness of the telescopes requirement is due to the fact that telescopes have to be easily transportable in order to reconfigure the array. For this reason a program was started three years ago to investigate the feasibility of manufacturing Carbon Fiber Reinforced Polymer telescopes, including the optics. Furthermore, since the unit apertures are now much larger than r0 there is a need to compensate the aperture with adaptive optics (AO). Since the need for mobility of the telescopes, compact AO systems, based on MEM devices, have been developed. This paper will present the status of our adaptive optics system and some of the results attained so far with it. We will discuss the integration program of the larger telescopes into the NPOI and the immediate and longer term plans for this facility.

6467-09, Session 2

A novel MEMS reflective wavefront sensor

J. R. Andrews, Naval Research Lab.; S. W. Teare, New Mexico Institute of Mining and Technology; S. R. Restaino, Naval Research Lab.; D. V. Wick, Sandia National Labs.; C. C. Wilcox, Naval Research Lab.; T. Martinez, Air Force Research Lab.; D. M. Payne, Narrascape

Sandia National Laboratory has constructed several segmented MEMS deformable mirrors that are under investigation for their suitability in Adaptive Optics systems for the Naval Research Laboratory. These mirrors are constructed in a hexagonal array and have been constructed with flat surfaces, or with optical power allowing each mirror to bring its subaperture of light to a focus similar to a Shack-Hartman array. Each mirror can use the tip, tilt and piston function to move the focused spots to the desired reference location, and the measurement of the applied voltage can be used directly to power a similar flat MEMS deformable mirror. This paper reports on the suitability of this reflective wavefront sensor for closed loop adaptive optics applications.

6467-10, Session 2

Testbed for the characterization of MEM devices using a liquid crystal aberrator

C. C. Wilcox, J. R. Andrews, S. R. Restaino, Naval Research Lab.; T. Martinez, Air Force Research Lab.; S. W. Teare, New Mexico Institute of Mining and Technology; D. M. Payne, Naval Research Lab.

Micro-electro-mechanical (MEM) devices are becoming more and more popular in the development of Adaptive Optics systems. One popular application of an Adaptive Optics system is compensating the aberrations induced by atmospheric distortions. Using a Liquid Crystal Device and a custom software application written in Matlab, standard atmospheric

simulators can be realized to provide controllable atmospheric distortions. The amount of atmospheric distortions and the speed in which they vary can be controlled using this testbed to determine the amount of correction possible with various MEMs devices. Extremely poor seeing conditions and very good seeing conditions can be replicated to evaluate the behavior of the MEMs devices used to correct the aberrations. Also, using these two devices simultaneously can provide a well-defined quantitative measurement of how well the system corrects because of the fact that the aberrations induced are well known from software and the Point Spread Function after correction can be measured. This paper outlines the development of the testbed and provides results of the integration with an Adaptive Optics system using MEMs mirrors.

6467-11, Session 2

MEMS active optics

D. V. Wick, B. E. Bagwell, Sandia National Labs.; T. Martinez, Air Force Research Lab.; S. R. Restaino, Naval Research Lab.; W. D. Cowan, O. B. Spahn, Sandia National Labs.

MEMS mirrors are becoming increasingly capable as design and electronics development continues to improve device performance and reduce fabrication costs. The recent development of large stroke devices (i.e. greater than 25 microns) has significantly increased the number of potential applications for these devices. These devices are currently being integrated in imaging applications in order to improve the performance and flexibility of the system while simultaneously reducing the size and weight compared to a conventional system. We will present recent progress at Sandia National Laboratories, working with the Naval Research Laboratory, in developing foveated imaging and active optical (aka nonmechanical) zoom using large stroke MEMS mirrors.

6467-12, Session 2

Nonmechanical zoom using MEMS mirrors

B. E. Bagwell, D. V. Wick, O. B. Spahn, W. D. Cowan, Sandia National Labs.; T. Martinez, Air Force Research Lab.; S. R. Restaino, Naval Research Lab.

