MOEMS-MEMS 2006

Micro & Nanofabrication

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Micro/Nanofabrication

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Conference 6109: Micromachining and Microfabrication Process Technology XI

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6109-01, Session 1

Injection molded microfluidic devices for biological sample separation and detection

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We are developing a variety of microsystems for the separation and detection of biological samples. At the heart of these systems, inexpensive polymer microfluidic chips carry out sample preparation and analysis. Fabrication of polymer microfluidic chips involves the creation of a master in etched silicon or glass; plating of the master to produce a nickel stamp; large lot chip replication by injection molding; precision chip sealing; and chemical modification of channel surfaces. Separation chips rely on insulator-based dielectrophoresis for the separation of biological particles. Detection chips carry out capillary gel electrophoresis to detect fluorescent tags that identify specific biological samples. Since the performance and reliability of these microfluidic chips are very sensitive to fluidic impedance, electromagnetic flux, and zeta potential, the microchannel dimensions, shape, and surface chemistry have to be tightly controlled during chip fabrication and use. In this talk, we will present an overview of chip design, fabrication, and testing. Dimensional metrology data, surface chemistry characterization, and chip performance data will be discussed in detail.

6109-02, Session 1

Nanofabrication of electrochemical probes for single cell analysis

R. J. Fasching, S. Bai, F. Prinz, Stanford Univ.

Needle shaped probes with a dual electrode system in submicron size have been developed for electrochemical analyses of living single cells. In particular, the probe system is designed for local probing of the cytosolic cell environment and cell organelles using amperometric, potentiometric and impedance spectroscopic methods.

Silicon nitride cantilevers with an electrode metal layer system are fabricated on four-inch wafers using conventional micro fabrication techniques. The probe needle structures with a tip in sub micron scale are patterned using Focus Ion Beam (FIB) technology. A focused ion beam is utilized to write the probe needle shape into the pre-shaped cantilever and, for a dual electrode system, the probe is divided into two parts to create two separate electrodes. Subsequently, the needle structures are released from the supporting bulk silicon during a wet etching step, and a silicon nitride layer is deposited to isolate and embed the electrode metal layer. Finally, FIB milling is used for a precise exposure of the buried metal layer by cutting the top of the tip.

Single as well as dual probe systems were fabricated with Ag/AgCl electrodes for potentiometric and impedance spectroscopy measurements and with platinum electrodes for amperometric probing. Electrochemical characterization of probes showed full functionality of both transducer systems.

Initial measurements of cell membrane potentials and cell membrane impedance of rat fibroblast cells using Ag/AgCl electrode probes demonstrate the analytical capability of these probes in biological environments.

Applying the fabrication schema to pre-etched wafer surfaces results in bended silicon nitride probes. These probes with their high aspect ratio tip, low spring constant of the silicon nitride layer, and nano scale dual electrode system allows for simultaneous Atomic Force Microscopy (AFM) and electrochemical analyses.

6109-03, Session 2

Fabrication of three-dimensional near-IR photonic crystals using deep-UV contact photolithography and silicon micromachining

B. S. Citla, S. Venkataraman, J. Murakowski, G. J. Schneider, D. W. Prather, Univ. of Delaware

We report our progress in the fabrication of three-dimensional photonic crystals (PhCs) to operate at near-infrared (IR) wavelengths using conventional planar silicon micro machining. The method involves patterning a single layer of planar etch mask and a custom etch process to create a three-dimensional array of spherical voids. The etch mask is patterned in Polymethyl methacrylate (PMMA) using a conventional contact Deep UV photolithography system and then transferred to a silicon dioxide hard mask. The three-dimensional spherical voids are fabricated using a sequence of etching and passivation steps. In this custom etch process performed in a fluorine-based inductively coupled plasma-etching system, first a layer of spherical voids is created. Then, the spherical voids are passivated by dry silicon oxidation. A subsequent anisotropic removal of oxide at the bottom of the sphere is achieved by high energy ion bombardment thus enabling the creation of etch mask for the successive layers. A plasma chemistry with high selectivity to oxide is utilized for opening the subsequent layer of spherical voids. By repeating these steps, buried three-dimensional array of spherical voids is obtained. This way a three-dimensional structure with simple cubic symmetry can be obtained from an etch mask initially patterned with a square lattice of circular holes. Our fabrication method has various advantages as it is based on the well-established CMOS mass fabrication technology, which has high yield, reproducibility and is compatible with the next generation optoelectronic circuits. This method is also cost effective and avoids the usage of complex procedures like layer-by-layer fabrication, interferometric lithography or self-assembly for the fabrication of three-dimensional PhCs to operate in near IR.

6109-04, Session 2

Assembled Fourier transform microspectrometer

J. Sin, W. H. Lee, D. Popa, H. E. Stephanou, The Univ. of Texas at Arlington

Microassembly process plays a key role in building 3-dimensional MEMS structures. This paper presents a miniaturized Fourier transform spectrometer (FTS) implemented by combining silicon micromachining and microassembly techniques. The FTS is based on a Michelson interferometer where a scanning mirror mechanism creates an interferogram, and the recorded interferogram is converted to a spectrum by Fourier transform. The Michelson interferometer is implemented on a microoptical bench, which is fabricated using Deep RIE process on a SOI wafer. Key components of the FTS optical bench are a linear moving stage, mechanical assembly sockets, and assembled mirrors. An electrothermal actuator with stroke amplification mechanism provides amplified scanning motion of a moving mirror. The sockets are female mechanical flexure structures that allow a precise snap-fit assembly with micromachined silicon mirrors. The dimension of the FTS optical bench is 1cm^2, and its embedded thermal actuator has a couple of V-beam structures whose beam length is 1mm. The mirror is a deep RIE micromachined structure with reflection area 500x450 micron and 750 micron long flexure structures for pick and place assembly. The flexure structure allows large deflection so that a microgripper can pick up the mirror by inserting the gripper tip into the structure, and snap-fit assemble it into the mechanical socket of the bench. Spectrum result showed a peak around 632nm with

FWHM (Full Width Half Magnitude) 25nm approximately when He-Ne laser was used.

6109-05, Session 2

Polymer-based Fabry-Perot filter integrated with 3D MEMS structures

P. Zhang, K. Le, S. M. N. Rao, L. Hsu, J. Chiao, The Univ. of Texas at Arlington

Polymers have been considered as one of the most versatile materials in making optical devices for communication and sensor applications. They provide good optical transparency to form filters, lens and many optical components with ease of fabrication. They are scalable and compatible in dimensions with requirements in optics and can be fabricated on inorganic substrates, such as silicon and quartz. Recent polymer synthesis also made great progresses on conductive and nonlinear polymers, opening opportunities for new applications.

In this paper, we discussed hybrid-material integration of polymers on silicon-based microelectromechanical system (MEMS) devices. The motivation is to combine advantages of demonstrated silicon-based MEMS actuators and excellent optical performance of polymers. We demonstrated the idea with a polymer-based out-of-plane Fabry-Perot filter that can be self-assembled by scratch drive actuators. We used a fabrication foundry service, MUMPS (Multi-User MEMS Process), to demonstrate the feasibility and flexibility of integration. The polysilicon used as the structural material for construction of 3-D framework and actuators has high absorption in the visible and near-infrared ranges. Previous efforts using polysilicon layer as optical interfaces suffer from high losses. We applied the organic compound materials on the silicon-based framework within the optical signal propagation path to form the optical interfaces. In this paper, we have shown low losses in the optical signal processing and feasibility of building a thin-film Fabry-Perot filter. We will discuss the optical filter designs, mechanical design, actuation mechanism, fabrication issues, optical measurements, and results.

6109-06, Session 2

An optical scanner based on electromagnetically actuated optical fiber

H. P. Hu, K. D. Le, J. Chiao, The Univ. of Texas at Arlington

To meet the performance requisites for some applications, which require small sizes, precise optics, low power consumption and non-electrical control in the devices, an optical fiber scanner using electromagnetic actuation has been developed. This paper acquaints a compact external magnetic field actuated fiber optic scanner, in which the main structure is an optical fiber coated with nickel magnetic gel. The advantages of device architecture are: (1) the scanner dimensions are in the same scales of an optical fiber diameter, (2) optical properties and information are well preserved in the fiber, and (3) the actuation control is external and requires no electrical wiring in scanner design and zero power consumption. Magnetic properties of the nickel based ferromagnetic gel were measured in order to carry out the theoretical calculations of static response and resonant frequencies. With the dynamic waveforms of input signals and output signals from the position sensing device at both modes of resonant frequencies, we conclude that it is significant to operate at the resonant frequencies so that the scanner requires the minimal power to reach large displacement and the oscillating motion of the scanner is purely sinusoidal. A simple and versatile rotary gel coating technique, static and dynamic performance characterization and potential applications of the fiber scanner will be discussed. Moreover, we will also discuss the practical issues in operation and possible waveform distortion that affects imaging and display quality.

6109-07, Session 2

Enhancement of structural stiffness in MEMS structures

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Many optical applications required micromirror reflective surfaces with good flatness and large radius of curvature. Usually when using surface micromachining technology and as a result of residual stress and stress gradient in thin films, the control of residual curvature is a difficult task.

In this work, two engineering approaches were developed to enhance structural stiffness of micromirrors: 1) by integrating stiffening structures and thermal annealing ; 2) by combining selective electroplating and flip-chip based technologies. The stiffening structures consist of U-shaped profiles integrated with the mirror (dimension 200x300 um2). With this approach, typical curvature radii of about 1.5 cm and 0.6 cm along mirror width and length were obtained, respectively. In the second approach, Nickel is used as electroplated material with optimal stress values around ±10 MPa for layer thicknesses about 10 um. With this approach, important improvement in the micromirror flatness was achieved with curvature radius up to 23 cm and roughness lower than 5 nm rms for typical 1000x1000 um2 micromirrors.

6109-08, Session 2

Process design and tracking support for MEMS

A. Wagener, J. Popp, Univ. of Siegen (Germany); D. Ortloff, Cavendish-Kinetics B.V. (Netherlands); T. Schmidt, K. Hahn, R. Brueck, Univ. of Siegen (Germany)

In microsystem technology, especially in the area of silicon-based non-electronic devices, the design is dominated by the fabrication of the devices. In contrast to micro electronics there is no possibility for Mead/Conway-abstraction. That is why most commercially available design frameworks are limited to the behavioral-driven and more abstract design.

Unlike in micro electronics the configuration of MEMS process step sequences and therefore the fabrication have a strong impact on the functionality of the system. The system designer has to take into account the fabrication process sequence while designing a micro system. To do so the designer has to have an extended knowledge of manufacturing processes and technology. In this paper we present a modular software suite dedicated to silicon thin-film process design for MEMS that supports the design as well the tracking of microsystems. On the one hand the suite provides a management and design module. This module allows the management of all data and information relevant to MEMS fabrication process steps, i.e. materials, parameters, and documents. Furthermore complete process sequences can be assembled using those data. On the other hand a sophisticated tracking module allows the tracking of the designed process steps and sequences running through a fabrication line. The module is based on the idea to build a system for managing and tracking of one or more information entities (e.g. process steps, process sequences, experiments, lots, artifacts) where additional ones can easily be added.

6109-09, Session 2

Fabrication of integrated light guiding plate for backlight system

Z. Chen, C. Chien, Tatung Univ. (Taiwan)

A Traditional LCD backlight system is consist of light sources, a light guiding plate and prism sheets, diffusion sheets and reflection sheet. Following the development of the thin LCD, modify the backlight system which has already become the trend. The light guiding plate is very important element in backlight unit which is usually made of Polymethyl methacrylate (PMMA). Generally, the light guiding plates is fabricated by injection

molding. MEMS and hot embossing technologies are applied to fabricate the integrated light guiding plate in this research. The micro-prisms, the micro pyramids and Al thin film are based on the integrated light guiding plate which is guiding light to the LCD panel evenly. So the backlight system will be simplified to use only one integrated light guiding plate without using any optical sheets. The light guiding plate can reduce three optical sheets in backlight, so it can save the space and lower the process cost. Non-prism LGPs and integrated LGPs are presented in this paper.

6109-11, Session 3

Advancing three-dimensional MEMS by complimentary laser micromanufacturing

J. A. Palmer, J. D. Williams, T. Lemp, Sandia National Labs.; F. R. Medina, R. B. Wicker, The Univ. of Texas at El Paso

This paper describes improvements that enable engineers to create three-dimensional MEMS in a variety of materials. It also provides a means for selectively adding three-dimensional, high aspect ratio features to pre-existing PMMA micro molds for subsequent LIGA processing. This complimentary method involves in situ construction of three-dimensional micro molds in a stand-alone configuration or directly adjacent to features formed by X-ray lithography. Three-dimensional micro molds are created by micro stereolithography, an additive rapid prototyping technology. Alternatively, three-dimensional features may be added by direct femtosecond laser micro machining. Parameters for optimal femtosecond laser micro machining of PMMA at 800 nanometers are presented. The technical discussion also includes strategies for enhancements in the context of material selection and post-process surface finish. This approach may lead to practical, cost-effective 3-D MEMS with the surface finish and throughput advantages of X-ray lithography. Accurate three-dimensional metal microstructures are demonstrated. Challenges remain in process planning for micro stereolithography and development of buried features following femtosecond laser micro machining.

6109-12, Session 3

Microstereolithography production of integrated Hadamard mask structures

C. J. Robinson, L. M. Southwell, J. A. Palmer, B. Chavez, M. W. Smith, M. B. Sinclair, Sandia National Labs.; F. Medina, R. B. Wicker, The Univ. of Texas at El Paso; B. Stucker, Utah State Univ.

The use of modern microstereolithography technology gives optics developers the freedom to integrate mounting and positioning structures directly into an optical mask assembly. Hadamard spectrometer masks have been created using the Sony SCS 6000 stereolithography apparatus (SLA) with increments of 150 microns and less. Due to laser over cure and other parameters, adjustments were made iteration by iteration until appropriate mask tolerances were met. A mounting structure was built directly onto the mask for testing or actual application. At a CAD level the mounting structure can be adjusted to fit any specific mounting apparatus. Through using the SC 6000, features as small as 75 microns and larger than 300 mm can be created in the same build. Additionally, the conceptual design of an entire positioning system that can be built using an SLA is underway. This positioning system will be able to be built as an integrated assembly encapsulating necessary components. Test results of the optical properties of such a mask will be presented.

6109-14, Session 3

Optical analysis of scanning microstereolithography systems

S. P. Deshmukh, P. S. Gandhi, S. K. Dubey, Indian Institute of Technology Bombay (India)

Microstereolithography (MSL) is rapidly developing technique for microfabrication. Vector by vector scanning MSL has a potential to create true 3D micro-devices as compared conventional VLSI techniques. Previous literature shows two different scanning methods :(1) Galvanomirror scanning, (2) Photoreactor tank scanning. Galvanomirror scanning technique has higher fabrication speed but poor resolution because of defocusing of laser spot on the resin surface. Photo-reactor tank scanning has higher resolution but produces a wavy structures and limited speed of fabrication. This paper proposes and develops a scanning technique for MSL and carries out optical analysis to compare its performance with the existing techniques mentioned above. The comparison clearly demonstrates improved performance with the proposed scanning technique.

6109-15, Session 4

High-aspect-ratio plasma etching of bulk lead zirconate titanate

S. S. Subasinghe, S. A. Tadigadapa, The Pennsylvania State Univ.

There is a growing need and interest in micromachining alternative materials such as lead zirconate titanate (PZT), lithium niobate, quartz etc. Recent development in high density plasma equipment and chemistries allow for etching these materials with high etch rates and aspect ratios. In this paper, we will present a fluorine chemistry based high aspect ratio etching of bulk PZT substrates using an inductively coupled plasma reactive ion etching (ICP-RIE) system. Figure 1 shows a schematic diagram of the ICP-RIE etcher with the five process parameters that were controlled during the design of experiments. The goal of this work is to achieve high etch rate (~0.3 μm/min) and high aspect ratio etching (\>10:1) in bulk PZT substrates.

6109-16, Session 4

Fabrication of micro-chambers and enclosures using synchronous localized electro-deposition

R. A. Said, United Arab Emirates Univ. (United Arab Emirates)

This work presents further development of the capabilities of localized electro-deposition technology to enable the fabrication of complex micro-structures. In this technology, a conducting tip at the end of a microelectrode is placed close to a conducting substrate while both immersed in an electrolyte containing ions to be deposited (Cu2+ in this work). The application of electric potential between the microelectrode and the substrate causes a faradic current to flow, thus resulting in a localized deposition of the metal ions over a region that has the same extent as the tip. Three dimensional structures are realized by displacing the electrode tip upon sufficient deposition at the current location.

The presented work proposes the synchronization of deposition activities with the electrode positioning to allow the controllable fabrication of arbitrary shaped micro-structures. Although the proposed method is capable of free forming of micro-structures, the method is demonstrated for the fabrication of micro-chambers and enclosures. In the presented work, the synchronized electrode positioning is implemented in two modes using continuous and stepping displacement algorithms.

In the stepping displacement algorithm micro-structures are treated as a stack of lateral trajectories, where each trajectory is formed by deposited dots side by side. In this mode of operation, the electrode is moved from a point on the lateral trajectory to a neighboring location only upon sufficient deposition at the current location. The continuous electrode displacement algorithm, however, allows deposition at all points along the active trajectory while the electrode is in motion along the same trajectory. Deposition quality, characteristics, and required deposition time resulting from both algorithms are compared as extracted from SEM images of deposited structures.

6109-17, Session 4

Enhanced filling of interconnect deep trenches using forced convection magneto-electroplating

R. A. Said, United Arab Emirates Univ. (United Arab Emirates)

The ability to fill interconnect trenches as narrow as 50 nm with a height to width ratio as great as 10:1 is crucial for the development of next generation of integrated circuits. The filling of such deep cavities is the only viable technology to fabricate interconnections for on-chip, wafer level, and chip packaging (widths ranging from hundreds of micrometer down to sub-micrometers). Currently filling of deep trenches and cavities is accomplished by copper electro-less plating technology since it can provide super-conformal deposition into narrow trenches without porosity. Since electro-less plating relies on chemical agents to activate the oxidation-reduction half reactions; special electrolytic paths must be used. This poses a challenge to the fabrication of narrower trenches, and thus requires the development of other deposition schemes.

The presented work proposes an alternative solution to the filling of deep trenches that eliminates the difficulties outlined above, using a forced convection magneto-electroplating method that has been conceptually demonstrated very recently. The technique operates as in typical electrolysis processes, however, with forcing the flow of the plating electrolyte, by hydro-dynamic means, in the presence of an externally applied magnetic field. This arrangement introduces a Lorentz type of force that enhances the transport of deposit species toward desired locations, such as deep regions in trenches and via structures. The induced Lorentz force magnitude is at least one order of magnitude stronger than typical forces affecting mass transport, and thus would overcome mass transport opposing forces. Efficiency of the proposed technique is demonstrated by SEM images of interconnect trenches filled by stagnant electroplating arrangement and the proposed forced convection magneto-electroplating method.

6109-18, Session 4

Anisotropic etching of single crystalline SiC using molten KOH for SiC bulk micromachining

K. Fukunaga, J. Suda, T. Kimoto, Kyoto Univ. (Japan)

MEMS devices made of single crystalline SiC are attractive for applications in harsh environment, because SiC is chemically inert and electrically stable at high temperature. Due to its chemical inertness, controllable etching of SiC has been difficult, although molten KOH has been used to detect crystalline defects in SiC. In this study we have developed the anisotropic wet chemical etching of single crystalline SiC using molten KOH for SiC bulk micromachining.

6H-SiC (0001) (Si-face) and (000-1) (C-face) substrates are used. For etching mask, 1 μm-thick Al layer is deposited at 350 degrees C by thermal evaporation and patterned by photolithography. A series of etching experiments is carried out at various temperatures. The etch rates of (0001) and (000-1) faces at 490 degrees C are 0.037 μm/min and 3.1 μm/min, respectively, indicating that the (0001) face is etched much slower than the (000-1) face. The activation energies are evaluated to be 1.4 eV and 0.065 eV for (0001) and (000-1), respectively.

To assess etching anisotropy, 5μm-deep trenches are formed on SiC (0001) surface by RIE. Molten KOH etching is performed for stripe trenches with a sidewall of (1-100) or (11-20). The etch rates of (1-100) and (11-20) faces at 490 degrees C are 2.5 μm/min and 3.0 μm/min, respectively, demonstrating anisotropic etching.

These results show single crystalline SiC can be etched anisotropically by molten KOH. This etching process can be used for SiC bulk micromachining.

6109-19, Session 5

Zero-crossing edge detection for visual force measurement in assembly of MEMS devices

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

In this paper, a visual force sensor is proposed to measure the microforces acting upon the jaws of passive, compliant microgrippers, used to construct out-of-plane 3-D microstructures. The vision-based force measurement technique is reduced to determining the microgripper deflections during the microassembly process. A video microscopic system is used to measure the deflections in the gripper's jaws, connected to a robotic workstation through thin elastic compliant beams, during the joining and grasping processes. Deflections in the beams give indications of the amount of force acting upon the microgripper. During real time operation of the microassembly system, microgripper deflections are determined visually through object recognition. Object recognition methods are used to determine the relative positions of all visible points and areas on the microgripper surface and thus make it is possible to determine approximate values of occurring beam deflections. Finite element analysis (FEA) simulations are used to develop an array including information of possible beam deflections and their corresponding microforces. The forces acting upon the microgripper can therefore be determined when the deflections are known.

6109-20, Session 5

Endpoint detection method for time division multiplex etch processes

R. J. Westerman, D. Johnson, S. Lai, M. Teixeira, Unaxis USA, Inc.

During the fabrication of many MEMs devices it is required to etch a layer of material to completion stopping on the layer below (e.g. Silicon on Insulator (SOI) - clearing a Si layer stopping on an underlying silicon dioxide layer). Allowing the etch process to proceed beyond the time when the first layer has been removed can result in reduced thickness of the underlying stop layer, or feature profile degradation (known as 'notching' for SOI applications).

One method commonly used to detect plasma process termination times is optical emission spectrometry (OES). OES analyzes the light emitted from a plasma source to draw inferences about the chemical and physical state of the plasma process. In semiconductor processing this technique is commonly used to detect material interfaces during plasma etch processes.

While this approach works well for single step processes or process with a limited number of discrete etch steps (such as an etch initiation followed by a main etch) it is difficult to apply OES techniques to plasma processes with rapid and periodic plasma perturbations such as time division multiplex (TDM) plasma etching processes for Si etching.

At Unaxis USA, we have developed a proprietary optical emission end point algorithm in conjunction with OES to detect material transitions in TDM processes. This technique requires no synchronization of the algorithm to the TDM process and has been applied to silicon on insulator (SOI) structures. The mechanism and performance of the algorithm will be discussed. The sensitivity of the technique has been evaluated over a range of silicon etch loads. Signal to Noise (SNR) ratios of greater than 15:1 have been achieved for samples with less than 10% exposed silicon.

6109-21, Session 5

Combined low-coherence interferometry and spectrally resolved reflectometry for nondestructive characterization of small-diameter high-aspect ratio microfabricated and micromachined structures, and mulilayer membranes

W. J. Walecki, T. Azfar, A. Pravdivstev, M. Santos II, A. Koo, Frontier Semiconductor Inc.

Infrared low coherence optical interferometry (IRLCOI) has been proven to be an effective tool for characterization of modern MEMs structures such as deep high aspect ratio trenches and thin membranes[1,2]. We propose novel tool employing both IRLCOI and spectrally resolved reflectometry (SRR) - the LCOIR-SSR sensor.

Application IRLCOI for measurements of the high aspect ratio structures [2] encounters challenges in regime where the aperture of measured features becomes comparable to wavelength of probing light. The demonstrate that the SSR spectrum of such structures allows us to extend range of IRLCOI to measure depth trenches with diameter from 2 um to 1 mm, and aspect ratio 0-20 and beyond with reproducibility 10 nm - 100 nm depending on range.

We also studied application of IRLCOI-SSR sensor for measurement of ultra-thin coated pressure sensor membranes. Application of auxiliary SSR allows to correct for systematic errors of IRLCOI which we demonstrate can be as large as 2 um.

1. Wojciech J. Walecki, Frank Wei, Phuc Van, Kevin Lai, Tim Lee, SH Lau, and Ann Koo , Reliability, Testing, and Characterisation of MEMS/MOEMS III, edited by Danelle M. Tanner, Rejeshuni Ramesham, Proceedings of SPIE Vol. 5343 p. 55-62 (SPIE, Bellingham, WA, 2004)

2. Wojciech J. Walecki, Kevin Lai, Alexander Pravdivdivtsev, Vitali Souchkov, Phuc Van, Talal Azfar, Tim Wong, SH Lau, and Ann Koo, Reliability, Testing, and Characterization of MEMS/MOEMS IV, edited by Danelle M. Tanner, Rejeshuni Ramesham, Proceedings of SPIE Vol. 5716 p. 182-188 (SPIE, Bellingham, WA, 2005)

6109-22, Session 5

Out-of-plane deformation of freestanding micro-rings for tensile stress measurements

Y. Chen, National Tsing Hua Univ. (Taiwan)

Micro-Rings have been widely used for measurement of residual tensile stress in thin films. This measurement approach provides a simple and convenient way to estimate the stress. However, it still lacks accuracy while compared to other methods. In conventional designs of the micro-rings, only the central beam portion of this device is supposed to be buckled after being subjected to residual stress. Nevertheless, in our study an out-of-plane deformation of the whole structure, including the central beam, the micro-ring, and the tie portion, has been observed when the device buckled. Limiting the out-of-plane deformation of planar devices has been a crucial issue in the MEMS field. To reduce the out-of-plane deformation, changing geometric sizes and shapes of the micromachined structure and successfully keeping it in horizontal position were implemented in the existing literatures. In this study, we arrange the central beam in the vertical orientation, shrink the beam width, and widen the ring width to limit the undesired out-of-plane deformation of the ring portion and thus to correct the measurement results. This research is performed through the finite element simulation predictions and experimental results. FEM simulations were executed with Ansys 5.7. Two typical types of models, in-plane and out-of-plane buckled micro-rings were established in the simulation. The simulation a results verified our prediction of conventional design; that is, the whole structure can be easily deformed in out-of-plane when subjected to residual stress, while our design can prevent the device from out-of-plane buckling. With the constraint on the out-plane deformation, that we suggested in this paper, a precise critical buckling length can be observed which will bring an accurate stress measurement. Furthermore, this design criterion may give a guideline on the geometric design of micro-rings.

6109-23, Poster Session

Research on Ni-electroplating of double-width micro-cantilever

Y. Liu, D. Sun, Xiamen Univ. (China)

Micro-electroplating technology has an increasingly wider application in the fabrication of MEMS devices. In order to fabricate the double-width cantilever beam which has three different electroplating areas°™ the base, the wide beam, and the narrow beam, the best composition of the bath solution is obtained through lots of experiments firstly in the paper. Then the effect of peak current density, duty and pause time on the surface of the pulse current electroplated nickel is studied experimentally to make sure the regulated range of pulse power parameters. And at last the double-width cantilever beam is fabricated using two lithographic processes, one micro-electroplating and sacrificial layer releasing process. The experimental result shows that the electroplated crystal grows steadily and the surface of the cantilever beam is bright and smooth. But the three parts of the cantilever beam with three different widths have different thickness, and the un-uniformity of thickness can be restrained by increasing the duty cycle and reducing the current density in a limited scope.

