MOEMS-MEMS

SPIE Photonics West

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Technical Abstract Summaries

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Conference 7590: Micromachining and Microfabrication Process Technology XV

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Micromachining and Microfabrication Process Technology XV

7590-01, Session 1

Ultrafast pulsed laser micro-deposition printing on transparent media

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We have studied near-threshold ultrafast pulsed laser ablation and micro-deposition in a confined space. During ablation, the target surface is covered with a transparent medium (e.g., a glass substrate) such that the laser plasma expansion is confined in a narrow gap. We first find that compared with open space ablation, on the target surface, the well-known near-threshold laser-ablation-induced periodical sub-wavelength ripples are drastically suppressed. On the other hand, on the opposite surface of the covering glass, the ablated material is deposited as nanoparticles. Based on this type of LIBT (laser-induced backward transfer) technique, with a high pulse repetition rate in MHz region and a programmable beam scanner, we first demonstrate printing of both bitmap and vector graphic images with a continuous gray scale on transparent glass. The printing linewidth is 2-3 times thick as the laser focal spot. A high printing speed of about 1 square centimeter per second is also obtained. We further find that the materials deposited on the covering glass maintain several physical properties of the target material, including alloy composition and optical emission. We attribute this phenomenon to the nanoparticle formation that is characteristic of ultrashort pulsed laser ablation. We then demonstrate printing of functional patterns that have additional properties such as phosphorescence. This laser printing technique can be applied to fabrication of flat panel indicators.

7590-02, Session 1

Coaxial real-time metrology and gas assisted laser micromachining: process development, stochastic behavior, and feedback control

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Material damage, redeposition and melt flow in percussion drilling with nanosecond and longer optical pulses is difficult to model and can be highly stochastic. This ultimately limits accuracy in thermal drilling with fixed parameters. By overcoming these challenges, the full potential of new low cost, turn-key, high brightness fiber lasers can be achieved in industrial processes.

The in situ, high speed (up to 300 kHz) metrology capabilities we present provide a window into the morphology of the laser keyhole with ~10 micrometer resolution over several millimeters. With coaxial delivery of assist gas, machining and imaging light, we directly measure machining rates and hole stability over the entire drilling process in real time. An iterative optimization procedure using post-processing analysis is completely avoided.

Here, we study the effects of assist gas pressure and chemistry on cut rate and repeatability in drilling steel with QCW and pulsed laser machining sources. Feedback from the imaging system is implemented to increase cut accuracy. This method can also be used to guide blind hole cutting in Si wafers without a priori knowledge of their thickness.

7590-03, Session 1

Sub-micron machining of semiconductors

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In recent years, a major interest in surface as well as bulk property modification of semiconductors using laser irradiation has developed. A.Kar et.al. and E.Mazur et.al. have shown introduction and control of dopants by long-pulse laser irradiation and increased absorption due to femtosecond irradiation respectively. With the development of mid-IR sources, a new avenue of irradiation can be established in a spectral region where the semiconductor material is highly transparent to the laser radiation. The characterization of the light-matter-interaction in this regime is of major interest. We will present a study on GaAs and its property changes due to pulsed laser irradiation ranging from the visible to the mid-IR region of the spectrum. Long-pulse as well as ultra-short pulse radiation is used to modify the material. Parameters like ablation threshold, radiation penetration depth and thermal diffusion will be discussed. The influence of the laser repetition rate on the interaction will also be investigated.

7590-04, Session 1

In-volume selective laser etching of 3D microstructures in sapphire and fused silica

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The miniaturization of products in micro optics, medical technology and micro system technology requires transparent components with structure sizes in the micrometer range and accuracies of about 100 nm. In-volume Selective Laser-induced Etching (ISLE) is an appropriate manufacturing process for micro machining of transparent materials such as sapphire and glasses, e.g. fused silica. By focusing the laser radiation (wavelength 1040 nm, pulse duration 500 fs, repetition rate 0.1-5 MHz, pulse energy <1 µJ) in the volume the material is locally modified. By scanning the laser focus with pulse overlap inside the material, connected volumes of modified material are created. The modified volumes are subsequently removed by chemical etching using aqueous solution of e.g. HF or KOH.

For micro fluidic systems in materials resistant against corrosive chemicals and high temperatures such as sapphire and fused silica micro channels, slits, shaped holes and micro components can be produced by ISLE. By selectively modifying a closed plane and subsequent etching both the micro component and the shaped hole result with a kerfs' width of 1-2 µm in sapphire crystals 500 µm in thickness.

To exploit the productivity of high repetition rate FCPA fs-lasers a scanning optics for fs-laser writing with high precision (100-300 nm), high speed (v=100-300 mm/s) and large numerical aperture (NA=0.4-1.2) is developed. New results which are achieved with ISLE method in combination with the developed scanning optics will be shown and discussed. Furthermore the potential for applications e.g. in micro optics is investigated.

7590-05, Session 1

Polarization converted laser beams for micromachining applications

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Polarization converters (PC) transfer a laser beam's global linear polarization state into a locally redistributed polarization state, such as radial or azimuthal polarization. These polarization states have increasingly attracted interest in the laser micro machining community during the last years. Relevant advantages for the practical laser machining, however, could only be identified for welding or high aspect-ratio laser processes, such as deep drilling, due to improved absorption conditions and better beam propagation in the ablation cavity. This paper presents our recent activities and results on polarization converted ultrashort laser pulses for the generation of ripple structures with predetermined sub-patterns. The formation of ripples fabricated in metals, ceramics, and semiconductors is analyzed by the morphological investigation of the structures (height, aspect ratio, spacing, orientation) as a function of laser parameters (local polarization, fluence, number of pulses, spatial and temporal pulse separation).