Zoom imaging systems have been a goal of designers since the early part of the last century. A host of techniques have been employed to achieve the goal of variable magnification while maintaining constant image plane location. With the advent of electronic focal plane arrays has come the proliferation of digital magnification, popular in so many consumer electronic devices. Digital magnification is simply post processing after the image has been captured and provides no increase in information. We will present resent results using MEMS mirrors to achieve true optical magnification without recourse to macro mechanical moving parts-specifically motion between the individual optical elements.

6467-13, Session 2

AO SLM demonstration system and test bed

M. Wildenhain, J. Knobbe, A. Gehner, M. Wagner, Fraunhofer-Institut für Photonische Mikrosysteme (Germany)

In order to demonstrate and to quantitatively evaluate the wavefront correction capabilities of a phase-only SLM for optical imaging enhancement a compact and flexible AO demonstration system and test bed has been developed. It basically consists of a projection system, where objects of different complexity and spatial resolution can be implemented and imaged through adaptive optics onto a CCD camera. Furthermore, static and dynamic wavefront errors of different severeness can be introduced by means of fixed and rotating phase plates. Allowing also a flexible integration of different sensor and corrector devices the system for the first time has been employed together with a 42 x 31 Shack Hartmann wavefront sensor from Optocraft to characterize the capablities of the IPMS 240 x 200 MEMS micromirror device for high-resolution optical wavefront control. Besides a description of the system design and the optical simulations hereto also measurement results on the wavefront error reduction as well as on the obtained imaging improvement are presented.

6467-14, Session 2

Task-based assessment of deformable mirrors

E. M. Daly, E. Dalimier, T. D. Farrell, C. Dainty, National Univ. of Ireland/Galway (Ireland)

What are the factors one must consider when choosing the most suitable deformable mirror for a particular task? Issues such as the mirror stroke, the number and spatial arrangement of actuators, the physical size of the mirror, its ease of use and cost, must all be taken into account. In vision science, one ideally requires a compact device with a stroke that is large enough to correct human-eye aberrations, and that is not too expensive if commercial applications are to be explored. On the other hand, these are not the most important considerations for correction of atmospheric applications on large telescopes.

We have defined our task to be fitting of typical ocular wavefronts as generated by the Thibos model, and we have simulated the capability of six commercially-available mirrors to perform this task. Only static aberrations are considered, and it is assumed that the influence functions add linearly. Our study includes two very different MEMS devices; a 140 channel continuous membrane mirror and a 48,000 pixelated micro mirror array, as well as a magnetically actuated mirror. Our simple model would suggest that no one mirror characteristic alone can be used as an indicator of that mirror's performance for the defined task. For example, if the stroke of a device is large but the actuator influence functions are broad, then that mirror may perform no better than a mirror with much fewer actuators but of more optimal spatial arrangement, each with lower stroke. Devices with many actuators of modest stroke may be best used to correct high-order modes in a system, leaving the gross low-order correction to a large-stroke device.

6467-15, Session 3

The open-loop control of MEMS - modeling and experimental results

D. T. Gavel, K. M. Morzinski, Univ. of California/Santa Cruz

We present a formulation for the precise open loop control of MEMS deformable mirrors. The electrostatic actuators in a discrete actuator device are attached via posts to a thin reflective top plate. The plate itself can be rather accurately modeled by the thin plate equation. The actuators, although nonlinear in their response to applied voltage and deformation, are independent of each other except through forces transmitted by the top plate and can be empirically modeled via a procedure we will describe. In this paper we present the modeling and laboratory results. So far in the lab we have achieved open loop control to 17nm surface accuracy in response to arbitrary commands of 1 micron amplitude. Open loop control enables a wealth of new applications for astronomical adaptive optics instruments, particularly in multi-object integral field spectroscopy, which we will describe.

6467-16, Session 3

Adaptive optics ophthalmologic systems using dual deformable mirrors

S. M. Jones, S. S. Olivier, Lawrence Livermore National Lab.; S. Joeres, Doheny Eye Institute; D. C. Chen, Lawrence Livermore National Lab.; R. J. Zawadzki, Univ. of California/Davis Medical Ctr.; S. Sadda, Doheny Eye Institute; J. S. Werner, Univ. of California/Davis Medical Ctr.; D. T. Miller, Indiana Univ.