6109-24, Poster Session

Investigation on overplating high-aspect-ratio microstructure

Y. Guo, G. Liu, Y. Tian, Univ. of Science and Technology of China (China)

Most previous research on electroplating in LIGA has focused on electrodeposition of metal into high aspect ratio resist molds. In overplating process how the metal grows up across the top of resist molds has been relatively neglected. Typical defects like holes formation at the top of cavities of electroplated metal mold usually occur due to improper process control especially when the space/linewidth ratio of microstructure increases. To help understand these problems, overplating process has been investigated. A model is developed to compute current density distribution based on LIGA mold feature using electroplating simulation tools. Results show that it is almost an isotropic growing model at the first stage of overplating. As the deposited metal grows bigger the space between electrodes is shortened and the current density distribution along electrode may be modulated by neighbor electrode. It doesn't show an isotropic growing model any more. The deposition rate in inward lateral direction is smaller than in vertical direction. The growing model based on calculation shows that the trench feature aspect ratio can reach a considerable magnitude especially when the LIGA mold feature space/linewidth ratio increases. In poor transport situation, ion depletion becomes significant and a stopped deposition may occur thus holes can be formed at the bottom of overlapped neighbor electrodes. An optimized experiment has been performed using low overpotentials at the first stage of overplating process before the overlapping of neighbor electrodes and a rigorous stirring of electrolyte. A nickel mold insert without holes-formation defects can be obtained.

6109-25, Poster Session

Characterization of nonlinear optical thin-film fabricated with dye-doped UV curing epoxy

K. Le, P. Zhang, H. P. Hu, J. Chiao, The Univ. of Texas at Arlington

Optical devices for fiber optic telecommunication, sensors, data storage, and biomedical applications are traditionally fabricated using semiconductor and crystalline materials. Which are expensive and difficult to manu-

facture. Organic optical materials provide an inexpensive and easily manufactured alternative to the traditional materials and have attractive optical performance when synthesized and processed properly. Some polymers have been demonstrated with losses and birefringence less than silica.

Optical second-order nonlinear polymer can be fabricated using high external electric fields to align the dipolar molecules within a guest-host system. When film temperature is higher than glass transition temperature (Tg) of the hosting polymer, the application of intense external electric fields result a rearrangement of the dipoles along the electric field vectors. This orientation of dipolar molecules is locked in the polymer matrix when temperature is lowered back to the room conditions. By doing so, the poled film will have a noncentrosymmetric structure which is a key requirement for optical second-order nonlinearity.

In our research, optical second-order nonlinear thin film was developed by doping dye organic molecules in a UV curing epoxy host polymer system and followed by an electric field poling step. Nanofabrication of thin film will be presented. Results from a systematic evaluation of the film physical and optical properties using AFM, ellipsometer and Maker Fringe will be provided. The film absorption spectrum shows a promising advantage for frequency doubling in the blue color window.

6109-26, Poster Session

A curled-hinge comb micromirror using CMOS-MEMS process

Y. R. Huang, H. M. Tai, H. Chou, National Tsing Hua Univ. (Taiwan)

This paper presents a large displacement static-electricity curled-hinge comb micro-mirror made by a CMOS-MEMS process. A micro-spring is incorporated to reduce the stress effects and the process variation. A mirror with a size of 500um x 500um is made using three metal layers. The micro-spring made a metal layer and a poly layer with a size of 4um x 21um. The nature frequency is 727 Hz and the maximum displacement of the micro-mirror is 32um using a driving voltage of 25 volts. The process variation has been successfully reduced from 30% to 10%.

6109-27, Poster Session

5~10 GHz surface acoustic-wave resonators and low-loss wide-band filters using submicron fabrication technology

K. Yamanouchi, Y. Satoh, H. Isono, Tohoku Institute of Technology (Japan)

The development of GHz-band surface acoustic wave (SAW) devices has become necessary because of the increasing volume of information and communication media, such as mobile telephone, satellite broadcasting, spread spectrum communications. Especially, zero TCF, wide band and low loss filters with an ultra-small size and high performance are required for mobile communication systems. We developed the SiO2/Rotated Y-cut, X-Propagating LiNbO3 leaky SAW substrates with a large k2 (over 0.2) and zero TCF at the very thin thickness of SiO2 of H/λ=0.2 (HSiO2:SiO2 film thickness, λ:SAW wave-length) and zero propagation attenuation in the case of metalized surface.

In this paper, the theoretical and experimental results of SAW resonators and resonator filters in the frequency ranges of 5~10 GHz using the above substrates and submicron fabrication technology are described. One of the important things at 5~10GHz-range SAW filters is the thickness effect of IDT electrodes due to decreasing the resistive loss. Therefore the filters were analyzed for the SiO2/Al-IDT/LiNbO3 substrates. The resonator showed the band width of 1.3GHz at the center frequency of 10GHz and resonator filters showed the band width of 2.0 GHz and insertion loss of 2dB in the center frequency of 10GHz at the HAl/λ=0.15(HAl=600A), HSiO2/λ=0.25(Only, HSiO2=1000A). The experimental results show the good agreements to the theoretical ones.

6109-29, Poster Session

Development of fabrication techniques for high-density integrated MIM capacitors in power conversion equipment

M. Brunet, P. Dubreuil, E. Scheid, J. Sanchez, Lab. d'Analyse et d'Architecture des Systémes (France)

In portable electronic equipments, miniaturisation, multi-functionalities and reliability are the main factors driving the power electronic industry. In this context, the realisation of all integrated high performance DC-DC micro-converters working at high frequencies (few MHz) is necessary. The passive components such as inductors, transformers and capacitors, are for the moment the bulkiest components and their integration on silicon substrate would constitute a real improvement in term of compactness and reliability of power converters. This paper deals with the fabrication of integrated capacitors realised on silicon using MEMS-type techniques. High energy storage capacity, low series resistance and inductance are sought. Structures using deep cavities etched in silicon were realised in order to increase the real area of the capacitor's electrodes while minimising the effective area on the substrate. The development of micro-fabrication techniques such as Deep Reactive Ion Etching (DRIE) and doped-polysilicon deep trenches filling are presented. Some preliminary results on the developed processes show that 100 nF/mm≤ capacitors can be realised.

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6110-01, Session 1

Advanced interference lithography for patterning nano-optics

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We report on the development a new grating pattering tool called the Nanoruler which utilized phase-locked scanning beams in order to pattern large gratings with very high phase and dose precision. Traditional grating patterning techniques, such as interference lithography and electron-beam lithography, are very slow and have difficulty controlling the period, phase, and line width of periodic patterns to the nanometer level. By interfering mm-sized scanning beams and using high-speed phase-locking electronics, grating patterns with excellent control of these parameters can be rapidly achieved on large substrates.

The initial Nanoruler was intended as a prototype and is difficult to re-align to change periods. A new optical system is being fabricated which will allow rapid period change under electronic control. With further development this improved system is intended to allow period change on-the-fly in order to pattern chirped gratings and other more sophisticated periodic patterns. In this paper we review the performance of the Nanoruler and report on progress towards our goal of achieving variable-period scanning-beam interference lithography.

6110-03, Session 1

SU-8 multiple layer structuring by means of maskless photolithography (DWL66)

A. A. Saghiri, M. Kaden, K. Rössler, R. Wijnaendts, S. Preus, A. Forozan, Heidelberg Instruments Mikrotechnik GmbH (Germany)

SU-8 is a negative tone proxy type resist which allows high aspect ratio for micro machining. SU-8 molds can be used by micro casting and embossing amongst others for making high aspect MEMS. A way to produce prototypes in a quick manner (Design —> Expose —> Prototype) gets an important task in the micro fabrication at the present.

In present work we demonstrate the ability of making multiple layer and binary structuring of SU-8 using mask less lithography by DWL66 device. As light source, we used a 30 mW He-Cd-Laser at 325 nm wavelength. The intensity is varied over 31 steps by an acousto optical modulator (AOM) which provides the desired gray tone levels. By means of micro lens arrays (MLA) we represent the achieved results by back side exposures[2]. It can be shown that additional to curvature of the lenses resulting by intensity modulation, the total height of lenses can be controlled by using supplementary attenuation. The total achieved height of micro lenses is ca. 65 μm resulting from a 100 μm thick SU-8 25[4] resist made by multiple coating method.

Good chemical, mechanical and optical proprieties assign SU-8 for different application as optical devices in micro optics and optoelectronic.

6110-04, Session 1

Modeling the fabrication of nano-optical structures

R. C. Rumpf, College of Optics and Photonics/Univ. of Central Florida

In the last two decades, considerable research has been devoted to micro-optic and nano-optical structures. Fabrication methods have become sufficiently mature to realize these structures, but due to physics inherent in the process the shape is distorted. Edges are rounded, sidewalls are sloped, and etching or deposition is not uniform. Deviations from 'perfect' geometry can dramatically affect optical behavior. This paper discusses how near-field nano-patterning can be comprehensively modeled to more accurately predict geometry of formed structures.

6110-05, Session 2

A new fabrication technique for complex refractive micro-optical systems

M. Tormen, A. Carpentiero, E. Ferrari, D. Cojoc, S. Cabrini, E. Di Fabrizio, Istituto Nazionale per la Fisica della Materia (Italy)

We present a new method that allows to fabricate structures with tightly controlled three-dimensional profiles in the 10 nm to 100 μm scale range. The technique consists of a sequence of lithographic steps such as Electron Beam (EB) or Focused Ion Beam (FIB) lithography, alternated with isotropic wet etching processes performed on a quartz substrate. SEM and AFM morphological characterizations show that 3D structures with very accurate shape control and nanometer scale surface roughness can be realized. Quartz templates have been employed as stamps in nanoimprint, hot embossing or casting processes to shape complex plastic elements. Compared to other 3D micro and nanostructuring methods, in which a hard material is directly sculptured by energetic beams, our technique requires a less intensive use of expensive lithographic equipments, for comparable volumes of structured material, resulting in dramatic increase of throughput.

Refractive micro-optical elements have been fabricated and characterized in transmission mode both with white and monochromatic light. The elements produce a distribution of sharp focal spots and lines in the three dimensional space, opening the route for applications of image reconstruction based on refractive optics.

This technique is expected to have many applications in different micro- and nanotechnology-related fields such as optics, nanomechanics, optical tweezing, microfluidics and plasmon nano-optics.

6110-06, Session 2

Fabrication of 3D photonic crystals by two-step dry etching of layered media

P. Srinivasan, R. C. Rumpf, E. G. Johnson, College of Optics and Photonics/Univ. of Central Florida

Photonic crystals have received growing interest over the past decade on account of their excellent functionality to guiding and manipulating electromagnetic radiation and their diverse applications Fabrication of photonic crystals with index modulation in three dimensions in high index media is central to the implementation of these structures in practical devices. 3-D crystals have a complete photonic band gap (i.e.) they present a band gap to light propagating in any crystal direction.[1]

Our approach is to fabricate crystals by a two step etching process in a semiconductor hetero-structure of gallium arsenide (GaAs) and aluminum gallium arsenide (AlGaAs) grown using molecular beam epitaxy (MBE). A PECVD grown silicon-di-oxide (SiO2) layer was used as the mask for etching holes into the substrate. A layer of chromium was used to transfer the patterns from resist to the etch mask. The process began with the patterning of a planar array of holes in e-beam resist, ZEP, upon a layer of chrome with a layer of SiO2 underneath. An array of holes of 200nm diameter at 400nm period was patterned using a Leica EBPG 5000+ sys-

tem. This pattern was then transferred into the chrome layer using chlorine plasma in an ICP etching tool and subsequently to the oxide layer by dry-etching in a CHF3/O2 plasma. Vertical sidewalls with minimal undercutting of the metal mask were obtained.

This template in chromium and SiO2 was then transferred to the layered GaAs/AlGaAs substrate. An array of holes was dry etched in Cl2/Ar inductively coupled plasma. Etching selectivity between the mask and the substrate was 6:1. The process was optimized to obtain smooth vertical sidewalls. Holes of 3 μm deep and 200nm in diameter were etched into the layered GaAs/AlGaAs. Index modulation in the third dimension is achieved by using a selective lateral etching technique.[2] By using SF6 in addition to the boron-tri-chloride (BCl3) chemistry, the GaAs is etched selectively over the AlGaAs with selectivities over 100:1. Thus a robust two-step etching process has been developed based entirely on dry etching.

Earlier efforts at fabricating 3D photonic crystals in layered media have exploited the difference in etching rates of oxidized III-V materials or have used using wet methods. However, our approach exploits the difference in etch rates of GaAs and AlGaAs in specific plasma chemistries. Thus, it does not modify the composition of the medium in any manner and lends itself to mass fabrication and provides excellent control over the undercut ratio.

In conclusion, photonic crystals that present a complete band-gap to light at 1.55μm were fabricated using a robust two-step dry etch process. The described process directly exploits the difference in etching rates of GaAs and AlGaAs in a SF6/BCl3 plasma chemistry. Excellent fabrication control and tolerance over the crystal dimensions has thus been achieved.

Reference:

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2. S. Salimian, et al., Applied Physics Letters, vol 51, no 14, 1987

6110-07, Session 2

Ion beams for fabrication of micro- and nano-optics

A. Schindler, Institut fuer Oberflaechen- modifizierung IOM (Germany)

Low energy ion beam processing has become an effective tool in high performance optics production technology for polishing error correction during the last decade. Additional new demands from optics technology especially from miniature optics as well as diffractive and micro-/ nano-optics technology together with the discovery of new ion bombardment related surface effects induce the development of advanced ion beam processing techniques.

The talk presents an overview of the technologies and of examples of latest results on (i) reactive ion beam etching (RIBE) for the proportional transfer of 3D microstructures for diffractive and refractive micro-optics and other high spatial frequency microstructures (ii) surface smoothing down to the sub-nanometer rms level and ion beam induced self assembling nano-structuring of surfaces for potential anti-reflection application and (iii) preliminary testing of deterministic surface figuring with nanometer depth accuracy on a sub-millimeter lateral scale using a small spot ion beam figuring system.

A technology for the fabrication of masters made from glass for a replica technology of curved grating elements with high spatial frequency 3D-structures has been developed and demonstrated to be mature for production. The technology comprises two main steps, first a holographic lithography for the preparation of the 3D resist masks on top of the master substrates and second a reactive ion beam etching step to transfer the structures proportionally into the substrate surface. After optimization of all processing steps the measured diffraction efficiencies are reliably near the design values. First test structures of very high spatial frequency cross gratings with 6900 lines per mm have been fabricated for anti reflection application.

6110-08, Session 3

Multiphoton polymerization of waveguides in self-assembled 3D photonic crystals

P. V. Braun, Univ. of Illinois at Urbana-Champaign

Three-dimensional photonic crystals offer interesting opportunities for scientific exploration and formation of functional materials and structures. Simple periodic photonic crystals have some interesting optical properties, however, many devices, such as lasers, waveguides, and chemical sensors will require the incorporation of new material and aperiodic defect structures within the photonic crystal. After a brief introduction to the optical properties of photonic crystals and photonic band gap materials, I will present our results on the use of multiphoton polymerization, electrochemistry, and chemical vapor deposition to enhance the functionality of photonic crystals. For example, multiphoton polymerization is used to incorporate aperiodic defects with dimensions on the order of the wavelength of light within photonic crystals. The defect structures formed will include 3-D waveguides with sharp bends, and embedded optical cavities. A number of issues still must be dealt with to create an optical device, and I will highlight our latest results in this area. The most critical issue is the refractive index contrast. Most polymers do not have a sufficiently high refractive index to form a photonic band gap structure, and thus strategies to enhance the refractive index contrast will be presented.

6110-09, Session 3

Optimization of SU-8 processing for integrated optics

T. A. Anhoj, A. M. Jorgensen, D. A. Zauner, J. Hübner, Technical Univ. of Denmark (Denmark)

SU-8 is a negative tone photoresist which can be structured using standard near-UV lithography. Structures fabricated in SU-8 have good mechanical stability and high thermal and chemical resistance. Furthermore, SU-8 has a high refractive index (1.59 at 800 nm) and is thus waveguiding when sandwiched between two lower index materials. This facilitates simultaneous integration of microfluidic channels, waveguide circuitry, and optical components, such as integrated spectrometers, in a single lithographic step.

We report the results of investigations concerning two aspects of SU-8 processing: 1) development of a process to remove the edge bead after spin, in order to reduce proximity effects in the exposure process, and 2) an investigation of parameters in the baking and exposure steps in order to optimise the resolution. Both aspects were investigated through design of experiment (DOE) and related statistical analysis. The first DOE investigated the significance of eight process parameters in edge bead removal using a built-in EBR function on a Karl Süss RC8 spin coater, and totalled 51 experiments. The second DOE covered six parameters; two in the soft bake step, the exposure time, and three in the post-exposure bake. This DOE contained 64 experiments.

We are now able to resolve trenches with aspect ratio 10 and mechanically stable ridges with aspect ratio 8 in 40 μm thick SU-8. The optimisations have doubled the realisable aspect ratio when compared to the starting point, and cracking has been eliminated. More importantly, the fabrication of integrated spectrometers based on reflective echelle gratings has improved greatly.

6110-10, Session 3

The study on spatial resolution in two-photon induced polymerization

K. Takada, H. Sun, Osaka Univ. (Japan); S. Kawata, Osaka Univ. (Japan) and RIKEN (Japan)

We have previously demonstrated that two-photon induced polymerization allows fabrication of complex three-dimensional structures such as photonic crystals and micromachines with a spatial resolution around 120

nm. In this report, we show the resolution improvement till 65 nm. Experimentally, 780-nm femtosecond laser pulses were focused into the photopolymerizable resin by a high numerical aperture objective lens. The resin that consists of photoinitiator, urethane acrylate monomers and urethane acrylate oligomers is polymerized by the radical initiation. In the radical polymerization, oxygen molecules dissolved in the resin inhibit the polymerization reactions by scavenging the radicals that initiate the polymerization. At controlled laser pulse energy, the radicals can survive and initiate polymerization only at the region where exposure energy larger than the polymerization threshold, by which sub-diffraction-limited resolution had been obtained. As the first step of this research, we introduced a radical quencher into the resin, and at an optimized concentration the resolution was improved to 100 nm judging from the lateral size of voxels. Secondly, we fabricated a suspended line connected between two anchors by controlling the exposure dose within the line. After removing the unsolidified resin by ethanol and drying, a 65-nm width line was obtained. The size less than 1/10 of the excitation wavelength could satisfy requirements of many photonic and optoelectronic devices.

6110-11, Session 3

Affect of two- and three-zone phase masks on the axial and transverse intensity distribution under high-numerical aperture focusing

S. M. Kuebler, T. Jabbour, College of Optics and Photonics/ Univ. of Central Florida

A combined scalar and electromagnetic approach was used to study how differential phase and relative radii of two- and three-zone phase-only diffractive optical elements (DOEs) affect the axial and transverse intensity distribution (point-spread-function, PSF) of a tightly focused beam. A scalar analysis based on Fresnel's diffraction integral was used to map the entire solutions space that results when the phase, phi-sub-i, and relative radii, r-sub-i, of the DOE zones are independently varied. Regions are identified in the phase-radii space for which the axial intensity distribution appears super-resolved versus the diffraction limit based on two definitions: (1) GA gives the relative width of the intensity profile between local minima around the central lobe; and (2) TA gives the relative width between points at which the intensity falls to a specified percentage of the peak intensity. It is shown that GA is well suited for imaging applications, such as confocal microscopy, whereas TA is more appropriate for photolithographic applications, such a multi-photon three-dimensional microfabrication (3DM). Super-resolved regions in the phase-radii space were evaluated more accurately using an electromagnetic approach based on the Richard-Wolf integrals, to account for the full vector nature of a beam focused using high numerical aperture optics. Results from the scalar and electromagnetic simulations are compared. It is found that two-zone phase-only DOEs do not super-resolve in terms of definition (2) (TA \> 1 for all phi-sub-i and r-sub-i), and thus are not suitable for improving resolution in 3DM, but these can super-resolve in terms of definition (1), making them suitable for improving resolution in confocal imaging. Preliminary studies indicate that three-zone and higher-order phase-only DOEs can super-resolve in terms of TA and may be suitable for use in 3DM.

6110-12, Session 3

Grey-scale electron-beam lithography in functionalized SU-8 for active optical devices

S. Balslev, T. Rasmussen, P. Shi, A. Kristensen, Technical Univ. of Denmark (Denmark)

We demonstrate grey scale electron beam lithography (EBL) in functionalized SU-8 2000 resist, doped with Rhodamine 6G laser dye, for the fabrication of miniaturized, single mode polymer dye lasers. These devices offer the possibility of easy integration of single mode laser sources in polymer based lab-on-a-chip microsystems. The laser device consists of a planar waveguide with a 1st-order distributed feedback grating (DFB) surface corrugation, which forms an optical resonator. When optically pumped at 532 nm, single mode lasing is obtained in the wavelength range 570 nm - 600 nm, determined by the grating period.

The planar waveguide devices are fabricated on top of a 2.5 micron thick oxide layer grown on a Si substrate. The negative SU-8 resist is doped to a concentration of 0.002 mM/g Rhodamine 6G perchlorate in the final polymer matrix, and spin-coated to an 800 nm film on the substrate.

The structures are defined electron beam lithography (100 kV), using alternating doses of 8 and 16 micro-C/cm2 After development the structure will be modulated in height according to the received dose, due to the contrast of the resist. Grating periods of 182-770 nm and grating corrugation heights up to 100 nm were achived.

Our results demonstrate the feasibility of fabricating advanced nano-structured active optical components in a rapid prototyping process. The functionality of the devices further demonstrates the possibility of using electron beam lithography on dye dyped SU-8 without destroying the organic laser dye molecules.

6110-13, Session 4

New nanofabrication technique using overlay for 15-nm zone plate

W. Chao, B. Harteneck, J. A. Liddle, E. Anderson, Lawrence Berkeley National Lab.; D. Attwood, Univ. of California/Berkeley

Soft x-ray zone plate microscopy has proven to be a valuable imaging technique for nanoscale studies. It complements nano-analytic techniques such as electron and scanning probe microscopies, and offers a unique set of capabilities including high spatial resolution, natural elemental/ chemical and magnetic sensitivities, large permissible sample thickness, and a myriad of in-situ sample environments. The highest spatial resolution demonstrated with the soft x-ray microscopy was 20 nm, achieved by imaging zone plates of 25 nm outermost zone width fabricated using electron beam lithography. To improve the resolution, extensive effort in reducing the outer zone width has been engaged worldwide. However, due to limitation in e-beam lithography, sub-20 nm zone widths cannot be reliably fabricated. To overcome this problem, we have developed a new zone plate fabrication technique based on overlay, in which a zone plate pattern is sub-divided into two semi-isolated, complementary patterns, and the patterns are fabricated separately and then overlaid with high accuracy to form the desired pattern. With this technique, zone plates of 15 nm outer zone width have been successfully fabricated. Imaging results show that the zone plates produce drastic improvement in image fidelity and resolution. With this technique, we anticipate fabricating zone plates with even finer zone widths, and 3-D zone plate structures which are not possible with conventional e-beam lithographic techniques.

6110-14, Session 4

Extreme ultraviolet phase contrast imaging

G. Denbeaux, SUNY/Univ. at Albany; A. Barty, Lawrence Livermore National Lab.; Y. Liu, K. Goldberg, Lawrence Berkeley National Lab.; R. Garg, SUNY/Univ. at Albany; O. Wood, SEMATECH, Inc.

Extreme Ultraviolet (EUV) lithography is the most likely candidate for adoption by the semiconductor manufacturing industry as the next generation lithography technique. In this technology, reflective optics coated with Mo/Si multilayers that provide high reflectivity in a narrow band of wavelengths near 13-nm are used for imaging. One of the remaining issues to be solved before EUV lithography can be commercialized is the reduction of defects on multilayer-coated EUV masks. Zone plate microscopy at 13-nm wavelength is an ideal technology to find and understand multilayer defects not only because it can provide very high spatial resolution (30 nm or possibly below), but also because it can relatively easily provide phase contrast imaging if a phase plate is placed in the back focal plane. In this talk we will present the design of and preliminary results from a phase-contrast zone plate microscope at the Advanced Light Source at Lawrence Berkeley National Laboratory that will be used for reflection imaging of EUV masks at 13-nm wavelength.

6110-15, Session 4

EUV binary phase gratings: fabrication and application to diffractive optics

F. H. Salmassi, Lawrence Berkeley National Lab.; P. P. Naulleau, SUNY/Univ. at Albany

Diffractive optics for extreme ultraviolet (EUV) applications typically require extremely precise topography control because the surface structure must be commensurate with the very short wavelength (13.5 nm for lithography). In this paper we discuss an approach to fabricating diffractive optics for the EUV regime.

Binary phase gratings serve as convenient and relatively efficient carriers for diffractive and holographic optical elements. When dealing with applications where both positive and negative orders can be used (such as for an optical element intended to produce dipole illumination), theoretical efficiencies of 80% can be achieved. The difficulty in fabricating these devices arises from the requirement of topography of only 3.4 nm to achieve a l/2 phase shift upon reflection. Small variations in phase have a substantial impact on the device performance.

Gratings of 200 nm period were fabricated by e-beam lithography on a Si-on-Cr surface structure using KRS-XE resist. The pattern was transferred into the Si using low energy, residue-free SF6 plasma. The gratings thus produced were multilayer coated for EUV and measured. The results show efficiency to be about 70% of expected from an ideal device.

Not only are these structures highly efficient, but also once Si thickness is calibrated they are also relatively straightforward to produce. Because the Si layer and not the resist define the topography, a fast chemically-amplified resist with modest resolution can be used which leads to a reduction in exposure times by a factor of fifty. The development of this approach enables the production of diffractive structures for EUVL such as diffusers and shaped illuminators.

6110-16, Session 5

Giant optical activity in quasi 2D planar nanostructures

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Advances in nano- and microscale fabrication make possible artificial materials with extraordinary optical properties such as photonic crystal slabs and waveguides with ultraslow speed of light or ‘left-handed’ metamaterials. Planar metal structures are easily fabricated by electron-beam lithography and can be operated at room temperature. In such structures, strong coupling between light and the collective motion of electrons (plasmons) leads to phenomena such as superefficient light transmission through sub-wavelength holes, reshaping of ultrashort optical pulses, suppression of light extinction, and enhanced second-harmonic generation. The next important challenge in tailoring optical properties of metal nanostructures is polarization control, which would be crucial in various applications including quantum information processing. Here, we demonstrate nanoscale polarization control in an optically active planar metal structure. An array of chiral gold nanoparticles, much thinner than wavelength, exhibits giant specific rotation (~104 ∫/mm) at normal incidence when the wavelength of light is near the surface-plasmon resonance of the structure. We find reciprocity of the phenomena, the rotation is the same for light incident on the front and back sides of the sample. This indicates the effect manifests three-dimensional optical activity, which is in contrast to recent interpretations of diffraction and imaging experiments of two-dimensional chiral structures[11,12]. Asymmetry in the photon-plasmon coupling for the front and back interfaces leads the three-dimensional effects in quasi-two-dimensional nanostructures .

6110-17, Session 5

Monolithic fabrication of hollow ARROW-based sensors

A. R. Hawkins, J. P. Barber, E. J. Lunt, Brigham Young Univ.; H. Schmidt, D. Yin, Univ. of California/Santa Cruz

Hollow waveguides are an important photonic technology because they allow for light guiding in very low refractive index materials, enabling guiding in gas or liquid media that fill the hollow cores. Optical sensors are a key application since guided light can have a long interaction distance with the gas or liquid media. A new class of hollow waveguides for picoliter volumes was recently introduced based on the anti-resonant reflecting optical waveguide (ARROW) principle. These waveguides are fabricated on silicon substrates making them attractive for optical sensor platforms.