Adaptive Optics (AO) have been increasingly combined with a variety of ophthalmic instruments over the last decade to provide cellular-level, in-vivo images of the eye. The use of MEMS deformable mirrors in these

instruments has recently been demonstrated to reduce system size and cost while improving performance. However, currently available MEMS mirrors lack the required range of motion for correcting large ocular aberrations, such as defocus and astigmatism.

In order to address this problem, we have developed an AO system architecture that uses two deformable mirrors, in a woofer / tweeter arrangement, with a bimorph mirror as the woofer and a MEMS mirror as the tweeter. This setup provides several advantages, including extended aberration correction range, due to the large stroke of the bimorph mirror, high order aberration correction using the MEMS mirror, and additionally, the ability to 'focus' through the retina.

This AO system architecture is currently being used in four instruments, including an Optical Coherent Tomography (OCT) system and a retinal flood-illuminated imaging system at the UC Davis Medical Center, a Scanning Laser Ophthalmoscope (SLO) at the Doheny Eye Institute, and an OCT system at Indiana University. The design, operation and evaluation of this type of AO system architecture will be presented.

6467-17, Session 3

Design of a MEMS laser guide star pulse tracker

O. A. Azucena, Jr., J. A. Kubby, Univ. of California/Santa Cruz

Adaptive optics improves the quality of astronomical imaging systems by using real time measurement of the turbulent medium in the optical path. The measurements are then taken and applied to a deformable mirror that is in the conjugate position of the aberrations in the optical path. The quality of the measurement directly affects the quality of the imaging systems. Poor measurements translate to poor corrections and as a result bad images. In astronomical imaging, telescopes are equipped with high power lasers that produce a guide star (Laser Guide Star, LGS) by exciting a sodium layer 90 kilometers above the sea level. The LGS is used as a reference to measure the random optical path differences produced by the atmosphere. The image of the LGS viewed at the wavefront sensor is circular but as the separation between the launch telescope and the wavefront sensor subaperture increases, the spot begins to elongate. The elongation of the spot increases the uncertainty of the measurement. In one possible solution to this problem, a pulsed laser can be used and a device can be added in front of the wavefront sensor that tracks the laser pulse as it travels through the sodium layer. We have designed a Micro-Electro-Mechanical tip tilt mirror that will follow the laser guide star light as it travels through the sodium layer. The tip/tilt mirror was designed to conform to the PolyMUMPs process, a 3 layer polysilicon surface micromachining process. While the mirror can be designed with only one degree of freedom we have chosen to include both tip and tilt to increase the flexibility of the device. The pattern we have chosen resembles that of a Fresnel lens which will be controlled to act as a dynamic refocusing system.

6467-18, Session 3

A model-based approach to wavefront sensorless adaptive optics

M. J. Booth, Univ. of Oxford (United Kingdom)

One of the simplest implementations of adaptive optics requires an adaptive correction element and a single photodetector. Aberration measurement is performed by the sequential application of chosen aberrations using the correction element and appropriate processing of the corresponding photodetector intensity measurements in order to maximise the detector signal. These wave front sensorless adaptive optics systems have been demonstrated in many applications, which have included confocal microscopy, intra-cavity aberration correction for lasers, fibre coupling and optical trapping. The maximisation procedure, the choice of the applied aberrations and the processing of the intensity measurements must be optimised if the system is to work efficiently. Much work in this area has used model-free, stochastic methods where parameter optimisation was performed empirically, but further insight can be obtained through an appropriate mathematical representation. Often, optimum parameters can be calculated directly, rather than empirically. This approach is illustrated using simple deterministic methods, such as exhaustive search and hill-climbing algorithms. A direct maximisation algorithm has been introduced that permits the measurement of N Zernike modes with only N+1 intensity measurements for small magnitude aberrations. By expanding the aberration as a series of Lukosz polynomials, functions derived from the Zernike polynomials, and employing a detector with spatially varying sensitivity, this approach is extended to cover arbitrarily large aberrations. This approach permits, for example, the global optimisation of deformable mirror shape using the fewest intensity measurements.

6467-19, Session 3

Closed-loop experiment of double deformable mirrors adaptive optics system for phase compensation

S. Hu, Institute of Optics and Electronics (China) and Univ. of Electronics Science and Technology of China (China); S. Chen, B. Xu, P. Yang, Institute of Optics and Electronics (China); J. Wu, Univ. of Electronic Science and Technology of China (China); W. Jiang, Institute of Optics and Electronics (China)

For conventional adaptive optics (AO) system, one DM can not meet the needs of large scale and high order aberration compensation. In this paper, a double DM is presented, which requires decoupling of the two DMs. In a double DM adaptive optics (AO) system, the decoupling algorithm of two DMs, where the stroke of one DM is large and the spatial frequency of the other DM is high, is deduced. According to the algorithm, the large stroke deformable mirror (LSDM) corrects only the low order aberration, and the high spatial frequency DM (HSFDM) corrects the other aberration. The experimental result for a two 61-DM AO system, in which one DM is used for correcting defocus and the other DM for high order abberation, is presented. The result indicates that the compensation result of a double DM AO system is almost the same as that of the conventional AO system using single DM with ideal stroke and equivalent spatial frequency.

6467-20, Session 4

Recent advances in MEMS deformable mirror technology

P. A. Bierden, Boston Micromachines Corp.

With the current expansion in the use of adaptive optics for industrial and medical applications, the demands on the wavefront corrector has also increased. This paper will discuss how the project team has been developing new devices and manufacturing processes to meet these needs, including increasing stroke, expanding actuator count, and improving surface quality. Current designs, modeling, and test results will be presented

6467-21, Session 4

Piston-tip-tilt positioning of a segmented MEMS deformable mirror

M. A. Helmbrecht, Iris AO, Inc.; T. Juneau, SiTime Corp.

The relationship between the shape of a continuous-facesheet deformable mirror (DM) and actuator control voltages is complicated because of the nonlinear electrostatic forces and mechanical coupling. In contrast, the position-versus-voltage relationship for a segmented DM is much simpler as there is no interaction between adjacent segments. As a result, models that relate segment position in piston, tip, and tilt to actuator control voltages can fit to within nanometers and microradians.

We have developed a piston/tip/tilt controller for the Iris AO segmented MEMS DM that simplifies DM control for the user by converting from

piston/tip/tilt commands to actuator control voltages. The controller also incorporates limiting to prevent snap-in failures prevalent with electrostatically actuated MEMS devices. Open-loop DM flattening with this controller results in segments that are positioned within 7 nm rms for piston and 17 μrad rms and 12 μrad rms for tip and tilt respectively. In this paper, we define the space of reachable DM positions and present experimental open-loop positioning results for the controller over the reachable space. We detail error bounds over the DM segment reachable space as well.

6467-22, Session 4

First results in application for the MIRAO 52 D a new type of MOEMS deformable mirror

E. Lavergne, X. Levecq, J. Ballesta, S. Bucourt, Imagine Optic (France)

A new generation of deformable mirror was born 2 years ago thanks to the LAOG (Laboratoire d'Astrophysique de l'Observatoire de Grenoble - CNRS), Imagine Optic and Imagine Eyes joint development.

Based on a magnetic actuation this technology offers very interesting performances such as a ± 50μm stroke, a 98% linearity, no hysteresis and a high density of actuators.

In this article we will present first results obtained in microscopy and high power ultra short pulsed laser after having made a global review on the performances of this new technology.

6467-23, Session 4

Novel development of tiny bimorph mirrors

A. V. Kudryashov, Night N (opt) Ltd. (Russia); V. V. Samarkin, Institute on Laser and Information Technologies (Russia); T. Cherezova, A. S. Sobolev, M.V. Lomonosov Moscow State Univ. (Russia)

The presentation will give the idea of advantage of the use of small aperture multy element bimorph wavefront correctors and show their application in different adaptive systems of laser beam control and imaging ones.

6467-24, Session 4

Electrostatic polymer-based microdeformable mirror for adaptive optics

F. Zamkotsian, Lab. d'Astrophysique de Marseille (France); V. Conedera, Lab. d'Analyse et d'Architecture des Systèmes (France); A. Liotard, P. Lanzoni, Lab. d'Astrophysique de Marseille (France); N. Fabre, H. Camon, Lab. d'Analyse et d'Architecture des Systèmes (France)

Next generation astronomical instrumentation relies on the availability of highly performing adaptive optical (AO) systems. These systems require deformable mirrors with up to 250 000 actuators and 500μm inter-actuator spacing. MOEMS-based devices are promising for the development of a complete generation of new deformable mirrors.