In this talk, we will discuss the bottom-up fabrication processes used to make these types of sensor platforms. This description will include the use of a variety of sacrificial core materials that produce waveguide cores of different geometries. We will explain methods for reducing waveguide loss by optimizing cladding layer thicknesses and building structures that surround the waveguide with air in as many dimensions as possible. The fabrication of solid-core ARROWs will also be discussed along with how they can be interfaced with hollow core waveguides to route optical signals over a chip’s surface. Finally, the creation of fluid networks using hollow waveguides will be highlighted along with considerations for interfacing with the macro world.

6110-18, Session 5

Fabrication of tapered air-core defects in 3D photonic crystals for multifunctional scanning-probe NSOM tips

G. J. Schneider, J. Murakowski, D. W. Prather, Univ. of Delaware

We propose a fabrication method that will yield photonic-crystal based multifunctional NSOM probes, using a process compatible with silicon-based microelectronics technology. The method is based on a combination lithography approach, utilizing electron-beam lithography (EBL) to generate conical defects, and interference UV lithography to surround them with a three-dimensional photonic-crystal lattice. The conical shape of the defects arises automatically from dot exposures during EBL, owing to scattering of the electron beam in a thick resist film. The UV interference exposure is generated in a controlled, repeatable manner by a monolithic array of diffraction gratings placed in flush contact with the sample to be exposed. Following exposures, the structure is revealed in resist by development, and subsequently inverted by chemical vapor deposition of amorphous silicon. Finally, the substrate may be further processed using standard silicon micromachining to create a cantilever with the photonic-crystal tip at the end, suitable for use in an arrangement similar to existing SPMs such as atomic-force and scanning-tunneling microscopes; however such a tip would also be capable of high-resolution, high-throughput NSOM. This paper explains our process in detail and presents samples fabricated by this approach.

6110-19, Session 5

Fabrication issues for a chirped, subwavelength form-birefringent polarization splitter

S. A. Kemme, J. R. Wendt, A. A. Cruz-Cabrera, D. W. Peters, R. R. Boye, T. R. Carter, S. Samora, Sandia National Labs.

We report here on an effort to design and fabricate a polarization splitter that utilizes form-birefringence to disperse an input beam as a function of polarization content as well as wavelength spectrum. The fabrication challenges here include those encountered when manufacturing a form-birefringent waveplate: deep, subwavelength features with smooth, rectangular etch profiles. We and others have presented successes in this arena,

where the spatial frequency is constant and the duty cycle may be optimized to produce a broad waveband device.

For this new component, the spatial frequency and/or the duty cycle is chirped to tailor the polarization dispersion and wavelength spread. However, this approach presents a considerable fabrication obstacle since etch depths are a strong function of feature size, or grating period. A typical fabrication result shows the grating period ranging from 400 nm to 4 microns, while the etched depth varies more than a factor of two.

Fortunately, these fabrication constraints are not complete impediments because we have at least two parameters that affect the polarization and wavelength dispersion bands; namely the duty cycle and the grating period. These are varied in concert to maximize the transmitted deflection angle difference and/or to spread the spectrum as a function of transmitted angle. We simulate their effectiveness at the realistic depths imposed by the fabrication process. Moreover, because these two parameters (duty cycle and period) are defined lithographically, we are not limited to a linear additive phase delay.

6110-20, Session 6

Fabrication of nano- and micro-optical elements by step and flash imprint lithography

D. L. LaBrake, N. Khusnatdinov, G. Doyle, M. Miller, N. Stacey, M. Watts, Molecular Imprints, Inc.

The Step and Flash Imprint Lithography (S-FIL) process is a step and repeat nano-imprint lithography (NIL) technique based on UV curable low viscosity liquids.[1,2,3] Investigation by this group and others has shown that the resolution of replication by imprint lithography is limited only by the size of the structures that can be created on the template (mold). S-FIL uses field-to-field drop dispensing of UV curable liquids for step and repeat patterning. This approach allows for micro and nano-fabrication of devices with widely varying pattern densities and complicated structures. Wire grid polarizers and micro lenses are two examples for optical components that can be formed using S-FIL technology.

Step and Flash Imprint Lithography Reverse (S-FIL/R) tone has been used to form resist patterns for a number of different device types [1,4,5]. The authors have employed S-FIL/R and dry develop techniques to form resist patterns with 100 nm period useful for the fabrication of wire grid polarizers. S-FIL/R has a number of advantages over interference lithography techniques for the fabrication of sub 200 nm period grating structures including but no limited to pattern repeatability, vibration insensitivity, high aspect ratio feature formation, greater extendibility and high resolution. The authors have devised imprint and dry etching processes for resist and substrate patterning to form Al based wire grid polarizers with 100 nm pitch. The fabrication processes and resulting devises will be described.

While S-FIL is useful for in the formation of resist patterned wafers, it is also capable of forming devices by functional material patterning. Polymer micro lenses are a good examples of functional material devices useful for a number of applications including CMOS and CCD cameras. The fact that lens geometry is defined by the template and requires no post imprint processing provides a strong advantage over current lens formation approaches. Recent results and the state of current micro lens fabrication by S-FIL is described.

6110-21, Session 6

Micro-optical module fabrication using nano-imprint technology

M. Rossi, H. Rudmann, Heptagon Oy (Switzerland); R. Pelzer, EV Group (Austria); M. G. Salt, Heptagon Oy (Switzerland)

Industrial manufacture of micro-optical modules and systems has recently made major strides. Strong advances in industrialized nanoimprint technology allow for low-cost, high-quality and highly precise micro-optical modules and systems to be produced in very large volumes. We present an approach to use a proprietary UV-replication process combined with the equipment and principles of UV-NanoImprint Lithography (NIL), allowing for highly reliable reproduction of optical microstructures on a wafer scale. The NIL process involves the creation of a 'master' structure, which acts as a mold for the creation of 'tools'. Each tool also acts a mold, shaping a layer of liquid polymer that is then solidified by exposure to UV light. When the tool is removed, a high-fidelity copy of the required structure is left behind in the polymer. High-quality, single-sided components can be manufactured in this way using relatively simple equipment. These components exhibit excellent thermo-mechanical performance (for example, they are fully compatible with Telcordia tests and IR reflow up to 280 ∞C) and an excellent layer uniformity and thickness control. When NIL and Heptagonís UV replication are brought together, complete optical modules (e.g. miniaturized cameras or illumination modules) can be fabricated. These modules can often be double-sided, include several micro-optical components and have patterned layers. For these modules, nanoimprint technology allows for the crucial precision alignment and registration of each layer. The UV-NIL process uses an EVG640NIL capable of handling substrates up to 200 mm in diameter. We present a fast, automated fabrication process that fulfils these requirements.

6110-22, Session 6

The impact of step and flash imprint lithography for nanomanufacturing applications in optics

D. L. LaBrake, Molecular Imprints, Inc.

Step and Flash Imprint Lithography (S-FIL(TM)) process is a step and repeat nano-replication technique based on UV curable low viscosity liquids. Investigation by this group and others has shown that the resolution of replication by imprint lithography is limited only be the size of the structures that can be created on the template (mold). S-FIL uses field-to-field drop dispensing of the UV curable liquids for the step and repeat patterning. This approach allows for nano-manufacturing of devices with widely varying pattern densities and with complicated structures.

There are numerous optical and device applications for imprint lithography. One of the more interesting is to imprint gratings, pillars and contacts for both passive optical devices and active emitters such as lasers or LED's. These applications and the underlying process requirements will be described. Images will be shown of distortion free 100 to 60 nm posts and gratings that are replicated by SFIL processing. Imprinted microlens device structures will also be shown. Process data for repeatability, process control, defects and etch pattern transfer of sub 100 nm posts and other features will also be shown. Finally, align results will be shown that illustrate how hybrid optical and electronic devices can be made by imprint.

To-date, the imprint lithography systems manufactured by MII have demonstrated:

- Up to 300mm wafer coverage with lithographically useful patterning.
- Full wafer residual layer thickness control to enable practical etching (thickness variation < 10 nm, 3 sigma.)
- Multi-day field-to-field CD uniformity measured on an analytical SEM of less than 2 nm, 3 sigma with no process adjustments.
- Etch pattern transfer including break-through etch of residual material, followed by a bilayer etch through thick planarization layers.
- Process life showing no degradation of 50 nm dense lines, 65 nm dense contacts, and 60 nm dense pillars for over thousands of imprints without requiring change of template or template surface treatment.
- Layer to layer align results better than 15 nm 3 sigma

6110-23, Session 6

High-performance plasmonic crystal sensor

V. Malyarchuk, F. Hua, N. H. Mack, V. T. Velasquez, J. O. White, R. G. Nuzzo, J. A. Rogers, Univ. of Illinois at Urbana-Champaign

We report a new type of two dimensional plasmonic crystal sensor fabri-

cated by imprint lithography using a soft, elastomeric mold. Plasmonic crystals manipulate the surface plasmon polariton (SPP) dispersion in ways that can lead to anomalously high sensitivity to surface binding events of the type that are useful for a range of sensor applications. The operation of these sensors depends on the optical properties of the SPP and in particular on how propagating light couples into and out of these modes. The required sub-micron features needed for such coupling at visible wavelengths are difficult, and expensive, to fabricate using conventional means. Low cost lithographic procedures based on printing and molding have the capabilities to fabricate high quality metal structures with the necessary dimensions needed to form the coupler. Angle-dependent, zero-order transmission experiments were employed for mapping the Brillouin zone of two-dimensional plasmonic crystals in order to understand their physical properties and evaluate their sensing capabilities. Full angle-dependent mapping using a model system consisting of an alkanethiolate self-assembled monolayer on Au, shows that the sensitivity to surface chemical binding events reaches maxima near regions of the plasmonic Brillouin zone where the dispersion curves of multiple surface plasmon polariton modes converge. This behavior, together with the simple, low cost procedures for building the structures, suggests a potentially important role for these devices in development of the future classes of the high performance chemical and biological sensors.

6110-24, Session 7

Fabrication of dual grating reflectors for high-power laser diodes

J. K. O'Daniel, O. V. Smolski, E. G. Johnson, College of Optics and Photonics/Univ. of Central Florida

A dual grating reflector is a scheme for wavelength stabilization of semiconductor lasers. The fabrication of a dual grating reflector involves the fabrication of a grating coupler on the p-side of a semiconductor laser and a feedback grating on the n-side of the same device. The fabrication processes of a dual grating reflector and the tolerances required for near optimum performance of the dual grating reflector are presented.

6110-25, Session 7

Investigation of the III-V oxidation process for the fabrication of sub-micron three-dimensional photonic devices

K. Swaminathan, J. Murakowski, C. Schuetz, G. Schneider, D. Prather, Univ. of Delaware

Oxidation of epitaxially grown GaAs/AlGaAs layers produces a high index contrast which can be used to develop novel photonic devices[1,2]. However, to realize this potential it is necessary to produce repeatable oxidation results in both the horizontal and vertical directions. To study the relevant processes we have developed a robust III-V oxidation system based on a conventional tube furnace operable in the open loop or closed loop configuration. The effects of both the open loop and the closed loop system on different devices have been investigated. The oxidation reaction is selective to the AlxGa1-xAs layers and their thickness. The different parameters that influence the oxidation reaction include process temperature, process time and flow rates of the carrier gas. We have also investigated the effect of etch profile, etch chemistry and artifacts on the oxidation process. The oxidation process is characterized as a function of various parameters.

Based on the above investigation of the oxidation reaction, we propose a unique method for realizing 3D photonic crystals in GaAs/AlGaAs-based material. First, layers of GaAs and AlGaAs are epitaxially grown on a GaAs substrate. A two-dimensional array of holes is then patterned. The two-dimensional array is then etched across all the GaAs/AlGaAs layers thus preserving the crystalline structure and allowing for the presence of active layers such as quantum well heterostructures for emission and/or detection of light. The sample is then oxidized. This method, relies on the dependence of the oxidation rate on the relative content of aluminum in the AlGaAs alloy. The Al concentration in consecutive layers depends on the desired profiles of final etched holes and varies continuously. Since the Al concentration varies with the distance from the top surface of the substrate, the oxidation, which starts at the inner surface of the cylindrical openings, will proceed sideways at rates that are a function of the distance from the top surface. In particular, it is possible to engineer the profile of Al concentration such that the resulting oxidized regions are spherical, spheroidal, or of another shape that is desirable for the completed device. Finally, the oxide is selectively removed in aqueous hydrofluoric acid solution to leave behind a three-dimensional array of spherical voids constituting a photonic crystal.

6110-26, Session 7

Manufacture and replication of a novel polymer anti-reflective structure

S. M. Scott, Reflexite Precision Technology Ctr.; M. Gebhard, Fresnel Optics GmbH (Germany)

A novel manufacturing technique has been developed to make a stochastic antireflective structure into polymer substrates. This paper discusses the production method, replication of the structure by electroforming, test results, and applications for a new antireflective structure, PlasmAR. This capability has enhanced performance properties over visible wavelengths when compared with conventional single and multilayer antireflective coatings on polymers. Applications of the surfaces into precision polymer optic are demonstrated.

6110-28, Poster Session

Fabrication of 3D photonic crystal by deep x-ray lithography

G. Liu, Y. Tian, Y. Xiong, Y. Kan, Univ. of Science and Technology of China (China)

Synchrotron radiation lithography is applied to fabricate three-dimensional photonic crystal (3D PC) because it has an extremely high level of accuracy. The general method is multi tile X-ray lithography. Although it is a simple method, it is difficult to meet the main requirements of 3D PC. In this paper, we present our progress in the fabrication of 3D PC by means of multi deep X-ray lithography. The process of multi deep X-ray lithography is: Firstly, the cube or cuboid of resist sample is shaped by lathe. Then, the microstructures are patterned by three times deep X-ray lithograph through three surfaces that are vertically each other. After develop, the 3D PC is obtained. In this process, the alignment is necessary.

The method possesses great flexibility because the size of microstructure in mask is independent. It can be used for fabricating 3D photonic structures of various types. In other words, the method holds possibilities for designing complex lattice. Another advantage is that a variety of lattice defects can be introduced. Forms and positions of defects can be varied within wide limits with high accuracy provided by X-ray lithography. This method compares with layer-by-layer technique that is the most promising methods at present. And it just needs three times X-ray lithography. This method has been demonstrated in NSRL. The result shows that it is suitable to meet the main requirements of 3D PC by means of this method.

6110-29, Poster Session

Novel method for fabrication of high-efficiency diffractive optics for short wavelength radiation

R. Garg, J. Evertsen, G. Denbeaux, SUNY/Univ. at Albany

Extreme ultraviolet lithography (EUVL) is the most likely next generation lithography technique which uses radiation near 13.4 nm wavelength. At this short wavelength, most materials readily absorb the radiation, making refractive lens optical system unusable. We demonstrate a novel method for fabrication of highly efficient diffractive optics for extreme ultraviolet (EUV) radiation using focused ion beam (FIB). These optics are

based on fresnel zone plates, similar to those used for x-ray microscopy, but with a geometry to improve the efficiency for EUV radiation. A typical zone plate has concentric rings with a radially decreasing feature size such that the path of light through every second zone to the focus differs by one optical wavelength following the Bragg's Law. An optic with a net efficiency of 21% can be achieved for 13.4 nm radiation using the standard zone plate design with 86 nm thick zones made from Mo and mounted on a 50 nm silicon nitride membrane. Further improvement in the efficiency can be achieved by fabricating blazed zone plates, which can have a net efficiency of 37% when fabricated on a 50 nm Si3N4 substrate. These lenses are cheap to manufacture and easy to align for imaging since it is a single optic. The preliminary data will be presented on the fabrication of standard as well as blazed zone plates optimized for EUV radiation.

6110-30, Poster Session

Technology development of mold fabrication for free-form surface, DOE, and microlens

S. Kitagawa, H. Owari, S. Kawai, M. Seigo, Nalux Co., Ltd. (Japan)

In mold fabrication of plastic and glass optics, we have successfully achieved diversification and wider combination in shape and higher accuracy with nanometer level, which recent more sophisticated optical design requires us.

By developing technology of, for example, grinding and magnetorheological finishing (MRF), new raster fabrication, and micro-milling, we fabricated a tungsten carbide tool for molding glass free-form surface (profile accuracy of less than 200nm in PV, surface roughness of less than Ra5nm), a molding tool for 188-microlens array with radial arrangement, microscopic pins by cutting (3um in diameter, 100um in height), and a molding tool for DOE with little optical loss.

Moreover, to create inventive glass optics, we need to develop mold materials which can be used at a high temperature. We have also worked on development of mold materials such as nano-structural sintered material or ceramic with partially stabilized molecular structure and obtained some positive results.

6110-31, Poster Session

Tolerancing microlenses using ZEMAX

A. Stockham, MEMS Optical Inc.

This paper demonstrates a new tolerancing technique that allows one to predict the optical performance of a microlens based on metrology measurements taken during the fabrication process. A method for tolerancing microlenses using the optical design code ZEMAX is presented. Parameters able to be measured by available metrology tools are assigned tolerances. The goal of the tolerance analysis is to assess the sensitivity of a given design to changes in the shape of the lens surface with regard to a specific optical performance criteria relating to the intended application. Two designs are presented as well as the results of the tolerance analysis. In the first design, the radius of curvature and conic constant are varied for an aspheric lens, and the change in the spot size is determined. For the second design, fiber-coupling efficiency is tracked for a biconic lens. In each case, a metric can be produced showing the ability of the design to meet performance goals within the specified tolerances. A fabrication technician can then use this tolerancing metric along with the metrology data to determine if the device will yield acceptable performance. The metric can also determine if a design is overly sensitive to expected tolerances, thereby allowing the optical designer to evaluate the design from a manufacturing perspective.

Conference 6111: Reliability, Packaging, Testing, and Characterization of MEMS/MOEMS V

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6111-01, Session 1

Stiction force estimation from detachment length and electrostatic measurements on cantilever beams

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An estimate of stiction force, rather than the more commonly reported surface energy, is necessary to design reliable surface micromachined structures where stiction is a major cause of failure. In this work, we report on the modeling and estimation of the stiction force from simple I-V measurements on cantilever beams that can be carried out even on packaged devices. We have fabricated oxide anchored cantilever beams of polysilicon by surface micromachining. Current is measured for bias applied between the beam and the substrate. Pull-in and pull-out voltages are determined as the points of maximum slope calculated by differentiating a cubic spline fit to the measured I-V data. The commercial package CoventorWare was used to develop an empirical model for estimating the pull-out voltage for the cases i) when there is no stiction and ii) in the presence of stiction. An analytical model is developed for finding the stiction force from the simulated and the experimental pull-out voltage. The method uses only measured values of pull-in and pull-out voltages and the beam length and does not require the value of Young's modulus. We also discuss an independent visual method to estimate the process stiction force from the cantilever beam array that is normally used to estimate the surface adhesive energy. An analytical model is developed to calculate the stiction force from the detachment length that uses the Young's modulus determined from pull-in measurements on shorter cantilever beams released in the same process.

6111-02, Session 1

The use of electrical actuation to repair stiction-failed micro-cantilevers

K. D. Murphy, A. A. Savkar, Univ. of Connecticut

Recently, it has been proposed that sticking contact between micro-scale components may be relieved (i.e., the components may be unstuck) using structural vibrations. The means to excite these vibrations plays a critical role in the physical mechanism responsible for the initiation of stick-release. For example, it has been shown that mechanical actuation using, say, an instrumented nanoindentor is most effective near a resonant frequency. Aside from showing the fundamental mechanism responsible for the repair (resonance), it also provides insight for choosing optimal excitation parameters, such as excitation amplitude and frequency, for stick-release. In the present paper, periodic electrical excitation is explored as a means of inducing structural vibrations. This is a more practical means of producing the necessary vibrations, since it uses the functionality of the micro-device to effect its own repair. It is shown that electrical excitation produces stick-release through a fundamentally different mechanism than its mechanical counterpart. Here, stick-release is achieved via unstable self-excited vibrations. This fact has a significant influence on the practical matter of choosing appropriate excitation parameters to produce the desired repair. Using the underlying physics, appropriate parameter combinations are mapped and then used successfully in experimental tests on stuck micro-cantilevers.

6111-03, Session 1

Electrical breakdown across micron scale gaps in MEMS structures

F. W. Strong, J. L. Skinner, Univ. of California/Davis and Sandia National Labs.; N. C. Tien, Univ. of California/Davis

Large voltage differences between closely spaced MEMS structures can cause severe electrical breakdown and device destruction. In this study, a variety of planar electrode configurations were designed and fabricated using standard MEMS surface micromachining methods and materials. These devices were physically tested for breakdown response to provide further understanding of electrical breakdown limits in planar MEMS structures, and more complete design constraints for surface micromachined thin film devices.

Paschen's law, based on impact ionization avalanche breakdown, states that the product of pressure and gap distance determines electrical breakdown voltage. All of our tests were performed in air at atmospheric pressure. The specific range of single gap distances investigated (0.5μm to 10μm) is significant because it includes a transition region between large gaps (> 7μm) that strictly follow the Paschen curve, and small gaps (< 2μm) in which electrode vaporization due to field emission becomes the dominant breakdown process. Tests were performed both on bare polysilicon structures, and devices with gold sputtered on top surfaces and electrode sidewalls.

We also investigated the addition of an electrically floating device region between widely spaced energized electrodes, with narrow air gaps separating the floating region's ends from the electrodes. Structures with both in-line and overlapping offset regions were tested. These double air gap configurations were able to stand off significantly higher voltages than comparable devices with single air gaps. This double air gap method can enable novel device configurations for high voltage switching applications.

6111-04, Session 1

Infrared laser deposition of Teflon® coatings on microstructures

R. F. Haglund, Jr., Vanderbilt Univ.; C. P. Grigoropoulos, K. Komvopoulos, Univ. of California/Berkeley; M. R. Papantonakis, Naval Research Lab.; K. E. Schriver, Vanderbilt Univ.

Polytetrafluoroethylene (PTFE, trade name Teflon®) has a wide range of unique and desirable physical, electrical and chemical properties. Its tribological properties are well-suited to anti-stiction applications, and its chemical inertness commends it as a barrier and passivation layer. However, conventional thin-film techniques are not suited for depositing Teflon® films on microstructures. Spin coating is impossible because of the well-known insolubility of PTFE. Plasma polymerization of fluorocarbon monomers, ion beam and rf sputtering produce PTFE films that are deficient in fluorine. Pulsed laser deposition (PLD) using excimer and Ti:sapphire lasers has proven unsatisfactory because UV or near-IR laser ablation 'unzips' the PTFE, thus requiring high temperature annealing to re-polymerize the deposited monomeric film.

We have demonstrated that a completely dry, vapor-phase coating technique - resonant infrared pulsed laser deposition (RIR-PLD) at a wavelength of 8.26 μm -produces crystalline, smooth Teflon® films at low process temperatures. Indeed, the films as deposited by RIR-PLD exhibit a surprising degree of crystallinity even at room temperature. The stoichiometry and local electronic structure are preserved during the laser vaporization process, as demonstrated by IR absorption and X-ray photoelectron spectroscopy. Films deposited on microscale structures show

good adhesion, excellent smoothness, and a high degree of conformability to the structures. Our most recent experiments compare the tribological properties of the PTFE films deposited by RIR-PLD with other standard tribological coatings. We will also discuss the implementation of RIR-PLD in practical processing schemes for MEMS applications, including the challenge in adapting existing solid-state mid-IR laser technology for this purpose.

6111-05, Session 1

Galvanic corrosion: a microsystems device integrity and reliability concern

D. C. Miller, Univ. of Colorado at Boulder; W. L. Hughes, Z. L. Wang, K. Gall, Georgia Institute of Technology; C. R. Stoldt, Univ. of Colorado at Boulder

Galvanic corrosion may occur when two or more dissimilar materials are electrically connected and then immersed in an electrolytic solution. In particular, we study the self-induced corrosion of phosphorus-doped polysilicon contacted with gold, when the materials are soaked in various hydrofluoric acid (HF) solutions. Significant change in device performance has been observed, including increase in through-thickness strain gradient (curvature), decrease in resonant frequency, increased electrical resistance, and catastrophic device failure (nonfunctionality). Change in device performance is facilitated through change in material properties, including change in surface morphology, increased porosity, decreased hardness, and decreased modulus. Chemistries investigated include mixtures of 'undiluted' 48% HF (UDHF), hydrochloric acid (HCl), ethanol (C2H6O), water (H2O), ammonium fluoride (NH4F), Triton-X surfactant, and vaporous HF (VHF). The consequences of the observed change in device performance and material morphology include impact upon the material properties, design, performance, fatigue, tribology (friction/ wear) and manufacture of micro- and nano-scale devices. This paper will describe MEMS devices used to demonstrate measurable change in performance after being exposed to the silicon dioxide etching chemistries most commonly used in the industry. Change in materials morphology will also be explored with discussion of anodic oxidation mechanisms and implications of the corrosion phenomenon.

6111-07, Session 2

Reaction layer evolution during cyclic loading of micron-scale polycrystalline silicon films used in MEMS

O. N. Pierron, C. L. Muhlstein, The Pennsylvania State Univ.

Delayed failure of cyclically-loaded silicon films at room temperature in laboratory air may be explained by the reaction-layer fatigue mechanism. During reaction-layer fatigue, materials that are ostensibly immune to cyclic degradation in their bulk forms accumulate damage in the surface oxide layer that evolves upon exposure to the service environment under high cyclic stress. In this study, 2 micron thick polycrystalline silicon film resonators (natural frequency: 40 kHz) were tested in controlled environments to establish the importance of relative humidity and stress, and to confirm the evolution of the surface oxide layer during fatigue. Consistent with the reaction-layer fatigue mechanism, damage accumulation measured via resonant frequency changes was strongly affected by atmosphere and cyclic stress amplitude. Specimens that failed after a larger number of cycles (lower stress amplitude) experienced a larger decrease in resonant frequency (as much as 30 Hz). In addition, increasing humidity levels increased the adsorbed water layer thickness and the fatigue damage accumulation rate. Field emission scanning electron microscopy (FESEM) revealed smooth failure origins on high-cycle fatigued specimens that did not appear to be influenced by the grain morphology. Furthermore, Auger electron spectroscopy (AES) confirmed oxide thickening due to high cyclic stress on a material initially covered with a thin native oxide. The implications of these findings for alternative mechanisms will be discussed.

6111-08, Session 2

Stiffness modification of micromachined silicon beams using carbon nanotubes

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

Carbon nanotubes (CNT) have been measured to have very high axial modulus of elasticity ~1 TPa. Incorporation of the high modulus CNT into MEMS thin films is expected to improve the elastic properties of deposited thin films. We incorporated CNTs on to MEMS structures and observed an increase in the stiffness of the micromechanical structure. In this paper we report the first observation of the improvement of the stiffness of MEMS structures by addition of CNT. A detailed analysis of the observed improvement in the mechanical properties of thin films and the practical implications of these findings for MEMS devices will be explored.

Micromachined bridge structures fabricated using dissolved wafer process were spray coated with single walled CNT (SWNT). Since the SWNT are suspended in NMP solvent, the spray coating was done locally on each bridge using a piezoelectric printhead. Resonance frequency measurements were done in vacuum on the bridges after successive SWNT depositions. An increase in the resonance frequency was observed which can be attributed to an increase in the stiffness due to the surface incorporation of SWNTs. A distinct logarithmic gas desorption behavior of the CNTs was inferred from the change in resonance frequency with time. Such logarithmic desorption behavior was not observed for uncoated bridges. A maximum change of ~37.9% (effective modulus of 237 GPa for B-doped Si) was inferred from resonance frequency changes.