We are currently developing a MDM based on an array of electrostatic actuators with attachments to a continuous mirror on top. The originality of our approach lies in the use of polymer structural materials. Active actuators have already been demonstrated, with a piston motion of 2μm for 30V and a resonance frequency of 6.5kHz, well suited for AO applications. We have attached on top of an array of 4x4 actuators a continuous mirror based on the same polymer material as the actuators with a print-through on the mirror below 3μm. Reduction of stress in the polymer and metal layers would flatten the device.

The electrostatic force provides a non-linear actuation, while AO systems are based on linear matrices operations. For this reason, we have developed a dedicated 14-bit electronics in order to "linearize" the actuation. After calibrating the behavior of the actuator and fitting the curve by a sixth order polynomial, the electronics delivers a linearized output. The response is nearly perfect over a 3x3 MDM prototype we have realized at Memscap foundry with a standard deviation of 3.5nm. Influence functions have also been determined with high accuracy.

6467-25, Session 4

Compact large-stroke piston tip-tilt actuator and mirror

W. Noell, Univ de Neuchatel (Switzerland); A. Hugi, S. Waldis, N. F. de Rooij, Univ. de Neuchatel (Switzerland); T. Overstolz, R. P. Stanley, Ctr. Suisse d'Electronique et de Microtechnique SA (Switzerland)

A compact stress-compensating piston/tip-tilt actuator and mirror design was fabricated and characterized that provides both optically flat surfaces and large vertical displacement. The actuators can be arranged in arrays to serve as an actuator for deformable-mirror membranes. The device is based on integrated vertical asymmetric comb-drive actuators, which provides a very small additional footprint. The suspension beams are curved around the central platform/mirror and compensate for lateral stress introduced by the substrate or the packaging. The springs provide a high stiffness against in-plane rotation, but are very flexible for out-of-plane actuation. Hence the problem of in-plane snap-in is avoided which is often seen with vertical comb drive actuators. The device fabrication is based on a self aligned two-heights deep reactive ion etching (DRIE) process on silicon-on-insulator (SOI) wafers with a 75 μm thick device layer. Various designs and sizes have been fabricated and evaluated. The typical vertical stroke of the central platform is theoretically about half of the device layer, in our case we achieved 20 μm of vertical displacement. The typical device diameters range from around 600 μm to about 1.2 mm. When using the central platform as a mirror, its surface stays optically flat over a large static displacement. During a dynamical measurement at 250 Hz we noticed only little warp. This is due to considerable different heights and hence stiffness of the suspension beams in respect to the central platform. Suitable applications are tunable optical-cavity devices (lasers, filters, etc.), beam steerers and scanners, and deformable mirrors.

6467-26, Session 4

CMOS integrable micromirrors with highly improved drift-stability

J. Schmidt, A. Gehner, J. Knobbe, Fraunhofer-Institut für Photonische Mikrosysteme (Germany)

The large-scale integration of analog operable MEMS micromirrors onto active CMOS address circuitry poses several challenges to the mirror fabrication technology. On one hand it must be CMOS compatible and on the other hand it has to enable both high quality optical surfaces together with a high analog deflection reproducability, i.e. not compromised by drift or creep effects. However, in conventional CMOS integration major impediments are given by the limited range of suitable materials and the available temperature budget. As one possible option the heterogeneous integration of highly elastic materials like mono-Si might be considered, e.g. by means of layer transfer bonding. Opposed to that, within this paper a new approach of low-temperature monolithic integration of creep-resistant TiAl mirror actuators is presented. Many crystalline materials are subject to relaxation effects (creep) caused by a displacement of grain boundaries when put under mechanical stress. The glassy structure of TiAl prevents this mechanism and contributes to its elastic behaviour. For first technology demonstrations 40 μm piston-type micromirrors have been implemented onto CMOS compatible substrates with fixed wired electrode arrays. Using a one-level mirror design, a 300 nm thick TiAl actuator core has been symmetrically coated with 25 nm thin Al films to ensure both a high reflectivity as well as a temperature-insensitive high planarity. With those devices a mechanical drift of about 3% at 500 nm static piston deflection has been observed with no residual imprinting after switch-off. Even further improvements might be obtained when changing to a

two-level design with separate pure TiAl hinges and a separate mirror plate. TiAl actuators therefore represent a promising approach for a monolithical mirror integration offering the perspective for a stable analog operation, which is essential to many applications especially in adaptive optics.

6467-27, Session 4

Nanolaminate deformable mirrors of multiple size-scales

A. P. Papavasiliou, Lawrence Livermore National Lab.

This paper will describe two nanolaminate-based deformable mirrors with electrostatic actuators fabricated with the same technology that have an order of magnitude difference in size-scale. The mirrors take advantage of the high optical quality and high material strength of nanolaminate foils and the batch fabrication and dense actuation of electrostatic actuators.

The mirrors are fabricated of three horizontal layers separated by electroplated nickel ridges and posts. The actuator is formed by bonding a continuous nanolaminate foil on top of ridges electroplated on a stiff silicon base layer. The mirror is attached by bonding posts on the bottom of the mirror surface to the top of the actuator. Since all of the vertical dimensions are defined by thin film processes, electroplating and sputter deposition, they can be held small regardless of the horizontal size scale. The horizontal dimensions are defined by technologies appropriate for the size scale. It will be shown that the sensitivity to horizontal errors scales with actuator pitch. Thus large-scale devices with larger lithography errors are less sensitive to those errors.

Two different scale deformable mirrors have been made in this technology. The large-scale mirrors, designed to be scalable up to 1 meter diameter have a pixel spacing of 9mm. We have demonstrated a 76-pixel array with 10-pixels across. The mirror fabrication has been completed and deflection data will be presented

The high-density mirrors have a pixel spacing of 1.255mm. We have fabricated a 1024 pixel 32x32 array and demonstrated deflection.

6467-28, Session 4

Design, processing, and materials for large-stroke actuators

B. R. Fernandez, J. A. Kubby, Univ. of California/Santa Cruz

Adaptive optics (AO) applications in astronomy and vision science require deformable mirrors with larger stroke, higher packing density and at lower cost than currently available technology. The use of high-aspect ratio Micro-Electro-Mechanical Systems (MEMS) processing techniques to fabricate large-stroke actuators that can meet stroke, packing density and cost specifications for AO applications have been explored. Different actuator designs, materials and post-processing procedures fabricated in two different high-aspect ratio processes have been investigated. These manufacturing processes allow high-precision multilayer fabrication, and both parallel plate and comb drive actuator deformable mirror designs have been created. Multilayer fabrication has reduced pull-in voltage requirements for large stroke actuators. The design, modeling and simulation of these actuators are compared to experimental measurements of their pull-in voltages, which characterizes their stiffness and maximum stroke. Test structures are used to characterize the mechanical properties of the thin films used to fabricate the actuators.

6467-29, Session 4

Large-stroke self-aligned vertical comb drive actuated micromirror arrays for adaptive optics applications

E. J. Carr, S. S. Olivier, Lawrence Livermore National Lab.; O. D. Solgaard, Stanford Univ.

A high-stroke micromirror array was designed, modeled, fabricated and tested. Each pixel in the 4x4 array consists of a self-aligned vertical comb drive actuator that has had a single-crystal silicon mirror successfully bonded to it. Two different bonding technologies were used, photoresist bonding and fusion bonding. The results of each of these bonding methods will be presented. Analytical models combined with CoventorWare(r) simulations were used to design these elements that would move up to 10 microns in piston motion with 200V applied. Devices were fabricated according to this design and difference measurements performed with a white-light interferometer demonstrated a displacement of 0.18 microns with 200V applied. Further investigation revealed that fabrication process inaccuracy led to significantly stiffer mechanical springs in the fabricated devices. The increased stiffness of the springs was shown to account for the reduced displacement that was observed. Resonance frequency measurements were also performed on these completed devices. A resonance frequency of 22.7 kHz was observed, which agreed with the analytical modeling that was performed on this device.