6111-09, Session 2

Experimental and computational study on laser heating of surface micromachined catilevers

L. M. Phinney, O. B. Spahn, C. C. Wong, Sandia National Labs.

The response of surface micromachined polycrystalline silicon (polysilicon) cantilevers after 808 nm laser heating was investigated experimentally and numerically in order to advance the understanding of the effects of lasers on microsystems. Lasers are broadly utilized in microelectromechanical systems (MEMS) applications as integral components in optical devices, as displacement detectors, and as fabrication tools in MEMS processing. For optical MEMS devices, laser irradiation of the device is integral to the functionality of the device. Polysilicon cantilevers were fabricated using the fourth structural layer, poly4, in the SUMMiT V process. The cantilevers are 250 μm wide, 500 μm long, and 2.25 μm thick. The polysilicon cantilevers were exposed to varying amounts of focused laser power and their surfaces were monitored using white light interferometry before, during and after laser irradiation. Up to 1 W of continuous wave 808 nm light was incident on the cantilever surface from a 100 μm core fiber with a lens on the end that re-imaged the fiber core onto cantilever surface. At low laser powers, the cantilevers are not significantly affected. However, as the laser powers are increased above 400 mW significant deflection is observed during the laser pulse. Permanent deformation is observed at laser powers above 650 mW. Additionally, a coupled physics analysis code, Calagio, was used to simulate the thermo-mechanical response of the cantilevers when they are being irradiated with a laser beam. The predicted maximum deflection compares reasonably well with the experimental measurement.

6111-10, Session 2

Bending of aluminum alloy beams depending on irradiance and repetition rate of UV-laser radiation

M. Krellmann, M. Friedrichs, U. A. Dauderstädt, Fraunhofer-Institut für Photonische Mikrosysteme (Germany)

Aluminum alloy beams having the same width but different lengths were made with semiconductor fabrication methods at the IPMS. The beams are clamped on one end with posts to the underlying plane. They are illuminated with 248 nm UV radiation created by an excimer laser and the bending was investigated in dependence on energy density and repetition rate. This behaviour is important for the development and the use of micromirror structures when used in UV applications.

Ultraviolet radiation is used for lithography as well as material processing. The light-material interaction is well investigated for high energy densities which are used for drilling holes or ablation of materials. In this work the influence of 248 nm low energy pulses (Ed < 200 μJ/cm≤) on thin beams of aluminum alloys having a thickness of several hundreds of nanometer is analyzed. The frequency of the laser radiation is varied from 500 to 2000 Hz. The beams have different lengths and are clamped on one end. Before illumination the beams are planar, after illumination the beams show a curvature which is related to internal stresses. The amount of curvature is dependent on the geometry of the beam, the energy density and the repetition rate of the radiation pulses. Also the relaxation behaviour of the curved beam is examined, i. e. does the curvature change after the end of irradiation. The results will help to predict the practicability of materials for MOEMS in UV applications (mirror structures) and to understand their behaviour.

6111-12, Session 3

Reliability of MEMS for space applications

H. R. Shea, Swiss Federal Institutes of Technology (Switzerland)

MEMS sensors, actuators, and sub-systems are extremely appealing for reducing the size and mass of spacecrafts without sacrificing functionality, first by replacing larger heavier components with lighter MEMS parts, then by replacing entire subsystems and finally by enabling the microfabrication of entire picosats. MEMS are playing a growing role on earth (TI's DMD chip, accelerometers for air-bag deployment, optical switching, -). So what is holding back MEMS from playing a lager role in space applications? In the harsh and remote environment of space, reliability is the crucial issue.

We begin with a brief overview of MEMS applications in space. We then examine how MEMS reliability is handled in commercial MEMS devices used in safety critical applications on the earth. We contrast the operating conditions on earth with those encountered during launch and in orbit. We explain the impact that vibration, mechanical and thermal shock, and radiation can have on MEMS devices. Accelerated tests adapted to space qualification are presented as a means to determine the major failure modes. We propose design rules for MEMS to avoid such failures, such as selective etching of dielectric for radiation hardness, material and suspension design for high shock resistance (over 1000 G), and anti-stiction coatings. Packaging is crucial to ensuring long-term reliability. We conclude with an outlook of MEMS reliability and examples of MEMS that will soon be flown in space.

6111-13, Session 3

Reliability testing and qualification of the TeraVicta rf-MEMS switch

J. S. McKillop, TeraVicta Technologies, Inc.

In the absence of standards for reliability testing and qualification of different families of MEMS components, each MEMS manufacturer is obliged to develop, implement and validate a system of manufacturing and testing procedures that insure that each component meets or exceeds its specified operating performance within its specified operating environment(s) over its specified operating life. This paper presents the results of work by Teravicta Technologies to adapt semiconductor industry standards and practices to the qualification of RF MEMS switch components. This includes a discussion of applicable qualification standards, an overview of parametric and reliability test results, identification of key failure modes, the development of failure accelerants and accelerated life test procedures, and final qualification results. Although some tests are unique to the RF MEMS switch, the methodology presented here provides a sound starting point for the development of qualification procedures for other MEMS devices.

6111-14, Session 3

Reliability of MEMS in liquid environments

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

In this paper, reliability and long term performance of MEMS in liquid environments is investigated. An understanding of reliability of MEMS in liquid environments is important because of the many possible applications of micro devices in chemical, pharmaceutical, biomedical, consumer product, and defense industries. Single Crystal Silicon (SCS) micro-cantilevers are subjected to long term cyclic actuation in enclosures filled with either corrosive or non corrosive liquids e.g. water and saline solution. The resonance frequency and Q factor of the resonant peak are periodically monitored to track changes in performance. Since MEMS are low power devices, these micro cantilevers are typically subjected to stress levels ranging between 1-100 MPa, much below their fracture strength of 1 to 3 GPa. While for such stress levels complete structural fatigue failure is neither expected nor observed, a shift in performance of the micro-cantilevers is observed. When subjected to long term cyclic stresses (=106-1010 cycles), resonance frequency of the silicon micro cantilevers is observed to change with increasing number of cycles. For example, the resonance frequency of silicon micro cantilevers actuated in water is observed to decrease with increasing number of cycles, while those in actuated in air showed an increased resonance frequency. The results of this study emphasize that shift in performance constitutes failure under cyclic stresses at the microscale, as opposed to complete structural fatigue failure at the macroscale. Further, our findings demonstrate that an understanding of MEMS reliability in air cannot be extended to explain and predict device reliability in liquid environments.

6111-15, Session 3

A density-viscosity MEMS sensor for oilfield applications

C. K. Harrison, S. Ryu, A. Goodwin, K. Hsu, Schlumberger; E. Donzier, Schlumberger (France); F. Marty, B. Mercier, Groupe ESIEE (France)

We present a sensor fabricated with MEMS (Micro-Electromechanical System) technology that upon immersion quickly measures a fluid's density and viscosity. 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. This sensor is sufficiently robust to provide valuable information of down-hole live fluids for the petroleum industry. By performing measurements in a series of gases and liquids over a wide range of temperature and pressure (20 to 150) C and (0.1 to 75) MPa, we have demonstrated a maximum inaccuracy in our density and viscosity measurements of approximately +/- 1 % and +/- 10 % respectively, in the density and viscosity ranges of (0.6 to 1.5) g/cc and (0.4 to 100) cP. Such measurements are required to determine the economic feasibility of recovering hydrocarbon from subterranean strata. Hydrocarbon bearing formations often have gross values that exceed one billion US dollars.

6111-17, Session 4

Failure mechanisms of DC and capacitive rf-MEMS switches

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MEMS switches hold great promise in a myriad of commercial, aerospace, and military applications including cellular phones and phased array antennas. However, there is limited understanding of the factors that determine the performance and reliability of these devices. Fundamental studies of hot-switched DC (gold versus gold) and capacitive (gold versus silicon nitride) MEMS radio frequency (RF) switch contacts were conducted in air at MEMS-scale forces using a micro/nanoadhesion apparatus as a switch simulator. This presentation will review our key experimental results and how they relate to failure mechanisms of MEMS switches.

For DC switch contacts, electric current had a profound effect on deformation mechanisms, adhesion, contact resistance (R), and reliability/durability. At low current (0-10 microAmps), junction growth/force relaxation, slightly higher R, and switching induced adhesion were prominent. At high current (1-10 milliAmps), asperity melting, slightly lower R, and shorting were present. Adhesion increased during cycling at low current and was linked to the creation of smooth surfaces, increased van der Waals interaction, and chemical bonding. Surface roughening by nanowire formation (which also caused shorting) prevented adhesion at high current. Aging of the contacts in air led to hydrocarbon adsorption and less adhesion.

Studies of capacitive switches demonstrated that excessive adhesion was the primary failure mechanism and that both mechanical and electrical effects were contributing factors. The mechanical effect is adhesion growth with cycling due to surface smoothening, which allows increased van der Waals interaction and chemical bonding. The electrical effect on adhesion is due to electrostatic force associated with excess charge trapped in the dielectric, and was only observed at 40 volt bias and above. The two effects are additive; however, the electrical effect was not present until the surfaces were worn smooth by cycling. Surface smoothening increases the electric field in the dielectric, which results in trapped charges, alterations in electrostatic force, and higher adhesion. Excessive adhesion can explain decreased lifetime at high bias voltage previously reported with actual capacitive MEMS switches. Switch sticking, self-actuation, failure to actuate, and self release can all be explained by the experimental results.

6111-18, Session 4

Reliabilty study of ohmic contacts in rf MEMS

R. Ramadoss, Auburn Univ.

No abstract available.

6111-20, Session 4

A transient charging model to predict actuation-voltage shift in rf-MEMS capacitive switches

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RF MEMS is an emerging technology for low loss switch, phase shifter, and reconfigurable network applications. However, commercialization of RF MEMS devices is hindered by the need for continuing improvements in reliability and packaging. In particular, the lifetime of electrostatically actuated RF MEMS capacitive switches is limited by dielectric-charging effects. For the state-of-the-art RF MEMS capacitive switch, a dielectric-charging model was constructed to predict the amount of charge injected into the dielectric and the corresponding shift in actuation voltage. The model was extracted from the charging and discharging transient currents of traps in the dielectric of the RF MEMS capacitive switches. Densities and time constants of different traps were extracted under various control voltages. The model was used to predict the actuation-voltage shift of real switches under accelerated life test conditions and found to be in good agreement with the experimental data. Effects of peak voltage, frequency, and duty factor on charging were analyzed using the model and validated experimentally. Peak voltage and duty factor were found to be critical acceleration factors, whereas the frequency had little effect on charging. Based on these acceleration effects, the present model can be used to design a favorable actuation waveform to minimize charging thus prolong the lifetime of RF MEMS capacitive switches. Conversely, the present model can be used to design an efficient actuation waveform to accelerate charging and to validate the lifetimes obtained through accelerated life tests.

6111-21, Session 4

A micromachined resonant force sensor for passive micrograpping applications: 3D microassembly

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In this paper, a polysilicon double-ended tuning fork (DETF) is proposed for use as a force sensor for integration into a compliant, passive microgripper used in a microassembly of 3D MEMS structures. The force sensor is also designed to operate in a manner similar to scanning probe microscopy (SPM) that is commonly utilized to study surface properties and topography of material. The design, modeling, and performance characteristics of the resonant force sensor are addressed. The force sensor design has a resolution of 1.0 pN/ in absence of electronics and power noises. Furthermore, a gauge factor (i.e. sensitivity) of 1700 is obtained with applied force of 30 μN. A DETF excitation and detection technique is proposed to minimize parasitic capacitance effects.

6111-22, Session 5

High-g testing of MEMS devices

R. O'Reilly, Analog Devices, Inc.

Replicating the mechanical environments to which MEMS devices are exposed requires extreme test strategies. Acceleration levels in the 10's of thousands of g's are a normal occurrence in today's MEMS applications. Traditional test methods in use for over a half century are no longer adequate. New test methods are constantly required to meet the demanding quality and reliability levels of everything from emerging consumer applications to safety critical automotive systems. This presentation will describe the path from traditional to extreme shock and vibration testing.

6111-23, Session 5

Experimental apparatus and software design for dynamic long-term reliability testing of a spring-mass MEMS device

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Long-term reliability testing of Micro-Electro-Mechanical Systems (MEMS) is important to acceptance and use of these devices in critical and high-impact applications. In order to make predictions on aging mechanisms, the experiments must be performed in controlled environments. Additionally, because the acceleration factors are not understood, the experiments can last for months. This paper describes the design and implementation of a test facility for accelerated life testing of MEMS devices. Some early results of a fatigue test will be discussed.

The system is comprised of a small environmental chamber mounted on an electrodynamic shaker with a laser Doppler vibrometer (LDV) and digital camera for data collection and is shown in Figure 1. The humidity and temperature controlled chamber has mounting places to test a 4 x 4 array of MEMS components. The shaker is used to dynamically excite the devices using broadband noise, chirp or any other programmed signal via

the control software. Driving amplitudes can be varied to maintain the actuation level of the test units at the desired level. The actuation is monitored optically via the LDV which can report the displacement or velocity information of the surface. A digital camera can take inspection images of the devices during testing and is also used for positioning the laser beam to the desired location. A translation stage allows the LDV to be automatically positioned over any of the 16 samples.

This experimental apparatus is ideal for fatigue testing of MEMS spring-mass systems in humid environments. One of the main concerns is that the mil-standard packaging environment of 5000 ppmv (~13% RH at room temperature) may be too humid for long-term reliability of these systems. Earlier work in thin-film silicon has shown that as long as the stresses stay below ~50% of the monotonic failure strength when in a 50% RH environment, the structures will likely survive more than 1011 cycles. However, no work has been done at lower humidity and stress levels, which may require longer time intervals.

The reliability testing has been automated via software to control and record all of the pertinent data. This includes an image of the device (Figure 2), temperature, humidity, LDV signal strength, and a time history of the vibration response. The current spring-mass devices are interrogated using a chirp signal containing the frequencies of interest. Modal analysis methods using the time-history of the velocity during the chirp are then used to accurately determine the resonant frequency of the MEMS component. During the dwell time between measurements, a broad-band noise signal (including all the frequencies of interest) is used to exercise the test samples. Vibration amplitude can be monitored and set via software. Sample measurement intervals can be set in the software and changed interactively.

The first experiment was started using a controlled environment of 5000 ppmv humidity and maximum displacement of the mass of ±80 μm. During the first part of the experiment, the resonant frequency was measured every 2 hours. From 114.5 to 450 hours under stress, measurements were taken every 12 hours and after that every 24 hours. Resonant frequency changes over time are being monitored. The initial data is shown in Figure 3. The resonance looks stable indicating no changes in the structures.

6111-24, Session 5

Guidelines for long-term performance testing of microelectromechanical systems in military applications

R. B. Mason, M. Rippen, L. Gintert, Concurrent Technologies Corp.; D. Skelton, J. L. Zunino, U.S. Army Research, Development and Engineering Command; I. Gutmanis, Sterling Hobe Corp.

Micro-electromechanical systems (MEMS) and microsystems technologies are seeing increased consideration for use in military applications. Assets ranging from aircraft and communications to munitions may soon employ MEMS. In all cases, MEMS devices must perform their required functions for the duration of the equipment's mission profile. Assurance of long-term performance in a given scenario can be assured through an understanding of the predominant MEMS failure modes. Once the failure modes have been identified, standardized tests will be developed and conducted on representative devices to detect the potential for these failures. Failure mechanisms for MEMS devices in severe environments may include wear and stiction. While corrosion is not usually a concern for commercial MEMS devices, as they are made primarily of silicon, other materials, including metallics, are being considered for MEMS to provide enhanced robustness in military applications. When these materials are exposed to aggressive military environments, corrosion may become a concern. Corrosion of metallic packaging and interconnect materials may also present issues for overall performance. Considering these corrosion and degradation issues, there is a need to implement standardized tests and requirements to insure adequate long-term performance of MEMS devices in fielded and emerging military systems. To this end, Concurrent Technologies Corporation has been tasked by the U.S. Army to initiate efforts to standardize test methods that have been developed under previous activities. This paper presents an overview of the MEMS activities under TDPMD and the MEMS reliability test guidelines that have been drafted as a first phase of the standardization effort.

6111-25, Session 5

The ultra-fine dynamics of MEMS as revealed by the polytec microsystem analyzer

E. M. Lawrence, Polytec, Inc.; C. Rembe, Polytec GmbH (Germany); H. Zhang, XCOM Wireless, Inc.

Polytec presents its latest Micro System Analyzer for dynamic characterization of MEMS. We have developed a new, optimized design based on confocal microscope optics. This paper explores the dynamic measurement capabilities of this system down to the fundamental limitations of current technology.

Polytec continues to advance laser Doppler vibrometry since its introduction as a MEMS characterization tool in 1990's. Laser vibrometer out-of-plane resolution down to 0.2 pm / root 15.6 Hz is achieved by combination of highly sensitive Doppler shift measurement, digital decoding techniques and FFT signal analysis. Laser spot sizes less than 700 nm are measured for a high magnification 100X microscope objective and compared to theoretical limitations. The sectioning characteristic of the optical setup was measured to determine depth of field. High bandwidth to 30 MHz is achieved by use of high frequency displacement decoding and fast data acquisition boards.

Furthermore, we have advanced in-plane response measurements with differential measurement capability and resolution better than 0.01 pixel. Example measurements that illustrate the unique measurement capabilities are performed on Sandia comb drive resonators, cantilever beam structures and RF switches. New measurements on the Sandia comb drive show clear advances in resolution, including the ability to place and focus the measurement beam on very tiny structures such as a 2 micron comb finger. Transient response measurements are taken to determine critical performance parameters on an RF MEMS device developed by XComWireless. This includes measurements of settling time, resonant frequency, snap down response and three dimensional deflection shapes of transient time response.

6111-26, Session 5

Novel combined low-coherence interferometry spectrally resolved reflectometry compatible with high-resolution Raman spectroscopy for nondestructive characterization of MEMS structures

W. J. Walecki, T. Azfar, A. Pravdivtsev, M. Santos, A. Koo, Frontier Semiconductor Inc.

Infrared low coherence optical interferometry (IRLCOI) has been proven to be an effective tool for characterization of modern MEMs structures such as deep high aspect ratio trenches and thin membranes [1], [2]. We propose novel tool employing both IRLCOI and spectrally resolved reflectometry (SRR) ñ the LCOIR-SSR sensor.

Application IRLCOI for measurements of the high aspect ratio structures [2] encounters challenges in regime where the aperture of measured features becomes comparable to wavelength of probing light. The demonstrate that the SSR spectrum of such structures allows us to extend range of IRLCOI to measure depth trenches with diameter from 2 um to 1 mm, and aspect ratio 0-20 beyond an with reproducibility 10 nm ñ 100 nm depending on range.

We also studied application of IRLCOI-SSR sensor for measurement of ultra-thin coated pressure sensor membranes. Application of auxiliary SSR allows to correct for systematic errors of IRLCOI which we demonstrate can be as large as 2 um.

IRLCOI-SSR is fully compatible with recently developed fully automated high resolution Raman spectroscopic system allowing us to achieve repeatability of Raman shift measurement better that 0.05 cm-1 which cor-

responds to strain of crystalline silicon of the order of 0.06% or less.

1. Wojciech J. Walecki, Frank Wei, Phuc Van, Kevin Lai, Tim Lee, SH Lau, and Ann Koo , Reliability, Testing, and Characterisation of MEMS/MOEMS III, edited by Danelle M. Tanner, Rejeshuni Ramesham, Proceedings of SPIE Vol. 5343 p. 55-62 (SPIE, Bellingham, WA, 2004)

2. Wojciech J. Walecki, Kevin Lai, Alexander Pravdivdivtsev, Vitali Souchkov, Phuc Van, Talal Azfar, Tim Wong, SH Lau, and Ann Koo, Reliability, Testing, and Characterization of MEMS/MOEMS IV, edited by Danelle M. Tanner, Rejeshuni Ramesham, Proceedings of SPIE Vol. 5716 p. 182-188 (SPIE, Bellingham, WA, 2005)

6111-27, Session 6

High and stable Q-factor in resonant MEMS with getter film

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The need to reach high and, mainly, stable values of the Q-factor is one of the most important issues of resonant MEMS in order to make high-performance sensors. The Q-factor is strongly influenced by the internal environment of the MEMS packaging, by total pressure and by gas composition. The most experienced and technically accepted way to keep the atmosphere stable in a hermetically sealed device is to use getter material that is able to chemically absorb active gasses under vacuum or in inert gas atmosphere for the lifetime of the devices. MEMS hermetically bonded devices such as gyroscopes, accelerometers, pressure and flow sensors, IR sensors, RF-MEMS and optical mirrors requires getter thin film solutions to work properly. Getter technical solution for wafer to wafer hermetically bonded MEMS systems is PaGeWafer, a silicon, glass or ceramic wafer ('cap wafer') with patterned getter film, few microns thick. In this paper, first the theoretical evaluation of Q-factor of a MEMS resonant structure in presence of a getter film is investigated and compared to the results of a Residual Gas Analysis of the same MEMS resonant structure and with the conventional measurement of Q-factor. Using getter thin film technology, total pressures down to 10-4 mbar with corresponding high and stable Q-factors have been achieved in MEMS resonant structures. We were therefore able to confirm that getter film can provide high Q-values, stability of sensor signal, performances stability during the lifetime, removal of dangerous gases like H2 and H2O in hermetically sealed MEMS resonant structures.

6111-28, Session 6

Wafer bonding for 3D integration of MEMS/CMOS

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The pressure for reduction in cost and development time in new product, together with the need to pack more functions into smaller volumes in silicon chips has been fueling the system-on-chip (SOC) development. However, the current SOC technologies available essentially involve merging of chips fabricated with standard CMOS technology. These SOC technologies provide an integration solution with compatible fabrication processes that require little changes in process integration. There is no standard cost-effective solution to make 3D MEMS and optoelectronic devices together with CMOS on the same chip without compromising material compatibility, process complexity and system performance. One solution is to fabricate MEMS and CMOS components on separate wafer substrates and then stack them together with well isolated interconnected vias. In order to demonstrate this wafer-level 3D integration technology, a novel wafer-level bonding technology is being developed. This paper reports a detailed study of 3D MEMS (Micro Electro-Mechanical Systems) integration through multi-wafer anodic and polymeric wafer bonding. Different from previously reported wafer bonding studies, this study focuses on the impact of bonding process (e.g. reverse of electrical field in anodic bonding, temperature, time) to the mechanical integrity and bonding quality of bonded multi-wafer stacks.

6111-29, Session 6

High-speed anisotropic etching of glass for microsystems applications

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To date, efforts in silicon dioxide (glass) etching have been primarily directed towards realizing submicron features for microelectronics applications. With the advent of microelectromechanical systems (MEMS) and microsystems in the last decade, focus has shifted to high aspect ratio etching of silicon dioxide for applications in microfluidics[1], quartz based microsensors[2], and laboratory on a chip applications . Many of these applications require greater than 100 μm of glass etching while maintaining the surface finish, with rms surface roughness of less than 5nm[3,4]. Hence, these applications impose additional new requirements on glass etching processes such as high etch rate, high selectivity to masking material, high anisotropy, low surface roughness for mirror polish, uniformity of etch across the wafer and within a pattern [5], etc. In this paper, we present a detailed study of the various process parameters (ICP power, substrate power, operating process pressure, gas flow rates, ratio of gas flows, substrate temperature and distance from source) on the etch rate of features in Pyrex® 7740 glass substrates. Figure 1 shows a schematic drawing of the Alcatel AMS 100 ICP-RIE etcher used in this work.

6111-30, Session 6

Hot gas stream application in micro-bonding technique

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Joining micro parts of dimensions in the range of 50 μm to 300 μm in functional units (Hybrid MEMS) is possible by melting or softening different kinds of adhesives with the stream of hot gas. Afterwards, a micropart can be embossed in the adhesive or covered and shielded by it. The gas is heated by passing through the heating element developed and realised on a stainless steel tube (inner diameter 2 mm, outer diameter 4 mm) by a conventional thick film process. The stream of hot gas cures liquid epoxy glue and melts and cures adhesive foils (thicknesses in the range from 2 μm to 50 μm) or adhesive powder (the size of particles in the range from 5 μm to 60 μm, on average 32 μm). In the first experiments, an optical glass fibre of 125 μm diameter was positioned in appropriate V-grooves. The working temperatures in all cases are below 110° C. The melting point of optical fibre cladding is 125° C; thus the geometry and optical properties of the fibre are not affected. This method enables the local targeted heating with minimal residual thermal stresses. Realized joins are reliable, long-lasting and firm. The advantages of this new approach are numerous: small size of system, low capital costs, electrical efficiency, simplicity of use, applicable to many material combinations, easy integration in existing production lines etc.

The heat dissipation of gas stream was simulated using ANSYS, and estimated temperatures of gas stream or of the nozzle outlet were in good agreement with the experimental results.

6111-31, Session 6

Hermeticity tests on organically sealed micropackages using FTIR spectroscopy

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Hermeticity is one of the main reliability issues for MEMS packaging. Actually, with their released and mobile parts, MEMS are very sensitive to numerous failure mechanisms. A lot of these failure mechanisms such as

stiction or charging effects are dependent on their operational environment. So, it is necessary to control precisely the hermeticity of MEMS packages.

Most of the time, hermeticity measurements are performed by helium leak detection. Nevertheless, several studies have proved that this detection technique is not adapted to micro-cavities with a volume of 10 mm3 or less. Consequently, it should not be used to assess the hermeticity of MEMS micro-packages. Moreover, helium leak tests are not appropriate to measure the hermeticity of organic adhesive bondings, commonly used in MEMS micro-packaging.

In order to assess the hermeticity of MEMS micro-packages, we develop an alternative method to helium leak detection. This method uses the Fourier Transform Infra Red (FTIR) spectroscopy. The infra red spectroscopy is an analysis method that allows to determine qualitatively and quantitatively the composition of materials. It can be adapted to the hermeticity measurement of micro-cavities. Actually, classical materials used for MEMS packaging can be considered as transparent for the IR wavelengths. It is thus possible to measure the amount of a gas contained in a micro-cavity through the packaging material.

IR spectroscopy measurements have been carried out on different silicon-silicon micro-packages with organic (BCB) adhesive bondings bombed with nitrous oxide (N2O). This study has validated the use of the FTIR spectroscopy to assess the hermeticity of micro-packages. It also permitted to underline the link between the width of the sealing ring and the hermeticity for an organically sealed micro-cavity.

6111-11, Poster Session

A critical comparison and development of nano-mechanical characterization on MEMS/NEMS thin-film materials

J. H. He, Institute of Microelectronics (Singapore); H. Le, D. F. Moore, Univ. of Cambridge (United Kingdom)

Thin film mechanical characterization is crucial for MEMS/NEMS. There were many methods in the literatures. However, there are not many papers discussing the same materials using different methods to characterize its material micro-/nano- mechanical properties and compare their pros and cons. This paper is going to compare three different methods: 1) scanning and bending cantilever, 2) nanoindentation and 3) response frequency method, on the same materials: LPCVD silicon nitride and then to further more MEMS materials. Surface profilometer is used to scan along the μ-machined cantilevers and produce the bending profile, from which the Young's modulus can be extracted. The effects due to undercut, initial curling and misalignment have been carefully studied. FEA has been used to estimate some possible error by ANSYS. Indentation profiled produced by Nano-indenter can deduce Young's modulus and hardness of the thin film materials. Vibrometer is used to detect the resonance of the thin film cantilever, from which the stiffness, and therefore the Young's modulus can be derived. The material properties characterized by three methods are consistent and comparable with one another. The following MEMS materials: SiN, Ni, Ni/SiN bimorph, Nano-Diamond, SiC have been characterized and compared by using different method. Their advantages and disadvantages are also discussed.

6111-32, Poster Session

Temperature compensation analysis of liquid lens for variable-focus control

S. J. Chen, C. Shen, National Changhua Univ. of Education (Taiwan)

In this letter, a fabrication and temperature compensation analysis and electrowetting for the liquid lenses is proposed. The unique capability of controlling the lens profile during the electrowetting fabrication processes is successfully demonstrated for different ambient temperature environment.

The control of the lens profile is achieved by adjusting the voltage across a hydrophobic dielectric layer sandwiched between an electrically conductive liquid and an electrically conductive wall (the electrode), and thereby introducing different degrees of the electrowetting phenomenon. For a lens fabricated on a hydrophobic Teflon layer, it is found that when the applied voltage is increased, the focal length increases, and the curvature decreases. One challenge for the liquid lens is operating temperature range. A camera should operate between -30° C and +70° C and survive temperatures from -40° C to +85° C.

Due to the environment temperature change, the ability of controlling the lens profile is analyzed and measured. The description of change in contact angle corresponding to the variation of ambient temperature is derived. Based on this description, we firstly derive the control of voltage vs. temperature for a fixed dioptric power. The control of lens during a focusing action was studied by observation of the image formed by the light through the transparent bottom of ITO glass. Under several conditions of ambient temperature change, capability of controlling the lens profile for a fixed focus is successfully demonstrated by experiments.

6111-33, Poster Session

Design and fabrication of the degradation level monitoring sensor for power transformer insulating oil

S. Kim, Y. Kim, J. Yang, Kyungpook National Univ. (South Korea); S. Lee, Korean Agency for Standards and Technology (South Korea); S. Park, Kyungpook National Univ. (South Korea)

This paper presented the method to detect the degradation level of insulation oil for transformer. Degradation of insulation oil for transformer is due to both mechanical and chemical deterioration. Metallic particle and organic material such as a dust are known as the main reason of mechanical deterioration. According to degradation and oxidation of insulation oil for the time of transformer operation, total acid number (TAN) will be increased, sludge will be appeared, and finally conductivity will be decreased. Designed sensor, which is an inter-digit capacitive type, was fabricated by using MEMS technology and tested with used insulation oil, and result shows the good proportionality with time.

6111-34, Poster Session

An intensity based optical technique for fast 3D surface profiling of MOEMS

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A fast and computerized non-interferometric optical technique for 3D surface profile of microdevices is proposed. It uses a 3D image reconstruction technique based on physical optics models of light propagation, scattering and transfer and simply requires a standard white light optical microscope. This technique finds its full potential when most usual optical profilometry techniques cannot be applied i.e. when vibration-insensitive measurements or fast acquisitions are required. This software technique being fully automatic, no changes to the existing hardware in the optical paths of microscopes is required. Moreover, the image acquisition protocol associated with the technique allows for simpler and cheaper measuring devices than interferometric or holographic systems and open the possibility for creating portable devices. 3D surface profiling of micromechanical devices or of M(O)EMS can be achieved by this technique without compromising accuracy and lateral resolution. This is demonstrated from measurements on micromachined devices and their comparison with phase shifting interference microscopy measurements. The simple operation mode of this technique, its lower implementation cost and its lower sensitivity to vibrations with respect to established techniques makes it a promising procedure for routine M(O)EMS quality control in industrial environments.

6111-35, Poster Session

Modeling and analysis of MEMS-based resonant beam sensor actuated by bent beam thermal actuator

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

Resonant sensors are having attractive applications in the area of the precision measurement because of their high sensitivity and resolution. They convert a change in one mechanical characteristic such as force, strain or mass to a shift in the natural frequency of a mechanical part such as a beam or a membrane. This semi-digital output, i.e., the shift of the frequency, eliminates any complications such as intensity fluctuations generally associated with the analog signals. In this study the governing equations of a system, consist of an actuator and a sensor, are derived. The actuator is in the form of a bent beam thermal actuator, which provides an axial force to the sensor. The sensor is a resonant beam whose natural frequency will be shifted with changes in its axial force. A comb-drive exciter-detector is designed to detect the natural frequency of the beam and its variations due to the changes in the axial force. It must be noted that the thermal, mechanical and electrical fields are all dynamically coupled in this system. The governing equations, which indicate this interconnection, are solved analytically and the results are verified using the finite element method. The parameters of the sensor, namely, the gauge factor and quality factor are determined.

Conference 6112: Microfluidics, BioMEMS, and Medical Microsystems IV

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6112-01, Session 1

Digital microfluidics for biosensors, bio-assays, and biomedicine

A. P. Lee, Univ. of California/Irvine

Recent advances in microfluidics have paved the way for a 'digital' era, when packets of biochemical information can be created, processed, and stored on a bioprocessor chip. Several bioprocessor chip platforms are being developed for the interrogation and manipulation of biological and physiological activities. One such platform we are working on utilizes the control of amphiphilic interfaces in microfluidic devices to generate micro and nanoscale droplets/particles/vesicles The presentation will describe how we utilize self-assembly forces in nature to design nanoscale structures that interface biological components with physical transducers that interrogate their activities or allow external manipulation. By designing microfluidic laminar flow patterns of co-flowing immiscible fluids, monodisperse droplets (<2% deviation) ranging from 100 nm to 100 μm and can be generated at rates as high as 1000 drops per second. Droplet arrays in microfluidic channels present a novel method for controlling chemistry and self-assembly at picoliter to femtoliter volumes, scales that approach the level of cellular activities. Based on the materials delivered, droplets can then form polymer nanoparticles, lipid bilayer vesicles, and multilayer drug particles to form a nano vesicle factory (NVF) platform. To date, the NVF we are developing is incorporating: targeted molecular recognition, controlled delivery of drugs/reagents, detection of molecular events, and controlled reactions (movement, synthesis). For molecular recognition I will discuss two of my active projects. Collaborating with renowned synthetic chemists we are working on synthesizing nanoparticles with highly controlled molecular imprints. The ultimate goal is to generate 'synthetic monoclonal antibodies'. For targeted drug delivery we are collaborating with cardiologists to develop myocardial infarction (MI) targeting particles encapsulating both ultrasonic contrast agents and therapeutic agents. On molecular detection side, we are actively working on an extremely sensitive protein sensor array based on electrical detection. On controlled reactions, we have demonstrated controlled fusion of picoliter droplet reactors for the synthesis of semiconductor quantum dots with extremely narrow bandwidths (HPFW 15 nm). Other nanoscale features that can be designed into these vesicles to mimic biological functions include power generation, protein synthesis, and controlled molecular transport. My presentation will briefly introduce these projects and show how the technology being developed can provide powerful tools for interrogating the biological and physical interfaces.

6112-02, Session 1

Fully integrated multiplexed lab-on-a-chip assay for enteric pathogens

B. H. Weigl, PATH; J. Gerdes, Micronics, Inc.; L. Dillman, R. Peck, PATH; P. Yager, Univ. of Washington; D. Hoekstra, Micronics, Inc.; P. Tarr, Washington Univ. in St. Louis; S. Ramachandran, M. Lemba, Univ. of Washington

Under this NIH-funded project, we are developing a lab-on-a-card platform to identify enteric bacterial pathogens in patients presenting with acute diarrhea, with special reference to infections that might be encountered in developing countries. Component functions that are integrated on this platform include on-chip immunocapture of live or whole pathogens, multiplexed nucleic acid amplification and on-chip detection, sample processing to support direct use of clinical specimens, and dry reagent storage and handling. This new diagnostic test will be able to rapidly identify and differentiate Shigella dysenteriae serotype 1, Shigella toxin-producing Escherichia coli, E. coli 0157, Campylobacter jejuni, and Salmonella and Shigella species. This presentation will report on progress to date on sample and bacteria processing methodologies, identification and validation of capture antibodies and strategy for organism immunocapture, identification and validation of specific PCR primer sequences for over 200 clinical isolates of enteric pathogens, and implementation of on-chip nucleic acid extraction for a subset of those pathogens.

6112-03, Session 1

Water analysis on a lab-on-a-chip system

H. J. Freimuth, F. von Germar, I. Frese, E. Nahrstedt, B. Baser, K. Drese, P. Detemple, T. Doll, Institut für Mikrotechnik Mainz GmbH (Germany)

The development of a lab-on-chip system which allows the parallel detection of a variety of different parameters of a water sample is presented. Water analysis typically comprises the determination of around 30 physical and chemical parameters. An even larger number can arise when special contaminations of organic molecules are of interest. In order to show the feasibility and performance of an integrated device for the determination of physical quantities like electrical conductivity, light absorption and turbidity as well as chemical quantities like the pH-value and the contents of ionic and organic contaminations a demonstration system has been realised. As an example for inorganic impurities the concentrations of Cu2+ and PO43- are determined. The detection of organic contaminants is demonstrated for instance by the fluorescence detection of estradiol.

The chip of credit card size will be fabricated by injection moulding. First prototypes has been manufactured precission milling. The fluid channels have a cross section of 1 x 1 mm2. The single technical elements have been realised by rapid prototyping and tested separately.

At the conference the complete chip will be presented.

6112-04, Session 1

Rapid and automated sample preparation for nucleic acid analysis on a microfluidic CD (compact disk)

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In this study we investigated CD-based rapid and automated preparation of PCR-ready DNA for B. globigii spores. As a purely mechanical lysis method, a multiplexed lysis CD that exploits spherical particles (zirconia-silica beads) for the disruption of biological cells, has been fabricated and characterized. Bead-cell interactions for lysing arise while the beads and cells are pushed back and forth through a continuously narrowing chamber wall by switching the CD rotational direction. This phenomenon is called the key-stone effect. The performance of the lysis CD was measured using real-time PCR and resulted in 95% lysis efficiency of B. globigii spores. After the lysis step, a siphon valve is applied for debris elimination. The debris is centrifuged down at the bottom of an intermediate chamber while the CD is spinning at 4500 RPM and is separated by the siphon priming. The siphon valve transfers the top portion of a lysate solution in the intermediate chamber into a collection chamber. The collected solution is then heated to 95° C for 3 minutes to degrade proteins which are, in this case, the most potent PCR-inhibitors. In the long term, this work is geared towards CD based sample-to-answer nucleic acid analysis which will include sample preparation, DNA amplification, and DNA hybridization detection.

6112-05, Session 1

Whole-cell luminescence biosensor-based lab-on-chip integrated system for water toxicity analysis

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A novel water chemical toxin sensor has been successfully developed and evaluated as a working portable laboratory prototype. This sensor relies on a disposable plastic biochip prepared with a 4x4 micro-laboratory (μLab) chambers array of E. coli reporter cells and micro-fluidic channels for liquids translocation. Each bacterial strain has been genetically modified into a bioluminescent reporter that responds to a pre-determined class of chemical agents. When challenged with a water sample containing a chemical toxin, the sensor responds with an increased bioluminescent signal from the biochip that is monitored over time. The signal is received by a motorized photomultiplier-based analyzer and interpreted by signal processing software. We have performed several levels of analysis: (i) the change in the bioluminescent signal from the sensor bacteria serves as a rapid indication for the presence of toxic chemicals in the water sample; (ii) the intensity of the change indicates the toxin concentration level; and (iii) the pattern of the responses for the different members of the bacterial panel on the biochip characterizes the biological origin of the toxin. The analyzer contains housing mechanics, electro-optics for signal acquisition, motorized readout calibration accessories, hydro-pneumatics modules for water sample translocation into biochip micro laboratories, electronics for overall control and communication with the host computer.

This prototype has a demonstrated sensitivity for broad classes of water-borne chemical toxins including naladixic acid, botulinum and acetylcholine esterase inhibitors. The bioluminescence activity of a single biosensor cell has been characterized as a function of the promoter, the selected target analytes and their concentration. This prototype has initiated an investigation of a novel handheld field-deployable device for the Water Toxicity Analysis (WTA). A mathematical modeling of the biosensor and environmental conditions in a manner of a Computer Aided Design (bioCAD) was started. Trials based on this technology will begin with increased number of shrunken micro laboratories (starting with about 200 units) interfacing with single photon counting image sensor replacing bulky motorized photomultiplier based analyzers. We have determined two kinds of typical μLab configurations for handled WTA and have applied two opto-mechanical approaches correspondingly. For the first configuration, where there is a single layer of biosensors, we present opto-mechanics for simultaneous imaging and signal quantification of a μLab array. For the second one, where the biosensors are distributed inside the volume of the μLab, the technique for simultaneous μLab array quantification of bioluminescence activity will be described. The added value of the lab-on-chip extremely sensitive microscope imaging rather then just signal intensity quantification initiates new research opportunities, for instance, stem cells arrays manipulation tracking or neural networks high throughput analysis.

6112-06, Session 2

Monolithic single-mode SU-8 waveguides for integrated optics

M. Nordström, D. A. Zauner, J. Hübner, A. Boisen, Danmarks Tekniske Univ. (Denmark)

We present the fabrication and characterization of single mode waveguides fabricated monolithically in SU-8. SU-8 is a negative resist, which can be structured by UV lithography followed by a baking step to induce cross-linking. As a material platform, SU-8 is well suited for systems used for biochemical analysis as it possesses very high chemical resistance and good mechanical stability. Here we show that single mode embedded waveguides can be fabricated using SU-8 as core material and the modified SU-8, mr-L 6050XP, as cladding material. The refractive index difference between the two materials is 0.004. Fabricating monolithic waveguides makes it possible for integration of optical detection methods as well as optomechanical structures into complete Lab-on-a-chip systems without the addition of extra process steps. Monolithic integration of optical components at the fabrication stage offers the advantage of removing the time-consuming alignment otherwise needed at the measurement stage. Due to the low optical absorption at wavelengths above 600 nm in combination with the fast, simple and cost-efficient fabrication process, we show that SU-8 is well suited as structuring material for waveguides for integrated optics.

All waveguides fabricated in this work have a height of 4.5 mu and their widths are 3, 5 or 10 mu. We have characterized the losses of these waveguides with the cut-back method both at 633 nm and 1535 nm. We have also studied changes in the refractive index of the material with changes in the process parameters of the SU-8 material. Finally, absorption analysis in the visible spectral range has also been performed.

6112-07, Session 2

Characterization of SU-8 optical multimode waveguides for integrated optics and sensing on microchip devices

A. Piruska, A. A. S. Bhagat, K. Zhou, E. T. K. Peterson, I. Papautsky, C. J. Seliskar, Univ. of Cincinnati

Our research group is interested in environmental sensing of heavy metals that are involved in heavy metal pollution in aqueous environments. As a result, we are developing chemical sensors within integrated microfluidic systems for sensitive and selective detection of these pollutants. Our approach is to combine established chemical sensing strategies with microfluidic structures, especially in plastic devices, to achieve a total heavy metal analysis system. In this regard, the combination of three complementary techniques ñ optical waveguide spectroscopy, electrochemistry and chemical partitioning offers the required selectivity and sensitivity essential for many environmental samples. On-chip optical waveguide spectroscopy promises to yield the necessary high sensitivity but relies on fabrication of optical structures with a material of appropriate refractive index, optical quality, and chemical stability by methods consistent with established fabrication methods. SU8, the epoxy-based negative photoresist, appears to satisfy these requirements and, thus, has become one of our candidate materials for waveguide fabrication on plastic microchips. Although the SU8 has been previously used for waveguide fabrication, its optical properties and more specifically the influence of processing conditions on resultant optical properties have not been thoroughly characterized. This work presents an evaluation of SU8-based multimode waveguides on glass and plastic substrates. Optical constants of waveguides have been characterized by spectroscopic ellipsometric and prism coupling techniques. Additionally, using the latter method, evaluation of propagation losses of various structures with different thicknesses has been made. Ellipsometric and prism coupling measurements gave comparable refractive indices for variously cured SU8 waveguide materials. Prism coupling analyses proved to be more useful for analysis of the many SU8 waveguide structures fabricated in the thickness range of 5 to 75 μm. Figure 1 shows typical prism coupling results determining the modes propagated at the wavelength of 532 nm. Due to its nature, ellipsometry is more suitable for detailed characterization of thinner structures especially those in the range of a nanometer to a few micrometers in thickness. In such cases we have compared the results of both techniques. A typical SU8 multimode waveguide has a refractive index about 1.60 (at 532 nm) and 1.59 (at 633 nm) with associated losses on order 3 to 5 dB/cm when constructed on a glass substrate (see Figure 2). The dependence of SU8 waveguide fabrication conditions (curing conditions: temperature and time; SU8 precursor chosen, etc.) will be presented.

6112-08, Session 2

Polymeric waveguides for orthogonal near-surface fluorescent excitation

P. Datta, S. Gurung, F. Xu, S. A. Soper, J. Goettert, Louisiana State Univ.

Fluorescence detection is one of the most sensitive optical detection methods for biological samples. In combination with polymeric microfluidic chips optical detection promises cost-effective solutions for Bio-Sensor systems for a number of different applications. Typically, target molecules are attached within the fluidic channels requiring that excitation light is delivered to the fluorescent dyes attached to the molecules in a way that maximum signal to noise ratio is achieved. One possible method of excitation is evanescent light leaking from a propagating waveguide embedded in the channel floor. Existing planar waveguide solutions require complicated multi step processes using dissimilar optical materials. In this paper, a novel method of integrating waveguides into the bottom of a polymeric microfluidic channel will be presented. In a single step hot embossing fabrication process utilizing double sided molding a polymer microfluidic chip with an optical waveguide embedded into the floor is formed. The chip is made from Polymethyl Methacrylate (PMMA) a material well-suited for biological applications and commonly used as optical waveguide. The design incorporates a very thin layer of polymer film that forms the bottom floor of the fluidic channel. This thin film of PMMA also acts as core material of waveguide with air and aqueous biological media acting as optical cladding. The design, detailed fabrication method and initial optical testing results will be presented.

6112-09, Session 2

On-chip integrated spectrometer and microfluidic fluorescence set-up

A. M. Jorgensen, D. A. Zauner, T. A. Anhoj, P. M. Moselund, J. Hübner, Danmarks Tekniske Univ. (Denmark)

In this paper we report on the progress towards a highly integrated biochemical microsystem with integrated optical components. The system is an approach to merge MOEMS and BioMEMS techniques on the same polymer-based fabrication platform useful for Lab-on-a-Chip devices.

Fluorescence has been chosen to supply biochemical specificity for the system. It does require a more complex detection set-up than for absorbance measurements; however the wider applicability of fluorescence detection makes up for this.

The system consists broadly speaking of two parts, on-chip and off-chip components. The approach followed in this work regarding location of subcomponents revolves around reducing the alignment sensitivity of the chip/world interface. This has directly meant that the spectrometer is placed on the same chip as the microfluidic channels. This is done to avoid active alignment of the signal collecting waveguide and the spectrometer input waveguide, here they are one and the same. Furthermore they are defined in the same step making them intrinsically aligned.

The opto/fluidic chip contains a spectrometer based on an eschelle grating. The fluidic part of the chip is a collection of different simple systems with a detection region for fluorescence. The structures are designed to be illuminated through the top. For both the fluidic systems and the spectrometer there are optical connections directly to the chip edge. This means that the usability of each part can be tested individually as well as the combined performance. In order to keep the optical components compact, extensive use has been made of low-loss 90* bends.

6112-10, Session 3

Extraction of coeliac disease toxic gluten from processed food and optical detection in a micro system

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Patients that suffer from coeliac disease depend strongly on a strictly gluten free diet. Today, there is no standardized system that extracts all the gluten components, ethanol soluble gliadins and insoluble glutenins, and determines the concentration of 'toxic' sequences. This paper reports a protocol that enables the extraction of gluten from flour and from processed food samples in a single step and its implementation into an automatic system. After extraction a small sample volume is delivered to a micro system in which the sample is further processed for an immunochemical assay. Here, a disposable polymer chip for an optical detection is presented. The chip contains optical functionalities which can be fabricated by injection moulding in the same step as the chip itself. The chip offers the choice for measurements of UV/Vis signals in a transmission mode or for fluorescence detection. Though no beam forming optics, no electronically enhanced data collection and treatment and only low cost components are used the sensitivity is comparable or even better than standard lab spectrometers.

These results show the functionality of some of the key components on the way to an automatic micro chip system for the determination of coeliac disease toxic gluten in processed food.

6112-11, Session 3

High-precision micromilling for low-cost fabrication of metal mold masters

M. L. Hupert, J. W. Guy, C. Situma, S. D. Llopis, S. Rani, D. E. Nikitopoulos, S. A. Soper, Louisiana State Univ.

High-precision micromilling was employed as a cost-efficient method of preparation of metal masters useful in fabrication of polymer microfluidic devices through replication techniques. In the first application, a brass mold master was used for hot embossing of microchip electrophoresis devices in poly(methyl methacrylate) (PMMA). The sidewalls of the milled microstructures were characterized by a maximum average roughness (Ra) of 110 nm and mean peak height (Rpm) of 320 nm. SEM imaging showed a transfer following hot embossing of the sidewall roughness from the molding tool to the polymer microdevice. The electroosmotic flow (EOF) values for micromilled-based microchannels were comparable to ones in the LiGA-prepared devices (sidewall Ra = 20 nm) with values of ca. 3.7 x 10-4 cm2V-1s-1 (20 mM TBE buffer, pH 8.2), indicating insignificant effects of wall roughness on the bulk EOF. Numerical simulations showed that the additional volumes present in an injection cross due to curvature of the corners produced by micromilling lead to elongated sample plugs. PMMA microchip electrophoresis devices were used for a separation of pUC19 Sau3AI double-stranded DNA. The plate numbers achieved exceeded 1 million m-1 and were comparable to the plate numbers for the LiGA-based devices of similar geometry. In the second application, a brass master was used as a tool for the preparation of poly(dimethylsiloxane) PDMS stencils for patterning of DNA microarrays onto a PMMA substrate. Four DNA probes were immobilized onto a PMMA surface, which detected allele-specific ligation products containing mutations in the KRAS2 gene (12.2D, 12.2A, 12.2V, and 13.4D) with minimal amounts of cross-hybridization or misligation.

6112-12, Session 3

Microelectrodes integrated cell-chip for drug effects study

Y. Chen, Institute of Microelectronics (Singapore); H. Cui, J. Ye, National Univ. of Singapore (Singapore); S. Chong, Institute of Microelectronics (Singapore); T. Lim, F. Sheu, National Univ. of Singapore (Singapore); H. Cheong, Institute of Microelectronics (Singapore)

The microelectrodes are useful tools for temporal recording of neurotransmitter releasing from neural cells. Invasive and non-invasive methods are targeted by different group researchers to perform electrical stimulating on neural cell study. A microfabricated microelectrodes integrated biochip will be presented in this paper. Which allows the dopaminergic cells to grow on the chip directly. The dopamine exocytosis can be detected non-invasively from drug incubated dopaminergic cells grown on the chip.

A silicon based electrochemical sensor array integrated chip has been designed with an electrode array located on the bottom of reaction chamber and each electrode is individually electrical controlled. MN9D, a mouse mesencephalic dopaminergic cell line, has been grown on the surface of the biochip chamber directly. Dopamine exocytosis from the chip-grown

MN9D cells was detected using amperometry technology. The amperometric detection limit of dopamine of the biochip microelectrodes was 0.12 μM (Signal/Noise = 3), the level of dopamine exocytosis from MN9D cells was undetectable if no drugs during incubation. In contrast, after MN9D cells were incubated with L-dopa, a dopamine precursor, K+ induced dopamine extocytosis was temporally detected.

The microelectrodes integrated biochip provides a non-invasive, temporal detection of dopamine exocytosis from dopaminergic cells, and holds the potential for applications in studying the mechanisms of dopamine exocytosis, and drug screening. It also provides a tool for pharmaceutical research and drug screening on dopaminergic cells. It also with the potential to be used for other cell culture and drug effects study.

6112-14, Session 3

Injection and manipulation of silicon microbeads in a customized microfluidic platform

D. Hoffmann, D. Brennan, M. Loughran, Tyndall National Institute (Ireland)

The fabrication and subsequent detection of optically encoded silicon microbeads with a miniaturised photonic detector has been described previously.[1] The detection was facilitated by the deposition photo-lithographically defined micro-barcodes on the surface of each elongated microbead. Similar encoded microbead technologies have enhanced the development of multiplexed bio-assays for clinical diagnostics, DNA hybridisation and immunoassay research.[2,3] However, most existing microbead assays involve use of microspheres suspended in solution and flow cytometry is then often used to identify the associated optical signal.[3] In a new development we report the very first on-chip injection and manipulation of circular microbeads in a customised microfluidic platform. Silicon microbeads are injected from a reservoir into a laminar fluid stream by hydrodynamic pulsing. In this manner single and multiple injection of silicon microbeads was accomplished. Careful control of the fluid velocity manipulation of microbead transport in a specific direction in a branched microfluidic channel network. In-situ identification of microbeads occurred at microbead velocities less than 50 cm per second. Identified microbeads can be diverted into a channel network on the basis of the unique optical signature. The diversion is facilitated by hydrodynamic switching. In the final part of this research we verify that the microbead technology enables detection of a specific DNA probe molecule. We anticipate that future incorporation of dedicated reaction chambers within the microfluidic network will further reduce the time taken for on chip DNA hybridization compared to existing microbead suspension array technologies which can require 1 hour for incubation of assay reagents.

6112-15, Session 3

Multiwell cell culture plate format with integrated microfluidic perfusion system

K. Domansky, W. Inman, J. Serdy, L. G. Griffith, Massachusetts Institute of Technology

A new cell culture analog has been developed. It is based on the standard multiwell cell culture plate format but it provides perfused three-dimensional cell culture capability. The new capability is achieved by integrating microfluidic valves and pumps into the plate. The system provides a means to conduct high throughput assays for toxicology and metabolism. It can be used as a model for human diseases, exposure-related pathologies, and cancer.

6112-16, Session 3

An injection micromixer fabricated by improved SU-8 processing for biochemical microfluidic systems

C. Liu, Z. Ling, K. Lian, J. Goettert, J. Hormes, Louisiana State Univ.

In this research, first a modular injection micromixer prototype has been designed, fabricated and tested. This micromixer is easy to be integrated into biochemical microfluidic systems under developing for BioMagnetICs DARPA funded projects at CAMD. Also an improved processing procedure of SU-8, an epoxy negative photoresist, has been proposed. Multi-layer SU-8 structures have been fabricated. Internal stress in patterned SU-8 structures has been thoroughly studied and an optimal processing of SU-8 has been provided. For SU-8's excellent chemical properties, by using techniques developed here the injection mixer will be fabricated for running some biochemical sample liquids. A polymer-based injection mixer prototype has been developed as shown in Figure 1. Multi-layered PMMA with structures by machining have been bonded and integrated with standard -28 inter-connectors. One liquid flows into the mixing chamber in the base part and the other flows into through nozzles with a diameter of 50 μm from the top, which dramatically narrowed the diffusing distance and increased the mixing efficiency. The simulation results of the mixer have been demonstrated. From the results, the two liquids have already mixed thoroughly at the outlet of the mixing chamber. Also from the experimental results, the similar conclusions can be drawn.

6112-17, Session 4

Multi-directional pumping of biofluids for efficient transport and mixing

S. Vijendran, Univ. of Cambridge (United Kingdom); M. Mpholo, National Univ. of Lesotho (Lesotho); C. G. Smith, Univ. of Cambridge (United Kingdom)

This research is based on the pumping of ionic fluids through microfluidic devices using AC electric fields. Effective fluid transport through microfluidic devices is paramount to their successful operation. Without active pumping, interactions between fluids are limited to diffusion kinetics only, resulting in extremely slow reaction rates especially for large molecules such as DNA. A number of pumping technologies have been developed to move and mix fluids on a chip allowing orders of magnitude faster reaction times than in simple diffusion processes. Mechanical pumps have the advantage of being able to pump all types of fluids but tend to be limited by the speed and reliability of actuation of their moving parts. Ultrasonic and electro-hydrodynamic pumps are promising, however they can have damaging effects on living cells and organisms when used in bio-applications.

Our pumping technology, which utilizes only low-voltage (<5V) AC electric fields, provides a simple alternative to other electrostatic pumping technologies which typically use relatively high voltages (>100V). We have demonstrated effective pumping (speeds greater than 400 micrometers per second) with a single array of interdigitated metal electrodes on a glass chip. We have also shown that the direction of the flow can be reversed easily simply by increasing the applied voltage above a certain threshold. This allows the possibility of efficient mixing of laminar fluids and the controlled transport and positioning of fluid plugs and particles in a microfluidic device.

6112-18, Session 4

Peltier-actuated microvalves for integrated microfluidic systems

R. P. Welle, B. S. Hardy, The Aerospace Corp.

We have developed a novel microfluidic valve, formed by creating a flow channel past a Peltier (thermoelectric) junction. Fluid flow through the channel is stopped when the Peltier junction is cooled sufficiently to cause the fluid to freeze. This forms a solid plug in the channel, stopping the flow. The valve is opened by reversing the current in the Peltier junction to heat and melt the fluid. Because the flow in the channel is blocked by the fluid itself rather than by moving a plunger against a valve seat, the valve has no moving parts and has zero dead volume. This type of valve is fundamentally leak-free, and is electrically actuated. At the same time, the valve is completely unaffected by particulate contamination; any par-

ticles present will freeze into the solid plug formed when the valve closes, and will continue to flow with the fluid when the valve re-opens. Analytical and finite-element models of the valve have also been developed to explore performance parameters. An optimized valve is predicted to have a cycle time on the order of 10 ms. We have fabricated several experimental prototypes and evaluated their performance. We find that they are reliably capable of closing in less than 100 ms, and of opening substantially faster. These Peltier junctions also have the capability to be incorporated into more complicated fluid control components such as pumps.

6112-19, Session 4

Passive micromixer with break-up obstructions

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

In this paper, we report the design and fabrication of a passive microfluidic mixer using obstructions inside the channel which break up the flow causing mixing. In this work we investigate the effect of diamond shaped break-up obstructions on the flow. Three parameters are examined: (1) obstruction height, (2) obstruction offset from the center of the channel, (3) alternating pattern of the obstructions. The mixer was modeled using CFD-GEOM software (CFD Research Corp., Huntsville, AL), and simulated in CFD-ACE+. Using results from modeling experiments, an improved design was then modeled and simulated. The mixing efficiency is determined for a range of Reynolds numbers (Re). The channels are 200 μm wide with a height of 55 μm. The obstructions are diamond shaped and 90 μm by 100 μm from corner to corner. Results show that the optimum placement of obstructions in the channels is 45 μm off-center. It was found for this geometry, that the best mixing occurred with obstructions placed alternately across the center and at full channel height. We obtain 100% mixing in less than 1 cm for lower Re which is characteristic of microchannel flows. The new design is capable of mixing liquids in shorter distances than existing passive mixers and thus will enable a wide range of lab-on-a-chip applications where space is limited

6112-21, Session 4

Theoretical and experimental study of electro-osmosis-driven two-fluid displacement in a microcapillary

H. Y. Gan, C. Yang, Nanyang Technological Univ. (Singapore); Y. M. Wan, G. C. Lim, Singapore Institute of Manufacturing Technology (Singapore); Y. C. Lam, Nanyang Technological Univ. (Singapore)

Fluid flow in microfluidic systems is easily achieved by electroosmotic (EO) pumping, with its own unique characteristics and advantages. In practice, multi-fluid flows are frequently encountered. This heterogeneous EO flow associated with non-uniform liquid properties is to be understood for precise flow control. Hitherto, it still remains elucidated.

This paper reports an EO-driven, two-fluid displacement in a cylindrical microchannel. A theoretical model developed takes into consideration the mismatch flow fields at the moving liquid/liquid interface, continuity requirement, and the non-steady states of the zeta potential and induced local pressure gradients. The electrical current monitoring method is adopted for measuring the flowrate and subsequently determining the zeta potentials which are required for the model prediction. The nonlinear change of the electrical current with time under a constant applied voltage is observed during the displacing processes.

The theoretical and experimental results validate the hypothesis that the non-uniform zeta potential and electric field induce local pressure gradients in the two different fluids. This results in the deviation of the velocity flow profile from the ideal plug-like flow profile expected for EO flow. The model predictions agreed well with the experimental data when a low concentration fluid displaces a high concentration fluid, but not vice versa. The time of displacement, and thus the flow velocity, is found to be dependent on the displacing flow direction, which is hitherto not reported. The precise mechanism that leads to the displacing flow direction is being postulated, but its confirmation required further investigation.

6112-22, Poster Session

Microfluidic DNA extraction using a patterned aluminum oxide membrane

J. Kim, B. K. Gale, Univ. of Utah

A DNA extraction system was designed and fabricated using an AOM (aluminum oxide membrane) with 200 nm pores and PDMS microfluidic channels. The membrane was patterned using soft lithography techniques and SU-8 photolithography on the membrane. After making the pattern with SU-8, the AOM was observed using an SEM (scanning electro microscope) to verify the AOM structure was not damaged. From the SEM images, the AOM structure was not different after modification with SU-8. To complete the system, a PDMS mold for the microfluidic channels was made by softlithography. Using this mold, PDMS microchannels were cast using PDMS with a low polymer to curing agent ratio to provide adhesion between the patterned membrane and microfluidic channel. Then, the patterned membrane was sandwiched between PDMS microfluidic channels in a parallel format. The completed system was tested with 10ug of Lambda DNA mixed with the fluorescence dye SYBR Green I. Following extraction, the surface of each well was examined with fluorescence microscopy while embedded in the microfluidic system. Extracted and immobilized DNA on the AOM was observed in almost every separation well. This microsystem, called membrane-on-a-chip, has potential applications in high-throughput DNA extraction and analysis, with the capability to be integrated into polymer-based microfluidic systems.

6112-23, Poster Session

Digital in-line holographic microscopy applied to microfluidic studies

J. I. Garcia-Sucerquia, Dalhousie Univ. (Canada)

Digital In-line Holographic Microscopy (DIHM) is a technique that provides depth and lateral resolution through a volume of at least 3 cube centimeters for visible light. This outstanding characteristic is reached by means of a simple optical setup and numerical reconstruction of the recorded holograms. This makes DIHM the right tool for applications in many microscopic studies.

In this paper we study microfluidic phenomena by means of DIHM. To this end we seed a fluid with micron-size trackers (latex microspheres) and follow their displacement within an observation volume. We apply this technique to several situations such as the flow around a big sphere, flow through microchannels, and around corners. By taking advantage in DIHM of the plane-to-plane reconstruction through a large depth of field, we generate 3D renderizations of the paths followed by the trackers to produce a fair representation of the flow in micron-size dimensions.

6112-24, Poster Session

Fabrication and test of an electrochemical microactutor

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

We have designed, analyzed, and fabricated a new type of electrochemical microactuator based bubble generation/reduction in a controlled reversible electrolysis process. A mathematical model was established for the microactuator to simulate the dynamic behavior of the system. A prediction of gas volume change, therefore the pressure in micro chamber, as a time function for a given control voltage was realized. The simulation results helped us to develop an optimal design for the ECM actuator.

6112-25, Poster Session

New approaches to speed up the development of complex disposable lab-on-a-chip devices

T. Stange, H. Brüning, H. Hartmann, L. Weber, thinXXS Microtechnology (Germany)

For quite some time the usual skeptics could doubt the feasibility of the lab-on a-chip concept developed some 15 years ago. By now, however, the success of companies such as Caliper, Agilent, or Sophion with their innovative devices has proved them wrong. The prospects of LOC technology are no doubt huge.

Yet, the obstacles for market entry remain considerable, especially as the potential OEM customers are not necessarily aware or convinced of the

advantages promised to them by the suppliers. And even if they are, they tend to shun the technological and financial risks involved with LOC development.

This can only be overcome by addressing these reservations. One approach is to make prototyping of LOC faster and less expensive. To this end, thinXXS

developed a number of microfluidic modules, which represent functions such as mixing, pumping, or splitting and which may be combined flexibly with each other to render a first model of the fluid system to be. This system then can be tested, subsequently improved, and eventually verified or falsified. Termed “microfluidic construction kit”, this approach allows to prove the LOC principle before the expensive development steps and to get potential customers more easily involved with microfluidics. Moreover, by using microinjection molding in the making of the modules there is no disruptive change in technology when going towards integration and mass production of the final LOC device.

6112-26, Poster Session

Metal complex speciation on-chip

K. Faure, National Univ. of Ireland/Cork (Ireland); M. Loughran, Tyndall National Institute (Ireland); J. D. Glennon, National Univ. of Ireland/Cork (Ireland)

With the continuing advances in the miniaturization of analytical techniques, and in particular of microchip capillary electrophoresis, the challenge of rapid metal complex speciation can now be taken up. The discrimination between different chemical species of metal ions is important as the environmental toxicity, biological activity and availability of many metals is often species dependent[1-3]. Although extensive studies have been dedicated to low molecular weight metal complex speciation by electrophoresis, little work has focused on the separation of species of different stoichiometries within the same metal-ligand system (speciation distribution).

Our research demonstrates the first example of rapid separation by microchip electrophoresis of individual species in equilibrium within selected metal-ligand systems. In recent years, microchip electrophoresis has proved its efficiency in high-speed separations. The extension of speciation ability within a single metal-ligand system from capillary electrophoresis to microchip electrophoresis has been demonstrated[4] with considerable success, highlighting the immense future potential for microchip electrophoresis in the field of rapid chemical speciation.

6112-27, Poster Session

Design of controlled drug delivery system with optimal release characteristics

X. Wang, T. Chen, Xi’an Jiaotong Univ. (China)

The biodegradable polymer microstructure with large array of micro drug chambers is a new drug controlled release device, which is made by MEMS technologies. This type of drug delivery system has some unique advantages in controlled long-term drug delivery, such more drug loading than the matrices release systems, easier control the release rate, and so on. In this paper, a method of optimization by which the drug release rate of the drug delivery system is regarded as the objective function, is introduced to the design of the drug delivery system. The final configuration of drug delivery system is decided combined with the required release rate and working conditions. The experimental results will show the release characteristics of the designed drug controlled release device. This result will indicate that this optimization method plays an important role in designing the drug delivery system using biodegradable polymers.

6112-28, Poster Session

The project and simulation of the compositive miniature spectrum instrument

W. Jianguo, Chongqing Univ. (China)

This paper advances a kind of micro spectrometer, which is based upon Fabry-Perot antrum’s character of filtering the waves. The basic structure of the micro spectrometer is the array of Fabry-Perot antrum which contains many different length of antrum on the substrate of silicon, consequently we can achieve the detector for several wavelengths simultaneously. The unit of probing is a Fabry-Perot antrum, which is made up of the substrate of silicon—metal film—silicon dioxide layer— metal film. We carried out the corresponding simulation. In the basic structure of aluminum film (14nm)- silicon dioxide layer - silver film (39nm), the resolution can reach 15nm. When the area of a unit of probing is 0.14mm x 0.14mm only, it can reach the luminous flux of miniature grating spectrum instrument (the minimum volume in the order of cm), but the volume of the part of spectrum detector is only the order of mm. The design size of the micro spectrometer is in a few millimeters. Furthermore it has no movable parts and could detect several wavelengths at the same time. It is possible to fabricate such micro spectrometer through existing process methods of IC technology.

6112-29, Poster Session

Micro-cantilever resonance sensor for biomolecular detection by using self-assembly nanoparticles

J. H. He, Institute of Microelectronics (Singapore); J. Ye, National Univ. of Singapore (Singapore); C. W. H. Li, Institute of Microelectronics (Singapore); T. M. Lim, National Univ. of Singapore (Singapore); H. W. Cheong, Institute of Microelectronics (Singapore)

There are more and more interest to use MEMS/NEMS (Micro-/Nano Electro- Mechanical-System) structures, such as Micro-/nano- cantilever, Micro-/nano- bridge, Carbon Nanotube (CNT) to detect and sense physical, chemical and biological signals from bio- molecules, e.g. virus, bacterial, DNA and protein. The bending of the cantilever due to surface stress has been used to detect the biomolecular binding such as DNA[1]. However it is difficult to detect the change of the deflection of the cantilever with real-time monitoring in the liquid with high sensitively. Resonance method does not require the real-time monitoring of the cantilever in the liquid and can be detected in the air mode. Once there is molecule binding on the cantilever, it changes the physical properties of the cantilever, which can be detected by resonance frequency shift. This paper is going to present the self-assembly surface binding of nano-gold particle and/or functional CNT on the cantilever structures, which can easily facilitate biomolecular detection by resonance frequency shift. The LPCVD SiN low-stress cantilever is produced by laser micromachining and alkaline KOH etching [2], which is a maskless, simple, convenient, fast-prototyping way to produce such cantilever sensor for biomolecular detection.

1 J. Fritz, M. K. Baller, H. P. Lang, H. Rothuizen, P. Vettiger, E. Meyer, H. -J. Guntherodt, C. Gerber, and J. K. Gimzewski, “Translating Biomolecular Recognition into Nanomechanics,” Science, vol. 288, pp. 316-318, 2000.

2 J. H. He, J. K. Luo, H. R. Le, and D. F. Moore, “MEMS Mechanical Characterization on Different Thin Film Materials by Bending and Scanning along Micro-machined Cantilevers,” presented at SPIE Microtechnologies for the New Millennium, 9-11 May 2005, Sevilla, Spain, 2005.

Conference 6113: MEMS/MOEMS Components and Their Applications III

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6113-02, Session 1

Silicon on insulator inertial MEMS device processing

W. D. Sawyer, M. S. Prince, Charles Stark Draper Lab., Inc.

During the 1980's and 1990's the methods used to manufacture inertial MEMS devices could be divided into two groups; bulk and surface micromachining. Institutions which developed high precision inertial MEMS devices usually employed bulk micromachining processes. This was done to fabricate devices with large proof masses and stiff beams which result in a high scale factor, as well as high drive, and sense frequencies. New processes have been developed which are based on silicon on insulator (SOI) wafers. These processes combine the advantages of bulk and surface micromachining while enabling the etching of thick proof masses. This paper illustrates the manufacturing and performance advantages of an SOI inertial MEMS process.

6113-03, Session 1

MEMS inertial sensors with integrated optical transducers

D. W. Carr, Sandia National Labs.

We are developing a new class of inertial sensors that utilize novel optical transducer mechanisms for measuring the motion of a suspended proof mass. Our primary application area thus far has been towards the detection of very low frequency seismic signals, but the sensitivity and stability of this approach make it quite amenable to navigation applications. We are building fully integrated optical systems that include a VCSEL source, a photodiode, and the MEMS mass and transducer element, all within a package that is less than 25 mm^3, and readily scalable to less than 5 mm^3. In bench top optical systems we have demonstrated a noise floor below 10 nano-g/Hz^(1/2) at 1 Hz. Our lateral transducer design also makes it possible to produce three-axis sensors in a single chip. This talk will explore some of the subtleties of the optical design and assembly, and describe where the real benefits are to be found in optical sensing approaches.

6113-04, Session 1

The effects of collateral modes on MEMS gyro errors

T. V. Roszhart, The Pennsylvania State Univ.

MEMS gyros are often approximated as coupled, dual mode, resonant devices that transfer energy between dither drive and Coriolis output modes as a function of rotational rate. This is done using a two degree-of-freedom (DOF) analysis with coupling between modes described by Coriolis, an-isoelastic, and damping cross terms. In practice, MEMS gyros often exhibit unused, collateral modes with resonant frequencies close to the drive and output modes. These additional modes provide a mechanism for the transfer of energy that is independent of rotational rate and, as a result, can generate errors in the gyro output. The purpose of this paper is to show the effects that collateral modes have on the bias and stability of coupled mode rate gyros. This is done by extending the conventional 2 DOF analysis to a three DOF model that includes one collateral mode. Calculations showing the differences between the 2 DOF and 3 DOF model are presented and discussed.

6113-05, Session 1

A novel excitation scheme for MEMS gyroscopes using parametric pumping for near inertial grade performance

B. J. Gallacher, J. S. Burdess, K. M. Harish, Univ. of Newcastle Upon Tyne (United Kingdom)

In this paper an excitation scheme employing simultaneous harmonic forcing and parametric excitation is applied to a MEMS gyroscope in order to improve the rate resolution performance to near inertial grade. A perturbation method is used to analyse the dynamics of the gyroscope and is used to develop a control methodology that enables the parametric pumping phenomena to be used effectively. The significance of the parametric instability boundary in facilitating the design of the required control strategies is demonstrated. The analysis shows that the quality factor of the primary mode of the gyroscope may be increased arbitrarily through parametric excitation. This allows forcing levels for the primary mode to be reduced by several orders of magnitude whilst sustaining the primary mode amplitude.

In conventionally actuated MEMS gyroscope, electrical feedthrough of the harmonic forcing results in contamination at the sense electrodes and therefore limits the rate resolution performance of low-cost devices to the range 0.1-1 deg/s. However, in the excitation scheme proposed, the parametric excitation and forcing are at different frequencies and thus minimises the effect of electrical feedthrough at the forcing frequency. The rate resolution may be improved by several orders of magnitude towards inertial grade performance.

Simulation of the oscillator scheme is achieved using MATLAB Simulink. The simulation demonstrates the Q-factor of the primary mode is increased by two orders of magnitude whilst the harmonic forcing amplitude is reduced by the same order, when the control scheme is operating. Agreement between the perturbation analysis and MATLAB Simulink models is within 8%. The increase in the Q-factor by two orders of magnitude results in a decrease in the electrical noise due to feedthrough by two orders of magnitude. This will enable a significant improvement of resonant gyroscope performance.

6113-06, Session 1

Markets and applications for MEMS inertial sensors

R. H. Dixon, J. Bouchaud, Wicht Technologie Consulting (Germany)

The ability to meet demanding specifications and stringent price points is driving applications for MEMS inertial sensors (gyroscopes and accelerometers) in cost-sensitive automotive and consumer markets. We predict the market for MEMS inertial sensors will grow from $800 million in 2004 to $1370 in 2009, a CAGR of over 11%.

MEMS gyroscopes and accelerometers will continue to add value to automotive safety systems for vehicle stability, roll-detection and in GPS-based inertial navigation units. Additional accelerometers with more intelligence will be introduced to react to front, side and rear-end impacts, or as sensitive anti-theft tilt sensors. MEMS gyroscopes will compete for high-end image stability solutions in camcorders, extending to digital cameras with video capability and mobile phones with high-resolution cameras. Civil aviation applications for MEMS gyros now include Attitude Heading Reference Systems in light aircraft. Other potential applications include sporting goods (e.g. golf club, pedometers) and medical applications for motion analysis.

The myriad applications for low g accelerometers to measure tilt, posi-

tion, vibration, motion and shock will enable consumer goods that are smarter, more intuitive and safer. 3-axis accelerometers: protect portable HDDs in MP3 players and laptops; sense motion to control games and navigate menus in PDAs and cell phones; record the forces experienced by products during shipping; monitor industrial equipment and warn for early damage; mitigate theft and save battery life in portable products. This paper summarizes market developments and emerging opportunities for inertial sensors in a variety of applications.

6113-07, Session 2

MEMS for the next generation of giant astronomical telescopes

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

New advances in Micro Electro-mechanical Systems (MEMS) deformable mirrors with high actuator count, high precision, and low cost have greatly influenced the design thinking for high resolution instruments on the next generation of large aperture telescopes for ground based astronomy. The use of MEMS as general purpose active optical components will open up a variety of capabilities for both sensing and controlling of astronomical light. In this talk we will describe the current thinking for instrument concepts on the Thirty Meter Telescope project and discuss some of our preliminary results from MEMS and AO system concept testing at the UCO/Lick Laboratory for Adaptive Optics.

6113-08, Session 2

MEMS-based extreme adaptive optics for planet detection

B. A. Macintosh, Lawrence Livermore National Lab.

As adaptive optics (AO) matures, it becomes possible to envision AO systems oriented towards specific important scientific goals rather than general-purpose systems. One of the most important goals for the next decade is the direct imaging detection of extrasolar planets. An “Extreme” AO system optimized for extrasolar planet detection will have require deformable mirrors with thousands of actuators operating at kilohertz update rates, but must also be relatively compact, making MEMS an attractive choice.

I will present the basic design of such a system, the Extreme Adaptive Optics Coroangraph (ExAOC) for the Gemini Observatory. I will discuss the science motivation and overall system design, and pay speccial attention to the requirements for the 48x48 actuator MEMS-based deformable mirror.

6113-09, Session 2

Requirements for MEMS mirrors for adaptive optics in the eye

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

MEMS is one of several emerging technologies for fabricating wavefront correctors for use in adaptive optics systems. Each technology has its own advantages and disadvantages. In order to compare devices, it is useful to define a task and make a comparison based upon the effectiveness of each device for this task. Such an approach implies, of course, that device A might be better suited for task X whereas device B is better suited for task Y. In adaptive optics, this situation is already known: deformable mirrors that are relatively effective at compensating for atmospheric turbulence are not necessarily the mirrors that one would choose for correction of the aberrations of the eye. This is essentially because the statistical modal distribution of the aberrated wavefronts in each case are different. In this talk, I shall present a method for systematically evaluating the effectiveness of different mirror (or transmissive) technologies in adaptive optics in the eye. It uses a model for the aberrations of the eye (such as that developed by Thibos et al) and a least squares fitting procedure. Results will be presented for at least 4 mirrors, including a 12x12 MEMS device. The key point is that is the effectiveness of each actuator signal is as important as the number of actuators.

6113-10, Session 2

MEMS-based ophthalmic adaptive optics

A. Roorda, Univ. of California/Berkeley

One goal in our laboratory is to develop compact and robust adaptive optics instruments for use in ophthalmic applications. Toward that end, we have built a new generation adaptive optics scanning laser ophthalmoscope (AOSLO) that uses a MEMS deformable mirror for aberration correction (141 actuators, 3.5 micron stroke, 400 micron pitch, Boston Micromachines Corp.). The AOSLO takes microscopic images of the living human eye in real time by recording the scattered light from a focused spot as it is raster scanned over a region of the retina. Controlled modulation of the laser beam during the raster scan allows for direct presentation of AO-corrected stimuli on the retina while simuiltaneously recording their exact position, to within a single cone photoreceptor, on the retinal image. The small size of the MEMS mirror, along with other design improvements has led to a portable instrument that fits onto a 30’ X 30’ breadboard. Moreover, it requires only one operator to perform all functions, which include adaptive optics, imaging, and other advanced functional testing, such as visual acuity, microperimetry and eye tracking. The talk will present details of the instrument along with recent imaging and functional imaging results.

6113-11, Session 2

Adaptive micro-optics inside the eye

G. V. Vdovin, A. N. Simonov, Technische Univ. Delft (Netherlands); M. Rombach, AkkoLens International (Netherlands); M. Y. Loktev, Flexible Optical B.V. (Netherlands)

Introduction of adaptive optics inside the human eye, aimed to those suffering from strong ocular aberrations or accommodation loss, will allow them to to benefit from an improved visual acuity and partial or even complete restoration of the accommodation ability.

Intra-ocular AO will require two major problems to be solved: 1. Development of the technology of the intraocular adaptive corrector and 2. The realization of a feedback, closed on subjective visual acuity.

We will present our latest results in the deveopment of intra-ocular adaptive optics and subjective control of the adaptive feedback loop.

6113-12, Session 2

Adaptive laser resonator control with deformable MOEMS mirrors

U. Wittrock, P. Welp, Fachhochschule Münster (Germany)

Output power, efficiency, and beam quality of almost all known solid state lasers are currently limited by aberrations in the laser crystal. Even though many novel laser concepts such as the slab laser or the thin disk laser have been developed that have lower aberrations, the thermo-optical aberrations in the laser crystal are still limiting the performance of these solid state lasers. One promising way to solve this problem is correction of the aberrations by means of a deformable mirror under closed loop control. I will give an overview of current concepts for such adaptive laser resonators and the present current experimental achievements. MOEMS deformable mirrors are frequently used in these systems because they are in principle very well suited due to their small size and low cost. However, problems with these mirrors such as limited stroke and damage threshold still exist and experimental data supporting this will be presented. Requirements for MOEMS (and other) mirrors in terms of stroke, number of actuators, size, surface fidelity, damage threshold, and many more will be discussed in detail. I will also report on our own work on novel deformable mirrors and on our work on adaptive laser resonators for Nd:YVO4-lasers and Nd:YAG-lasers with deformable mirrors.

6113-13, Session 2

Tiny bimorph mirrors for laser beam control

A. V. Kudryashov, Moscow State Open Univ. (Russia)

The presentation will describe new type of bimorph correctors to correct for aberrations of laser beams.

6113-14, Session 3

MEMs-based adaptive optics systems: the Naval Research Laboratory Program

S. R. Restaino, J. Andrews, T. Martinez, Naval Research Lab.; D. Payne, Narrascape; D. V. Wick, Sandia National Labs.; C. Wilcox, Naval Research Lab.

The use of adaptive and active optics (AO) is enabling the construction and test of flexible optical systems with performances unprecedented. This flourishing of technical advances is also due to the availability of new technologies that are much lower in cost, much easier to implement and use. Among these new technologies the use of Micro-Electro-Machined (MEM) mirrors is one of the primary sources of innovation. Several groups are actively working in bringing to fruition AO systems based on MEMs technologies and at the same time several groups are working to improve the MEMs technology and tailor it more and more towards various aspects of the AO problems. In this paper we will presents an overview of MEMs adaptive optics problems. We will especially focus on our experience in this field and discuss results from our AO system. We will discuss pros and cons on the use of MEM for adaptive optics and elaborate on our experience on field-testing of these devices. This paper will also briefly discuss the broader use of adaptive optics in fields other than atmospheric compensation.

6113-15, Session 3

Frequency stability of combined wavefront corrective elements for adaptive optics

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

In most adaptive optics systems, there are two elements that control wavefront correction, a fast steering mirror that corrects tip and tilt and a deformable element that corrects higher order aberrations. By mounting the deformable element onto the tip/tilt platform, complete wavefront compensation is now possible at one location in an optical system. The advantage of mounting a lightweight Micro Electro-Machined (MEM) deformable mirror on a tip/tilt stage is both fewer optical components and a simpler alignment process. The impact on the frequency stability of the of the MEM device on the tip/tilt platform is approximately 5% of the driving frequency.

6113-16, Session 3

Image sharpening and MEMS mirrors

L. P. Murray, C. J. Dainty, National Univ. of Ireland/Galway (Ireland)

A classical adaptive optics (AO) system, as described originally by Babcock in 1953, consists of a wavefront sensor, a wavefront corrector (such as a deformable mirror) and a control system. However, one of the very first implementations of AO, by Muller and Buffington, dispensed with the wavefront sensor and instead used the principle of image sharpening: a metric for “sharpness” is defined and the wavefront corrector is changed until the sharpness is maximised. This procedure has been superceded by wavefront sensing but in fact may prove to be useful in cases where wavefront sensing is not possible, for example in the correction of non-common-path errors in classical AO, or desirable, for example in potential commercial applications of AO, as pointed out by Vorontsov and colleagues. We have constructed a breadboard system to investigate experimentally the potential for image sharpening. It consists of an LED source, an object in the form of a photographic transparency, a Hamamatsu spatial light modulator to induce (known) aberrations, an OKO 37 element membrane mirror and a Q-Imaging CCD camera. Results of experiments using a number of different algorithms (simplex, conjugate gradient, simulated annealing) will be presented.

6113-17, Session 3

Characterization of contour shapes achievable with a 140 actuator and 4μm stroke MEMS deformable mirror

Y. Zhou, T. Bifano, Boston Univ.

MEMS deformable mirrors are finding increased use in adaptive optics controllers to compensate for aberrations in an optical system. Applications include astronomical imaging, microscopy, lithography, and vision science. An important consideration in the design of an adaptive optics controller is the range of physical shapes required by the DM to compensate the existing aberrations. Conversely, if the range of surface shapes achievable with a DM is known, its suitability for a particular AO application can be determined. In this work, we characterize one MEMS DM that was recently developed for vision science applications. The device has 140 actuators supporting a continuous face sheet deformable mirror having 4mm square aperture. The total range of actuation is 4μm, achieved using electrostatic actuation in an architecture that has been described previously.

We incorporated the MEMS mirror into an adaptive optics (AO) testbed to measure its capacity to transform an initially planar wavefront into a wavefront having one of thirty-six orthogonal shapes corresponding to the first seven orders of Zerinke polynomials. Such Zernike polynomials are often used describing the wavefront shape of the pupil plane in an optical system. The testbed included a superluminescent diode source emitting light with a wavelength 630nm, a MEMS DM, and a Shack Hartmann wavefront sensor (SHWS). The DM was positioned in a plane conjugate to the SHWS lenslets, using a pair of relay lenses. Wavefront slope measurements provided by the SHWS were used in an integral controller to regulate DM shape. The control software used the difference between the the wavefront measured by the SHWS and the desired (reference) wavefront as feedback for the DM.

With a maximum 4 micron stoke, the DM is able to produce all 36 terms with a wavefront height root mean square (RMS) from 1.8μm for the lower order Zernike shapes to 0.15μm for the 7th order.

6113-18, Session 3

Extreme adaptive optics testbed: performance and characterization of a 1024-MEMS deformable mirror

J. W. Evans, L. Poyneer, B. Macintosh, G. Sommargren, Lawrence Livermore National Lab.; S. Severson, D. Dillon, Univ. of California/Santa Cruz; D. Palmer, S. Olivier, Lawrence Livermore National Lab.

High Contrast or Extreme, Adaptive Optics systems are necessary for ground based extrasolar planet imaging and require deformable mirrors with a large number of actuators. Micro-Electro-Mechanical-Systems (MEMS) deformable mirrors are a potential key to high-contrast instrumentation. Technology development for high-contrast imaging, including performance and characterization of the 1024-Boston Micro-Machines MEMS deformable mirror, is ongoing on the Extreme Adaptive Optics testsbed at UC Santa Cruz. We use a simple optical design to minimize wavefront error and maximize the experimentally achievable contrast. A phase shifting diffraction interferometer (PSDI) measures wavefront errors with sub-nm precision and accuracy for metrology and wavefront control. The system without a deformable mirror has < 1.5 nm total RMS

wavefront error and contrast measurements of 6.5nm;10-8 have been made. Using the PSDI as a wavefront sensor we have flattened the deformable mirror to an RMS wavefront error of < 0.8 nm within the control band, and corresponding contrast measurements of 7.8nm;10-7 have been made. We have characterized several types of irregular actuators on multiple devices that limit closed loop performance. Stability and go-to capability of these devices is also being tested. Ultimately this testbed will be used to test all aspects of the system architecture for an extrasolar planet-finding AO system. Closed loop performance of the MEMS deformable mirror with a spatially filtered Shack Hartmann wavefront sensor is ongoing.

6113-20, Session 4

MEMS analog light processing: an enabling technology for adaptive optical phase control

A. Gehner, M. Wildenhain, H. Neumann, H. Schenk, Fraunhofer-Institut für Photonische Mikrosysteme (Germany)

Various applications in modern optics are demanding for Spatial Light Modulators (SLM) with a true Analog Light Processing (ALP) capability, e.g. the generation of arbitrary analog deflection or phase patterns for adaptive optical phase control. For that purpose the Fraunhofer IPMS has developed a high-resolution MEMS Micro Mirror Array (MMA) with an integrated active-matrix CMOS address circuitry. The device provides 240 x 200 piston-type mirror elements with 40 μm pixel size, where each of them can be addressed and deflected independently at an 8bit height resolution with a vertical analog deflection range of up 400 nm suitable for a 2pi phase modulation in the visible. Full user programmability and control is provided by a newly developed comfortable driver software for Windows XP based PCs supporting both a Graphical User Interface (GUI) for stand-alone operation with pre-defined data patterns as well as an open ActiveX programming interface for a closed-loop operation with real-time data from an external source. An IEEE1394a FireWire interface is used for high-speed data communication with an electronic driving board performing the actual MMA programming and control allowing for an overall frame rate of up to 500 Hz. Successful proof-of-concept demonstrations already have been given for eye aberration correction in ophthalmology, for error compensation of lightweight primary mirrors of future space telescopes and for ultra-short laser pulse shaping. Besides a presentation of the basic device concept and system architecture the paper will give an overview on the obtained results from these applications.

6113-21, Session 4

Performance of a high-stroke segmented MEMS deformable-mirror technology

M. A. Helmbrecht, T. N. Juneau, M. R. Hart, N. Doble, Iris AO, Inc.

For adaptive optics to take hold in commercial applications, high-performance low-cost deformable mirrors (DM) must be made available. Furthermore, many commercial applications such as free space optical communications and medical imaging require DMs with a small form factor. Portable applications dictate the need for low-power DMs. Microelectromechanical Systems (MEMS) technologies are well suited for fabricating DMs with these attributes.

For several years, Iris AO has been developing a hybrid MEMS DM technology that uses surface-micromachining techniques to fabricate actuator arrays. Because of segmentation, high-stroke actuation of greater than \> 7 μm has been experimentally verified while keeping actuation voltages within reasonable bounds (< 130 V). Three electrodes under each actuator allow for piston/tip/tilt motion.

High-fill-factor mirror arrays are flip-chip bonded onto the actuator arrays to provide superb optical quality (< 8 nm rms). The single-crystal-silicon mirror segments, fabricated from silicon-on-insulator (SOI) wafers, provide a robust substrate for optical coating.

This presentation will present detailed characterization results of the Iris AO 37-segment deformable mirror. In addition to stroke and optical quality, we will present frequency response data and preliminary results from cyclic testing. The paper will also discuss wavefront correction using a position controller Iris AO has developed and is currently testing.

6113-22, Session 4

High-performance adaptive optics using microscale assembly

M. B. Cohn, MicroAssembly Technologies, Inc.

Applications for advanced optical MEMS include high-speed, high-resolution beam scanning and adaptive optics. A key concern in the latter area is to maintain a high fill factor, without sacrificing dynamic performance. Simulation and experimental results are demonstrated for a new actuator design, based on a highly 3D, batch assembly process. Actuator arrays up to 256x256 (10 cm) are targetted.

6113-23, Session 4

Characterization of a new deformable mirror technology based on a magnetic technology

J. Ballesta, Engineering Synthesis Design Inc.

No abstract available

6113-24, Session 5

Design and development of a 329-segment tip-tilt piston mirror array for space-based adaptive optics

J. Stewart, Boston Univ.; S. Cornelissen, Boston Micromachines Corp.; T. Bifano, Boston Univ.

A new lightweight, low power MEMS deformable mirror (DM) system is under development in the Precision Engineering Research Laboratory at Boston University for the hyper-contrast nulling coronagraph telescope architecture invented by the Jet Propulsion Laboratory for NASA's Terrestrial Planet Finding Mission. TPF seeks to image Earth-like extrasolar planets using a shearing interferometer with a unique DM to null parent starlight, enhancing the contrast ratio of detected planet light. The DM design consists of 329-hexagonal segments on a 600mm pitch, each with piston and tip/tilt degrees of freedom. For successful coronagraph implementation, the mirror segments must have 1mm of stroke and 600 arc-seconds of tip/tilt. More importantly, DM motion must be highly repeatable, with 0.1nm piston and 0.06 arc-second tip/tilt positioning accuracy. The mirror segments must also have excellent optical quality to achieve the intended coronagraph contrast ratio, with a local surface roughness of less than 1nm RMS and a radius of curvature greater than 10m. DM fabrication uses silicon surface micromachining with intermittent polishing steps to eliminate print through for optimal optical surface quality. To maintain structural integrity during mirror segment motion, a thick epitaxial polycrystalline silicon layer is grown on the otherwise pliant mirror surface to give it rigidity. The results of an in depth finite element analysis of the mirror as well as the electromechanical and optical characterization of several smaller arrays will be presented. The modeling and fabrication results for an alternative actuator design that uses flexure structures to reduce mirror bending during motion (instead of epi-poly) will also be described.

6113-25, Session 5

MEMS-actuated nanolaminate deformable mirror

A. P. Papavasiliou, Lawrence Livermore National Lab.

This ongoing work concerns the creation of a deformable mirror by the

integration of MEMS actuators with Nanolaminate foils through metal compression boning. These mirrors will use the advantages of these disparate technologies to achieve dense actuation of a high-quality, continuous mirror surface. They will enable advanced adaptive optics systems in large terrestrial telescopes.

While MEMS actuators provide very dense actuation with high precision they can not provide large forces typically necessary to deform conventional mirror surfaces. Nanolaminate foils can be fabricated with very high surface quality while their extraordinary mechanical properties enable very thin, flexible foils to survive the rigors of fabrication. Precise metal compression bonding allows the attachment of the fragile MEMS actuators to the thin nanolaminate foils without creating distortions at the bond sites.

This paper will describe work in four major areas: 1) modeling and design, 2) bonding development, 3) nanolaminate foil development, 4) producing a prototype. A first-principles analytical model was created and used to determine the design parameters. A method of bonding was determined that is both strong, and minimizes the localized deformation or print through. Work has also been done to produce nanolaminate foils that are sufficiently thin, flexible and flat to be deformed by the MEMS actuators. Finally a prototype was produced by bonding thin, flexible nanolaminate foils to commercially available MEMS actuators.

6113-26, Session 5

Large-scale nanolaminate deformable mirror

A. P. Papavasiliou, Lawrence Livermore National Lab.

This work concerns the development of a technology that uses Nanolaminate foils to form light-weight, deformable mirrors that are scalable over a wide range of mirror sizes. While MEMS-based deformable mirrors and spatial light modulators have considerably reduced the cost and increased the capabilities of adaptive optic systems, there has not been a way to utilize the advantages of lithography and batch-fabrication to produce large-scale deformable mirrors.

This technology is made scalable by using fabrication techniques and lithography that are not limited to the sizes of conventional MEMS devices.

Like many MEMS devices, these mirrors use parallel plate electrostatic actuators. This technology replicates that functionality by suspending a horizontal piece of nanolaminate foil over an electrode by electroplated nickel posts. This actuator is attached, with another post, to another nanolaminate foil that acts as the mirror surface.

Most MEMS devices are produced with integrated circuit lithography techniques that are capable of very small line widths, but are not scalable to large sizes. This technology is very tolerant of lithography errors and can use coarser, printed circuit board lithography techniques that can be scaled to very large sizes.

These mirrors use small, lithographically defined actuators and thin nanolaminate foils allowing them to produce deformations over a large area while minimizing weight.

This paper will describe a staged program to develop this technology. First-principles and FEM models were developed to determine design parameters. Three stages of fabrication will be described starting with a 3x3 device using conventional metal foils and epoxy to a 10-across all-metal device with nanolaminate mirror surfaces.

6113-27, Session 5

Polymer-based micro-deformable mirror for adaptive optics

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

Next generation astronomical instrumentation relies on the availability of highly performing adaptive optical (AO) systems. These systems require deformable mirrors with very challenging parameters, including number of actuators up to 250 000 and inter-actuator spacing around 500μm. 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 elaboration of a sacrificial layer and of a structural layer made of polymer materials, using low-temperature process. Mirrors with very efficient planarization and active actuators have already been demonstrated, with a piston motion of 2μm for 30V. Using our dedicated characterization bench, we have measured the dynamical behavior of actuators by time-averaged interferometry. The response is close to a second-order system with a resonance frequency of 6.5kHz, well suited for AO applications.

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 fourth order polynomial, the coefficients of the polynomial are loaded into the electronics which delivers a linearized output. The response is then nearly perfect with a standard deviation of 20 nm.

Based on the design of this actuator and our polymer-based process, realization of a complete polymer-micro-deformable mirror is under way.

6113-28, Session 5

Poly-SiGe MEMS actuators for adaptive optics

B. C. Lin, T. King, R. S. Muller, Univ. of California/Berkeley

Many AO applications require mirror arrays with hundreds to thousands of segments, necessitating a CMOS-compatible MEMS process to integrate the mirrors with their driving electronics. This paper describes a novel microfabrication process to fabricate MEMS actuators using low-temperature polycrystalline silicon-germanium (poly-SiGe) surface-micromaching technology (total thermal budget is less than 6 hours at or below 425°C). Each MEMS actuator consists of three flexures and a hexagonal platform, on which a micromirror is to be assembled. The flexures are made of single-layer poly-SiGe with stress gradient across thickness of the film, making them bend out-of-plane after release to create a large nominal gap. The platform, on the other hand, has an additional stress-balancing SiGe layer deposited on top, making the dual-layer stack stay flat after release.

6113-29, Session 5

Large-stroke self-aligned vertical comb drive actuators for adaptive optics applications

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A high-stroke micro-actuator array was designed, modeled, fabricated and tested. Each pixel in the array contains a self-aligned vertical comb drive actuator structure that is to become the actuator for a micro-deformable mirror for adaptive optics (AO) applications. These actuators are 800 microns x 800 microns and were designed to move 10 microns in piston motion with 100V applied. Analytical modeling of the folded springs was performed as well as system modeling using CoventorWare to determine the theoretical voltage versus displacement characteristics of this actuator. A high-stroke deformable element is important in many AO applications and a displacement of 10 microns is well beyond what has been previously demonstrated for a pixilated MEMS deformable mirror. To create these high-stroke devices, a four-mask process was developed that incorporated self-aligned vertical comb drive actuators that allowed a low voltage to be used to get the desired amount of piston motion. During the fabrication process, critical thickness parameters were changed from what was modeled in our original analytical spring model and the

CoventorWare simulations. With the thickness of the springs increased by a factor of 3.6, the displacement was lower than originally predicted. We achieved a displacement of 1.4 micron displacement with 200V applied, which is consistent with our models after modification to account for the fabricated spring thicknesses. Future work will involve modifications of the fabrication process to produce thinner springs so that larger displacements will be achieved.

6113-30, Session 5

Large stroke actuators for adaptive optics

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

This presentation will review the use of a 3-dimensional MEMS fabrication process to prototype long stroke (\>10 μm) actuators as are required for use in future adaptive optics systems in astronomy and vision science. The Electrochemical Fabrication (EFABTM) process that was used creates metal micro-structures by electroplating multiple, independently patterned layers. The process has the design freedom of rapid prototyping where multiple patterned layers are stacked to build structures with virtually any desired geometry, but in contrast has much greater precision, the capability for batch fabrication and provides parts in engineering materials such as nickel. The design freedom enabled by this process has been used to make both parallel plate and comb drive actuator deformable mirror designs that can have large vertical heights of up to 1 mm. As the thickness of the sacrificial layers used to release the actuator is specified by the designer, rather than by constraints of the fabrication process, the design of large-stroke actuators is straightforward and does not require any new process development. Since the number of material layers in the EFABTM process is also specified by the designer it has been possible to gang multiple parallel plate actuators together to decrease the voltage required for long-stroke actuators.

6113-35, Session 5

A novel elevating structure design applied on the motion behavior analysis of micro-otical devices

C. Tsai, Z. Fan, J. Chen, P. Lin, Ming Hsin Univ. of Science and Technology (Taiwan)

The paper proposed a novel structure for elevating the micro optical devices by the driving force of micro array thermal actuator, MATA. The effects of spring and curb structures on the maximum displacements and the stability of the level difference of the elevated micro mirror surface varied with operation voltage are investigated. 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 the wider of width, longer of pitch and more pitch numbers of spring are, the maximum displacements of elevated micro mirror are larger. Compared the effects of spring and curb structures on the maximum displacement of the elevated micro mirror, there are more influence on the variation of maximum displacement by the varied spring structure than that by the varied curb structure. On the other hand, the level difference of the elevated micro mirror is more significant variation by the varied pitch number of spring structure and the varied width of curb structure. However, the difference of the level is between 0.6 μm and 0.9 μm based upon the two metal layers design of the elevating arm. Nevertheless, the level difference is improved to 0.3 μm by the three metal layers design of elevating arm due to the high rigidity. The maximum displacement and inclined angle of the proposed micro optical device is 58.6 μm and 17.04o, respectively. The device is fabricated by Taiwan Semiconductor Manufacture Cooperation, TSMC, based upon CMOS-MEMS process and its performance analysis will be shown in the paper.

6113-31, Session 6

MEMS deformable mirror embedded wavefront sensing and control system

D. Owens, M. Schoen, K. A. Bush, AgilOptics, Inc.

Electrostatic Membrane Deformable Mirror (MDM) technology developed using silicon bulk micro-machining techniques offers the potential of providing low-cost, compact wavefront control systems for diverse optical system applications. Electrostatic mirror construction using bulk micromachining allows for custom designs to satisfy wavefront control requirements for most optical systems. An electrostatic MDM consists of a thin membrane, generally with a thin metal or multi-layer high-reflectivity coating, suspended over an actuator pad array that is connected to a high-voltage driver. Voltages applied to the array elements deflect the membrane to provide an optical surface capable of correcting for measured optical aberrations in a given system. Electrostatic membrane DM designs are derived from well-known principles of membrane mechanics and electrostatics, the desired optical wavefront control requirements, and the current limitations of mirror fabrication and actuator drive electronics. MDM performance is strongly dependent on mirror diameter and air damping in meeting desired spatial and temporal frequency requirements. In this paper, we present wavefront control results from an embedded wavefront control system developed around a commercially available high-speed camera and an AgilOptics Unifi MDM driver using USB 2.0 communications and the LINUX development environment.

6113-32, Session 6

USB-based controller for generic MEM device deformable mirrors

J. Andrews, C. C. Wilcox, S. R. Restaino, T. Martinez, Naval Research Lab.; D. Payne, Narrascape

The use of Micro-Electro-Machined (MEM) devices as deformable mirrors (DM) for active and adaptive optics is increasing dramatically. Such increase is due to both the cost and simplicity of use of these devices. Our experience with MEMs DMs has been extremely positive, however the controlling protocols of these devices is an issue. Based on our experience and needs we decided to design a generic controller based on a fast communication protocol. These requirements have pushed us to design a system around a USB-2 protocol. In this paper we present our architectural design for such controller. We present also experimental data and analysis on the performance of the controller. We describe the pros and cons of such approach vs. other techniques. We will address how general such architecture is and how portable is to other systems.

6113-33, Session 6

Chip-scale integrated driver for electrostatic DM control

D. J. Kim, T. G. Bifano, A. E. Hubbard, Boston Univ.

A CMOS electronics driver chip to control a deformable MEMS mirror has been developed. With the advances in CMOS technology, it has become possible to design and fabricate electronics operable at higher voltages than those in traditional integrated circuits. Since MEMS structures require relatively high operating voltages to achieve electrostatic force, these high voltage CMOS processes offer promise for miniaturization of the corresponding drivers. Using the capability of low voltage logic together with high voltage output stages, a compact driver chip has been designed and fabricated. The chip was developed and fabricated though a high voltage CMOS process. The driver is digitally controlled through address and data input bits, and through a smart low-voltage to high-voltage transition output stage, voltages of up to 300V are output to each mirror electrode. A compact design allows the control of 144 channels through a single chip with 8-bit resolution at 100Hz refresh rate. The low-voltage stage consists of address logic together with latch stages to store the data, which in turn is converted to a high voltage signal through a current mode, binary weighted scheme. This technique combines the digital-to-analogue conversion stage and a high-voltage amplifier stage, thus saving on substrate area. Using this method, the 144 channel high-voltage driver was fabricated on a single chip less than 2cm2 in area. In this paper, design, fabrication and testing of these drivers are reported.

6113-36, Poster Session

Microfabrication and test of pre-aligned fiber bundle couplers using UV-lithography of SU-8

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

We report an approach using 3-D UV-lithography of SU-8 photoresist for fabricating pre-aligned fiber bundle coupler. This fiber bundle coupler includes a piece of pre-aligned out-of-plane refractive microlens array and fiberport collimator arrays. With the optical axis of each pixel parallel with the substrate, the each pixel of the out-of-plane microlens array can be pre-aligned with the corresponding pixels of fiberport collimator arrays in the mask design. The microlens array and fiberport collimator arrays are made using photolithography so that high precise alignment can be obtained without accumulation of tolerances. As a simple example for pre-aligned integrated optical system, an out-of-plane polymer microlens array is pre-aligned with the fiber collimator arrays in mask design. In each pixel of fiber bundle coupler, lateral misalignment and angular misalignment are minimized by this pre-alignment technology. The longitudinal misalignment also can be minimized by the stop function of the fiber-fixing groove in the coupler. As the result, no additional adjustment or assembly is required, leading to dramatically reduced running cost and the significantly improved alignment quality and coupling efficiency. This technology for the fiber bundle coupler can also be used to fabricate pre-aligned fiber coupler for just single one fiber-to-fiber junction.

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6114-01, Session 1

High-performance blazed GxLTM device for large-area laser projector

Y. Ito, Sony Corp. (Japan)

GxLTM is SONY's laser projection display technology using the Grating Light ValveTM (GLVTM) devices; the advantage of this technology is its supreme color reproduction, high speed, high resolution, and high contrast ratio. This paper presents a blazed GxL device with high optical efficiency > 70% @RGB, high contrast ratio > 10,000: 1, and high reliability for a large-area laser projection system. The blazed GxL device has a step-etched region on each ribbon surface, which causes the ribbon tilting. The key technologies are as follows: (1) a robust design and precise stress control technology to maintain a uniform shape (bow and tilt) of more than 6,000 ribbons, (2) 0.25- um CMOS compatible fabrication processing and planarization techniques to reduce fluctuation of the ribbons, and (3) reliable reflective aluminum-alloy material technology against a high power laser. No degradation in characteristics of the GxL device was observed after operating a 5,000- lumen projector for 2,000 hours and conducting a temperature cycling test at -20°C and +80°C 2,000 times. Consequently, the world's largest laser projection screen with a size of 2005 inches (10 m X 50 m) and 6 million pixels (1,080 X 5,760) was demonstrated at the 2005 World Exposition, in Aichi, Japan.

6114-03, Session 1

Large-scale drift-free monocrystalline silicon micromirror arrays made by wafer bonding

T. Bakke, B. Voelker, D. Rudloff, M. Friedrichs, H. Schenk, H. K. Lakner, Fraunhofer-Institut für Photonische Mikrosysteme (Germany)

Large scale arrays of more than 67k micromirrors of monocrystalline silicon with underlying planar actuation electrodes have been fabricated. The mirrors were fabricated by transferring a 300nm thick silicon layer from a silicon-on-insulator (SOI) wafer to a wafer containing metal electrodes by adhesive wafer bonding in a thermo-compression bonding tool. The bonding was followed by grinding and spin-etching of the handle silicon and the buried oxide, which leaves only the thin device silicon on the electrode wafer. Mirrors and metal plugs were formed using standard micromachining techniques such as sputtering and dry etching. The arrays consist of 16μm x 16μm mirrors with 0.7μm wide and 2μm long torsional hinges. Deflection is achieved by applying a voltage between the mirrors and one of two underlying electrodes. It was found that 15V is enough to deflect the mirrors 48nm, which is sufficient to create a black pixel in a diffractive deep UV application that involves modulation of 193nm light. Furthermore, no measurable instability due to plastic hinge deformation or charging could be determined by static deflection for more than one hour. The developed fabrication process is fully CMOS compatible and can be directly applied to fabricate spatial light modulators (SLM) with mirror arrays in excess of one megapixels with individually addressable analog mirrors that are truly drift free. Application areas are photolithographic mask writers or systems for maskless lithography.

6114-06, Session 1

Global flatness of spatial light modulators

M. Wagner, U. Künzelmann, H. Schenk, H. K. Lakner, Fraunhofer-Institut für Photonische Mikrosysteme (Germany)

During the last years innovative deep UV lithography tools have successfully been introduced for semiconductor mask writing offering high production throughput at excellent performance, especially with respect to minimum feature size and CD uniformity. In contrast to the e-beam in conventional writers the DUV-optical writers (e. g. at 248 nm wavelength) are using spatial light modulators (SLM) as pattern generating system.

The Fraunhofer Institute for Photonic Microsystems (IPMS) Dresden (Germany) has developed an optimized one megapixel SLM device with 2048x512 individually adressable tilting micromirrors (ASLM1M). The active optical mirror area of approximately 9 x 33 mm≤ is asymmetrically located at an 15 x 38 mm≤ large chip. Analogue addressing of the micromirrors at frame rates of up to 2 kHz produces phase modulation patterns which are converted into a two dimensional high resolution intensity pattern at the photomask plane by the Fourier-optics of the writer.

Besides many other chip parameters surface planarities strongly determine its optical performance as well as the quality of the image. There are local surface planarities in the micromirror range (local flatness) as well as global planarity demands over the complete active mirror matrix (global flatness, GF). Starting with the description and definition of GF, influences of package cavity depression and of die bonding process parameters on GF are investigated and elucidated. These results might be transferred to GF improvements in the case of other large scale optical chips, e. g. image sensors. In the future active optical chip areas will rise due to the fact that growing pixel counts dominate over pixel size reduction. Therefore proper GF control for SLMs will gain importance.

6114-05, Session 2

Perspective of MEMS-based raster scanning display and its requirements for success

Y. Park, J. Lee, S. Shin, J. Sunu, SAMSUNG Advanced Institute of Technology (South Korea)

The customers' demands for real life-like display with natural colors and high definition is increasing and hence laser display with the best expression of natural color is being proposed as a way to realize this. The applications of laser display are diverse ranging from ultra small, portable to large screen such as the HMD, mobile projector, projection TV and cinema projectors.

In particular, the raster scanning display using the high-speed reflective MEMS scanner plus compact laser light source enables realization of ultra-small optical engine with great optical efficiency so large screen video can be realized through low power consumption.

By the way, in recent years the conventional display systems including FPD and projection-based systems show rapid improvements in terms of picture quality, form factor as well as cost. This leads war-like competition between display devices for at least coming several years until the market portions are settled.

First, this presentation focuses on technical analysis of the key success factors of the MEMS based rater scanning display through a comparison study with the conventional displays. Brightness, color, contrast, resolution, form factor, power consumption and cost-effectiveness are considered as comparison measures.

Second, as a successive work from the last year, the raster scanning display with eye-type 2D scanning mirror is demonstrated as one of the promising new generation displays. Through the demonstration, the technical pros and cons, and huddles to the success in terms of the comparison measures will be pointed.

6114-07, Session 2

New applications for DMD

E. Mounier, Yole Développment (France)

For a long time, Optical MEMS applications have been separated in two main fields.

- Telecom applications. This market has driven the optical MEMS community during the 90's.
- Non telecom applications. Applications were quite confidential except in the TV and projection systems with the success of DLP Texas Instruments technology.

In 2001, the sudden downturn of Telecom business changed the optical MEMS landscape. Some MEMS companies who were focusing only on telecom applications shut down (OMM as the most famous example) and many companies stopped their optical MEMS developments (Atmel, Memscap). However, some companies succeed to explore new applications outside the telecom area with their telecom technological platform.

Today, there is a renewal of the MOEMS business and there are very interesting market opportunities for DMD. This article describes the new market trends for DMD applications. Several new applications are now appearing aside TV and projections systems that will widespread the use of DMDs. Maskless lithography, wavefront correction (adaptive optics) adaptive front light signal for cars, digital printing are applications currently in development where matrix of micro-mirrors could be used.

Maskless lithography is still in a R&D status. It will be a low volume market but high R&D investment application that could benefit to other applications. Market acceptance may be an issue: the two main players ASML and Canon have internal projects under evaluation but it still have to prove that it is an attractive technology.

We have estimated that the MOEMS market will grow from $ 756 million in 2003 to $ 3089 million in 2008. DMD will be the largest market.

6114-08, Session 2

MEMS microdisplays: overview and markets

J. Bouchaud, Wicht Technologie Consulting (Germany)

MEMS based microdisplays have been given a lot of attention recently since DLP based products have started to generate substantial revenues for Texas Instrument in projectors and TVs. Will other mass markets? Is anyone in the position to challenge TI? The presentation will address these questions and give an overview on MEMS-based displays technologies, developers, applications and markets.

There are four MEMS techniques for micro-displays

- Micro Mirror Arrays (MMA) including the DLP from Texas Instrument
- The scanned beam displays based on a single single scanning mirror
- The Grating Light Valve (GLV) developed by Silicon Light Machines
- The Interferometric Modulator, or iMoD developed by Qualcomm

In 2004, micro-displays based on MMAs and scanned beam displays where on the market. The total market for MEMS based displays was around US$ 870M.

Texas Instrument has been largely dominating the market in 2004 with micro-mirror arrays for front projectors and rear projection. A few hundreds of scanning mirrors based head mounted displays have been also commercialized by Microvision.

In 2009, WTC expects the market for MEMS microdisplays to reach US$ 2,7 billion. Front projectors and rear projection TV will still account for the bulk of the market. However, new products and applications are expected:

- Head up displays for automotive based on scanning mirrors.
- Professional displays based on the GLV technique licensed to Sony
- Displays portable electronic devices such as PDA, cell phones etc using the iMoD technique developed by Qualcomm.

6114-09, Session 3

Development of high-efficient NIR-scanning gratings for spectroscopic applications

F. Zimmer, T. Sandner, H. Grueger, A. Heberer, A. Wolter, H. Schenk, Fraunhofer-Institut für Photonische Mikrosysteme (Germany)

In recent years, Micro Opto Electro Mechanical Systems (MOEMS) have been reached more and more importance in technical applications. This is caused by the increased reliability of micro systems combined with the reduction of costs by high volume productions. In this paper, we will present a resonant scanning grating chip with high diffraction efficiency, developed for the NIR region (900 ñ 2500 nm), which is based on our resonant scanning micro mirror chip. The grating was additionally applied to the silicon mirror plate by a chemical wet etch process. Compared to investigations with direct structured gratings in the reflective aluminium surface, gratings with up to 714 lines/mm could be fabricated combined with an improved process parameter control. These new resonant driven scanning gratings are still compatible to the scanning mirror fabrication process and show higher diffraction efficiencies in the first order. They have a large surface of 3 * 3mm≤ and resonant frequencies of only 150Hz, which results in a lower demand on the bandwidth of the electronic read out, when applied to a spectrometer setup. The maximum scan angle of the grating mirror plate could be increased to +/-11∞ mechanically at an applied voltage of 36V. First measurements results and an improved design of a micro spectrometer, working with only one single InAs-Detector in a spectral range of 900 to 2500 nm will be presented and discussed.

6114-10, Session 3

High-fill factor micromirror array for multi-object spectroscopy

S. Waldis, P. Clerc, W. Noell, Univ. de Neuchâtel (Switzerland); F. Zamkotsian, Lab. d'Astrophysique de Marseille (France); M. Zickar, N. F. de Rooij, Univ. de Neuchâtel (Switzerland)

Programmable multi-slit masks are required for next generation Multi-Object Spectrographs (MOS) for space as well as ground-based instruments. A promising solution is the use of MOEMS devices such as micromirror arrays (MMA) or micro-shutter arrays (MSA), which both allow remote control of the multi-slit configuration in real time. In the present work we develop and microfabricate a novel micro mirror array suited for this application. The requirements are: high contrast, optical flat (lambda/20) mirrors in operation, uniform tilt angle over the whole array and low actuation voltage.

In order to fulfil these requirements we use a combination of bulk and surface micromachining in silicon. The mirrors are actuated electrostatically by a separate electrode chip. The mirrors are defined by deep reactive ion etching in the 10 μm thick device layer of a silicon-on-insulator (SOI) wafer, whereas the suspension of the mirrors is defined by a patterned poly-silicon layer hidden on the backside of the mirrors. The mirror size is 100 x 200 μm^2 and the dimensions of a typical cantilever suspension are 100 x 5 x 0.6 μm^3. On a separate SOI wafer the electrodes and the spacers are processed by using a self aligned delayed mask process. The first results on the mirror chips show that the micromirrors can easily achieve the desired mechanical tilt angle of more than 20°, which is necessary for a high contrast spectroscopy.

6114-11, Session 3

Principle and applications of a new MOEMS spectrometer

R. Saupe, Technische Univ. Chemnitz (Germany); T. Otto, Fraunhofer-Institut für Zuverlässigkeit und Mikrointegration (Germany)

Near Infrared (NIR) spectroscopy has developed to an important and useful analysis method over the past years. The existence of compact, portable devices offers a lot of applications possibilities, even in harsh environments. Compact devices, mostly based on detector arrays, are quite costly caused by the expensive Indium Gallium Arsenide (InGaAs) detector arrays. By using MOEMS the set-up can be realised much more efficiently. With an adapted optical set-up detector arrays can be replaced by single

element detectors.

We have realised a new miniaturised spectrometer based on a scanning micro mirror. The mirror is combined with a diffraction grating and other optical components. It periodically disperses the polychromatic radiation into its spectral components. The radiation is measured by an InGaAs-single element detector, which can be thermoelectrically cooled depending on the application. The radiation coupling is possible either directly or by using fiber optics. It allows an easy attachment of substance samples for reflectance measurements as well as attenuated total reflection (ATR) probes, cuvette holders and flow cells. Lowest noise preamplifiers enable high-precise measurements over a wide dynamic range. With a spectral range of 1000 - 2100 nm and a spectral resolution of approx. 12 nm the device is able to fulfill various requirements. Applications for food stuff industry; clinical chemistry and identification of polymers were tested and will be discussed.

Furthermore we will show the advanced optical and mechanical design. In addition advanced performance issues and reliability test results of the device will be reviewed.

6114-12, Session 3

Design and fabrication of a tunable Fabry-Perot interferometer/photodiode (FPI/PD) spectral image sensor for visible wavelengths

H. Yang, J. Su, W. Porod, P. J. Fay, G. H. Bernstein, Univ. of Notre Dame

The design and fabricating of a tunable FPI/PD spectral image sensor on silicon with unambiguous response in the visible wavelength range using CMOS compatible processes is reported. The sensor will ultimately be integrated on a cellular neural/nonlinear network visual microprocessor chip for target detection, navigation, tracking and robotics. Using the transfer matrix method, FPIs with distributed Bragg reflector mirrors and Ag mirrors are investigated. Although the FPI with DBRs provides higher transmittance and finesse, its tuning range is too small to provide an unambiguous transmission peak in the Si spectral range, while the FPI with Ag mirrors can meet this requirement. A transmittance of 0.4 can be achieved using 40 nm Ag mirrors. The moving Ag mirror needs to be mechanically supported and an insulating layer needs to be added to separate the PD from the fixed Ag mirror. After adding the supporting layer or insulating layer, the transmittance changes periodically with the thickness of the supporting layer or the insulating layer. The changing period and amplitude is a function of the refractive index of the supporting layer or the insulating layer, which helps to choose the supporting layer and the insulating layer. Interdigitated PIN photodiodes with different geometry were fabricated on Si and tested. The spectral response shows that a quantum efficiency of near 80% is achieved by the PD in the visible wavelength range. The quantum efficiency increases with increasing gap width to finger width ratio, and the increase is more significant at shorter wavelengths.

6114-13, Session 4

Tunable microcavities in planar photonic crystals

I. Marki, H. P. Herzig, Univ. de Neuchâtel (Switzerland)

Micro- and nano-optical structures offer the possibility to control light on a wavelength scale. This allows further miniaturization of integrated optical circuits. Planar photonic crystal waveguides and microcavities are considered basic building blocks for applications such as microlasers, filters, multiplexers and optical switches. The possibility to tune or switch photonic crystal devices by various ways such as temperature, refractive index change using liquid crystals, free charge carrier density or non linear material effects increases their functionality to form multifunctional, intelligent devices. High-Q cavities in planar photonic crystals exhibit highly localised fields and narrow transmission bands. Due to their strong light confinement even a small perturbation of the localized field can change their transmission properties of the cavity. We present different ways of perturbing the optical environment near a photonic crystal cavity enabling tuning and modulation of the in-plane transmission.

In particular, optical switching and wavelength tuning is obtained by means of induced thermo and electro optical effects when focusing a laser onto the cavity structure. The feasibility of high-speed optical integrated circuits based on silicon photonic crystal structures is shown. On the other hand, an AFM tip can be used for tuning and damping the in-plane transmission by mechanically perturbing the optical environment near the resonant cavity suggesting a stand-alone MEMS solution to create a chip-based on-off switch or tunable filter. A future challenge is the integration of more than one silicon tip to combine filter and tuning functionalities on one device.

6114-14, Session 4

Deformable MEMS grating for wide tunability and high-operating speed

M. Tormen, Ctr. Suisse d'Electronique et de Microtechnique SA (Switzerland); Y. Peter, École Polytechnique de Montréal (Canada); P. Niedermann, A. Hoogerwerf, R. P. Stanley, Ctr. Suisse d'Electronique et de Microtechnique SA (Switzerland)

In the optical MEMS field, the family of diffractive MEMS structures is attracting increasing interest. In addition to the well-established moveable and tiltable mirror technologies used in displays, scanners and switching applications, diffractive MEMS structures present an opportunity for improved performance and new applications. Already commercially available diffractive MEMS devices are used in displays, in spectroscopy and in the optical telecom domain. Other interesting application fields are submicron maskless lithography or as tuning element, e.g. in external cavity lasers.

The diffractive MEMS structure presented in this paper is a deformable grating, with wide tuning characteristics and high operating speed.

The design, fabrication and characterization of the deformable grating are presented and the results are in agreement with mechanical and optical simulations.

The grating is 10 micron thick made from a silicon on oxide wafer in a single mask process. The grating beams are attached to each other using leaf springs. Actuation is achieved through two electrostatic comb drives, guaranteeing low power-consumption. Experimentally a variation of the grating period up to 2.5% has been achieved and the first resonant mode of the structure is located near 26 kHz.

A blazed version of the MEMS grating has been designed. Despite the need of an extra mask, the grating provides high diffraction efficiency. Process details and preliminary characterizations for the blazed deformable MEMS grating will be provided.

The device can be used as tuning element in external cavity lasers.

6114-15, Session 4

Integrated heterodyne optical system (IHOS)

N. Elman, M. Sternheim, Y. Y. Shacham-Diam, Tel Aviv Univ. (Israel)

A novel MEMS-based modulation scheme is introduced as a method to enhance the signal-to-noise ratio (SNR) of photodetectors adapted for the detection of light-emitting bio-reporter signals. Solid-state photodetectors exhibit limited sensitivity to optical dc signals, as the low frequency noise is comparable to signal magnitude. The enhancement scheme is based on a design of transmissive optical modulators that operate in the 1-5 kHz range in order to overcome the low spectral (flicker) noise. Furthermore, a new fabrication process was developed to implement the optical modulators, which combines multiple-aspect ratio structures that include large displacement combdrive actuators integrated with large aperture shutters. We have denominated this two mask process MASIS for Multiple Aspect Ratio Structures. Optical modulators were electrostatically tested and demonstrated maximum displacement of about 40 μm at approximately 1 kHz in resonance at an actuation voltage of 50

Vpp in air, and 3.5 Vpp in vacuum (8 mTorr). IHOS allows the implementation of inexpensive silicon based photodetectors with greater signal sensitivity for the detection of very low intensity optical signals, providing 20-30 dB SNR improvement. The applications include detection of bio-reporter signals of biological systems, real-time monitoring of cell markers, optical modulation for communication systems, and optical detection in space exploration.

6114-16, Session 4

Optical characterization of 9 x 9 optical cross connect utilizing silicon lens scanners with spider-leg actuators

H. N. Kwon, J. Lee, Gwangju Institute of Science and Technology (South Korea); K. Takahashi, H. Toshiyoshi, The Univ. of Tokyo (Japan)

We proposed a micro XY stage with spider-leg actuators for low driving voltage and high independency in two orthogonal driving axes. The micro lens scanner was fabricated by lens-profile-transferring to the structural layer of an SOI wafer by the RIE from thermally reflowed photoresist and by the continuing two deep RIEs. The XY stage moved more than 55 um independently in the X and Y directions.

We constructed a 9 x 9 OXC by aligning fibers and the fabricated lens scanners. The light with a mode field diameter of about 640 um was successfully collimated and transferred over the distance of 20 cm. The light was switched to the nearest fiber at 2 mm distance by the actuator's displacement of about 35 um. Voltage required to move the lens by 35 um was about 84V, and the resonant frequency was found to be 213 Hz and 230 Hz in the X and Y directions, respectively.

Every insertions (coupling) loss between input and output fibers was less than 13 dB in the 9 x 9 OXC utilizing the fabricated lens scanners, and the channel uniformity showed about 4.5 dB. The insertion losses were dependent on time, polarization, and wavelength as much as 0.6 dB, 0.7 dB, and 0.9 dB, respectively.

6114-17, Session 4

Performance optimization of MOEMS-based diffractive optical elements: new designs and theory results

J. Castracane, G. Panaman, J. P. Verheggen, L. P. Clow, Jr., B. Altemus, SUNY/Univ. at Albany

The use of miniaturized optical components for chip level communication is seeing a steady increase. The possible applications include: optical switching, signal monitoring, modulation, and add/drop multiplexing. Silicon micromachining based MEMS are moreover being used to develop these components for ease of integration into mainstream circuitry. MOEMS devices based on dynamic diffractive elements are currently investigated for both their switching capabilities and de-multiplexing properties. These characteristics are expected to increase the speed of optical data transfer.

This paper focuses on the current status of the MOEMS research program for Free Space Optical inter-chip communication at the College of Nanoscale Science and Engineering, University at Albany-SUNY (CNSE) based on the MOEMS Compound Grating (MCG) design. Operational characteristics of these MCG devices have been shown to operate at high voltages (>20V) compared to 5V levels prevalent in conventional integrated circuits. The specific goal of this work is to improve performance while minimizing the power consumption. A design change that incorporates a higher capacitance and a lighter suspension system has been studied. A new fabrication process has been constructed utilizing Polyimide as a structural material. Fabrication steps have been optimized for best MCG device performance. A comprehensive theory review of the optical, mechanical, and electro-dynamical properties is included. Optical testing and metrological results of the MUMPs® and polyimide MCG devices are detailed and compared with previously obtained results.

6114-18, Session 4

Design, characterization, and control of a large aperture MOEMS Fabry-Perot tunable infrared filter

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A miniature Fabry-Perot tunable infrared filter under development at the NASA Goddard Space Flight Center is fabricated using micro opto electromechanical systems (MOEMS) technology. Intended for wide-field imaging spectroscopy in space flight, it features a large 10-mm diameter aperture structure that consists of a set of opposing suspended thin films 500 nanometers in thickness, supported by annular silicon disks. Achieving the desired effective finesse in the MOEMS instrument requires maximizing the RMS flatness in the film. This paper presents surface characterization data for the suspended aperture film prior to, and following application of a multi-layer dielectric mirror. A minimum RMS flatness nanometers was measured prior to coating, leading to an estimate of the maximum effective finesse. Results show evidence of initial deformation of the silicon support structure due to internal stress in the substrate and thin film layers. Film stress gradients in the dielectric coating on either side of the aperture add convexity and other localized deflections. The design of a tuning system based upon electrostatic positioning with feedback control is presented.

6114-19, Session 5

Highly reflective optical coatings for high-power applications of micro scanning mirrors in the UV-VIS-NIR spectral region

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This paper addresses different highly reflective optical coatings on micro scanning mirrors (MSM) for applications at high optical power density in the UV-VIS-NIR-spectral region to enable new applications like laser marking. In the common case of MSM with an unprotected Al coating, the absorption limits the maximal power density because of induced heating. In contrast to macroscopic optics HR-micro-mirror coatings have to guarantee, beside high reflectivity, additional demands like (a) low-stress to enable the required flatness of the fragile micro mirrors and (b) the integration of NIR-coating deposition into the fabrication process of MSM.

To overcome the mentioned problems, highly reflective low-stress optical coatings for the next-generation of micro mechanical mirrors have been developed enabling novel MOEMS applications in the UV-VIS-NIR spectral region. Stable highly reflective coatings were investigated according to a triple strategy of (a) broadband metallic reflectors, (b) dielectric multi layers and (c) enhanced hybrid coatings.

For NIR-applications Au and Ag based metallic broadband reflectors reach a reflectivity of 98.7% at 1064nm and enable an high mirror planarity, i.e. smaller than lambda/100, whereas hybrid-HR-coatings reach a higher reflectivity of up to 99.8% at 1064nm equal to thicker dielectric multilayers. For the UV-VIS spectral region low-stress hybrid HR-coatings have been developed enabling high reflectance up to 99.8% at 633nm or 98.8% at 308nm at comparative low total thickness favorably for highly planar MSM. The enhanced hybrid coatings are characterized by an excellent laser damage threshold of up to Ppulse >130MW/cm≤ at 1064 nm verified by a harsh short pulse irradiation.

6114-20, Session 5

Micro-actuator with extended analog deflection at low-drive voltage

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Electrostatic Micro-actuators are being increasingly used for a wide variety of applications such as spatial light modulators, scanning mirrors, optical cross connects, micro-valves, and others. Usually the electrical forces operate in one direction and are balanced by a mechanical spring. The resulting deflection is then either defined by a mechanical stop, or it is only a meta-stable equilibrium position: after an additional external force or deflection it will snap to a different position, frequently again defined by a mechanical stop. This issue is well known and is often called 'pull-in'.

In the often used parallel-plate capacitor actuator, the instability already begins at a deflection of only on third of the original capacitor plate separation. For safety reasons and due to the steep response-curve one can only use an even smaller fraction of the mechanically possible movement. This means, that the gap below the actuator has to be designed very much larger than the required maximum deflection. To get the predescribed force and deflection, a much higher voltage is needed than for potential smaller gap widths.

The useable range of deflection for many types of micro-actuators can be extended without the penalty of large drive voltage or low shock resistivity, by employing springs with steeper-than-linear restoring force. Alternatively, the voltage needed for a given range of deflection may be reduced. This paper shows the benefits and how to design and dimension these type of springs.

6114-21, Session 5

Extended damping model for out-of-plane-comb driven micromirrors

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Since damping is deciding for the reachable maximum deflection, it is a very important issue in the context of out-of-plane-comb driven micromirrors. In this paper we present an optimized comb design and an extended damping model for out-of-plane driven scanning micromirrors. It bases on the compact analytical model published by Sandner et. al. at the SPIE conference Photonics Europe in 2004. The basis idea of this model is that viscous damping in the comb gaps is the dominant contributor of damping moments.

To verify and extend this analytical damping model we use a fluidmechanical FEM model of the out-of-plane electrode comb. The met assumptions are proved by analyzing and comparing results like velocity profiles and shear forces. Furthermore the FEM model allows to investigate and understand the condition of the fluid while the transition from engaged to disengaged position of the comb. With this knowledge it is possible to improve the analytical damping model. Therefore parameters are extracted from the FEM simulations. The result is an extended analytical model which fits the FEM results very well. The predictions of the improved analytical model are also compared to experimental results. Therefore dedicated damping structures with varied comb geometries are used.

The primary goal of damping analysis and optimization is the minimization of the power consumption respectively the reduction of the driving voltage of the device. To consider that, the damping of the out-of-plane electrode comb is discussed in the context of its capacitance. One of the results presented in this paper is a out-of-plane comb drive with optimized drive efficiency.

6114-22, Session 5

A new deformable mirror for adaptive optics

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We present here a deformable mirror (DM) with a continuous mirror using new zipping actuators compatible with a simplified collective process and electronic integration. The originality of these new zipping actuators is the presence of a rotation support and a lever to push the mirror. Therefore a small electrostatic gap is enough to obtain large strokes. The device is a bi-directional electrostatic actuator with two other adjacent levers which pull the mirror down. The mirrors are silicon reflective membranes obtained with SOI wafers to bring flexibility in the mechanical design, as well as superior mirror flatness and surface roughness.

Using finite element analysis (FEA), simulations have been performed so as to evaluate the performance of the actuators. The recent simulations have shown that the actuator design should enable inter-actuator strokes larger than 1 μm and a global deformation of 10 μm (peak to valley), allowing thus to meet the ophthalmological applications.

A first device has been realised to show the feasibility. It is DMs with 19 actuators and a mirror of 1 cm in diameter. Experimentally observed actuator strokes of more than 4.5 μm were obtained for an applied voltage of 60 V when the mirror was pulled down and the first promising results were obtained when the mirror was pushed up from 10 V to 80 V; electrical tests are in progress for complete validation. The specific shape of the links between the membrane and the actuators provides remarkable optical properties. The optical print-through due to the pillar architecture has been reduced to 1.5 nm RMS, which is close to the mirror roughness

6114-24, Session 6

Scanning 2D micromirror with enhanced flatness at high frequency

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We present a scanning micromirror with 5x better flatness of the mirror plate compared to our previous devices. The devices are designed for a laser scanning displays with VGA resolution.

Scanning laser displays are certainly the most demanding application for scanning micromirrors. The fast axis must provide a large mirror plate that remains flat, when deflected to large angles must at high frequency. The presented devices meet the specifications for VGA-resolution (640x480 pixels). Oscillation frequency is 16kHz. The mirror-plate has 1mm diameter and can be deflected by ±10 degree. Dynamic deformation is below lamba/10 under this conditions.

The devices is fabricated in the established SOI process of Fraunhofer IPMS Dresden. Mirror plate and springs are made of 30um of crystalline silicon. Operation is resonant with lateral comb-drives.

In this article we present the design, simulation results, measurement results and the performance in a small VGA laser projector.

6114-26, Session 6

Digital photographic imaging using MOEMS

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Unlike traditional cameras that use film to capture and store images, digital cameras use electronic solid-state devices called image sensors (e.g. CCD, CMOS). The design goal of these systems is to maximize the resolution of the captured image. This can be achieved by reducing the size of the photo-sensors in order to fit more sensors in the same space. However, a smaller photo-sensor covers less area, which means fewer photons are captured. This is a fundamental optics problem that all image sensors face and it is the bottleneck for creating ultra high-resolution image sensors.

Our solution is to introduce a micro-mirror array into the optics of the image sensor. With this device, we now can image a given surface and establish a correspondence between the surface and the image sensor. Such correspondence can be created for every state of each of the mirrors on the array. Due to the fact that the final image is a result of a reconstruction of many image points, we are able to create an image of a much higher resolution than the native resolution of the employed camera.

In this paper we will present our actual prototype results of the previous experiment using Lucents Lambda-router micromirror array of 256 mirrors and the image sensor Sony DFW-V300 that will extract one or more pixels from each of the micromirrors of the array at any given mirror state. These individual pixels will be used to reconstruct a high-resolution final image of the original object.

6114-27, Session 6

Investigation of optical information for a single micro grating device combined with MATA by SMart process

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The concentric circles type and saw-tooth type of Micro Grating Device based upon the diffraction theory are proposed in this study. The geometry dimension of micro optical device is 200 ◊ 200 μm, the interval of grating is 4 μm, and the depth is 0.75 μm. The Micro Array Thermal Actuator, MATA, is applied to drive the Micro Grating Device, and the pre-elevating structure is designed to lift the Micro Grating Device by the residual stress of polysilicon combined with metal. The Micro Grating Device is fabricated by Surface Micromachining for applications and research technology platform, SMart, common process. The incident ray of He-Ne laser focused by a lens which focal length is 250 mm is applied to be the light source for the experiment, and then analyzes the optical information of the outgoing ray. From the experimental results, the basic optical features are examined based upon the concentric circles type and saw-tooth type of Micro Grating Device, respectively. The outgoing ray angle of central spot is 60∞ in theory. The measurements are 59.475∞ for the concentric circles type and 59.88∞ for the saw-tooth type. The outgoing ray angle of the first stripe is 46.9∞ in theory, and 46.81∞ for the concentric circles type and 46.67∞ for the saw-tooth type are measured from the experiment. The variation of outgoing ray angle is smaller than 1% compared the measurement results with theory of diffraction on the central spot and first stripe characteristics. The work successfully demonstrates the micro grating device with highly accurate performance by the verification of optical information. All of the efforts will be contributed to Controlled Blazed Diffraction Micro Grating Device, CBDMG, and that will be the main device of Integrate Opto-Electronics applied on display to develop in the future.

6114-28, Poster Session

Laterally driven electrostatic actuators with extended travel range

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A novel lateral drive mechanism is proposed and studied to solve pull-in problem of electrostatic actuation in MEMS to allow Fabry Perot interferometers (FPI) with large tunability easy to be made. This method is to build electrodes not directly opposite to each other, but with a lateral shift. By assuming a beam structure with double substrate electrodes, Mathematica calculations show that lateral drive method requires a smaller driving voltage than does other method, and covers nearly the full travel range. It is also found that drive performance is influenced by parameters of structure: lateral gap, substrate electrode width, beam electrode width and vertical gap. For lateral gap and beam width, the smaller the better; for substrate electrode width and vertical gap, the larger the better. The stability of the system has also been studied when the left and right gaps are unequal. Calculations show that when the spring constant of the beam is the same in the vertical and horizontal directions, unequal gaps do not contribute to instability. A test structure has been designed and fabricated, consisting of an aluminum beam suspended across two poles. Directly below the beam is located the capacitance electrode. Next to the capacitance electrode are two lateral electrodes. Driving voltage is applied across the aluminum beam and lateral electrodes, pulling down the beam and causing the capacitance to change between the beam and electrode. By measuring this change, the lateral drive is verified and characterized.

6114-29, Poster Session

Using MEMS in spectroscopy applications

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Digital Transform Spectroscopy (DTS) constitutes an innovative approach in the large and mature molecular spectroscopy industry. Currently, many in-line or factory-based 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 fluids received at a pharmaceutical manufacturer), or alternatively, sample identification must be conducted immediately and accurately (e.g. Coast Guard requirements to verify the identity of specific white powders). 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 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.

The portability, effectiveness and low cost of these compact spectrometers will be a driving force in the generation of numerous new applications in which a spectrometer can be brought to the sample as opposed to current practices that require bringing samples into the lab.