7590-06, Session 1

Enhancing laser scanner accuracy by grid correction

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Lasers are used in micro manufacturing and microwelding applications. Manufacturing in micrometer scale features requires good laser beam properties, but also axis of the laser machining system have to be accurate. One of the alternatives is a scanner. Scanners are equipped often with galvanometric actuators, which enable accurate beam movement by changing beam angle with mirrors and focusing beam with a scanner lens. Both actuators and lens cause inaccuracy to the system. Lens optical shape is not ideal due structure of lens and lens grinding. Actuator performance is not ideal and one of the biggest reasons for scan angle error is drift. Temperature changes may affect significantly to the scanner working accuracy. Thus, thermal stability of scanner becomes important factor in micro manufacturing with laser scanner. In this paper is presented one solution to compensate whole scanner working field accurately, and calibrate scanner field to match actual working field. In the calibration process a circle matrix is marked on a plate and locations of the circles are measured accurately with a coordinate measuring machine. Desired points and measured points are given to the scanner grid correction software, which calculates new correction file to the scanner software.

7590-07, Session 1

Enhanced Si processing at 1-micron wavelength using a MOPA based Yb fiber laser

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Nanosecond laser operating at infrared regime are not commonly used for micromachining silicon due to its low absorption coefficient. However, the new MOPA based configuration offers a range of optical pulse shapes, maximum peak power densities approaching ~2GWcm^-2, and pulse repetition rates up to 500 kHz. These processing parameters offer a broad range of material response characteristics. In this study, single crystalline silicon wafers of 650µm thick was percussion drilled, and grooves were formed with Yb doped fibre laser, which operates up to 20W average power. Results presented here show no signs of the usual thermally induced deleterious effects (micro cracking, heavy recast layers, surface damage) normally associated with Si interactions at 1064nm.

Hole depth and geometry were measured using SEM and Optical Interferometric Profilers. Results revealed that the material removal rate was greatly influenced by the pulse energy and repetition rate. Moreover, different etch depth and surface finish were detected for the same pulse energy but different pulse profile. High speed imaging was also used to look at plasma expansion.

It was found that pulse duration of 200ns (full width) at 25kHz, 20W average power, and 0.8mJ pulse energy resulted in optimum removal and surface finish, whose volumetric etch rates reached 230,000,000 um^3s^-1. It was suggested that the long tail of pulse shape at 25kHz, enriched vaporisation and plasma formation during laser ablation of Si, leaving a limited resolidification.

7590-08, Session 2

Multilayer metal micromachining for terahertz waveguide fabrication

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Thick multi-layer metal stacking offers the potential for fabrication of rectangular waveguide components, including horn antennas, couplers, and bends, for operation at terahertz frequencies, which are too small to machine traditionally.

Air-filled, TE10, 3 THz rectangular waveguides were fabricated using two stacked electroplated gold layers on substrates with and without topography. The initial layer of lithography and electroplating defined 37 micrometer tall waveguide walls in both straight and meandering geometries. The second layer processed on top of the first, defined 33 micrometer thick waveguide lids. Release holes periodically spaced along the center of the lids improved resist clearing from inside of the electroformed, rectangular channels. Processing tests of hollow structures on optically clear, lithium disilicate substrates allowed confirmation of resist removal by backside inspection.

The developed techniques enabled construction of hollow, THz rectangular waveguides on planar silicon substrates and also integration of waveguides with 10 micron tall quantum cascade lasers on gallium arsenide substrates.

Obtaining empty volumes presents the unique challenges of processing on top of resist molds filled with electroplated metal and removing the sacrificial photoresist from the internal volume. Developing these processes required modifications to standard lithography, controlled electrodeposition and high temperature, mega sonic resist stripping. The paper and presentation will include details, results, and conclusions from these processing experiments and waveguide fabrication.

Sandia is a multi program laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

7590-09, Session 2

Fabrication of a microlens array by diamond milling with spherical shaped milling tools

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High power achromatized array microscopes have applications in image

cytometry for diagnosis of infectious diseases and high throughput cancer research. Production of these arrays requires a method of quickly fabricating arrays of lenses that are reliably spaced, which conventional diamond turning does not accomplish well, and with a steeper sag than what slow tool servo can accomplish. Also array lenses of both concave and convex surfaces are needed in at least two different types of substrates whose optical properties allow for them to be combined in an achromatized system. Diamond milling with shaped tools is a novel fabrication method that meets all of these needs. Results are shown of both concave and convex lens arrays cut into polystyrene and PMMA using shaped tools in a diamond milling configuration. These are all 5 × 5 arrays of lenses with clear aperture of greater than 3 mm and radius of curvatures less than 2.2 mm. The roughness and shape of these arrays are analyzed and compared with arrays produced by other diamond turning techniques. Sources of error in the shape of diamond milled lenses originating from both the tool and the milling process are analyzed. Decoupling tool error from process error and possible designs for a high power achromatized system of lens array surfaces stacked and aligned with kinematic mounts are discussed.

7590-10, Session 2

Diamond turning of aspheric steel molds for optics replication

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Ultra precise steel parts with optical surface qualities and complex shaped geometries are required for modern optics fabrication e.g. in plastic injection molding or precision glass molding processes.

Nowadays optical molds for injection molding are coated with a nickel layer, in order to be able to machine the surface. Directly machining the steel parts would decrease production time, making the coating process step unnecessary. Additionally, the life time of the mold is increased dramatically and therefore the single optic price is reduced. Steel tools have a higher scratch resistance and no risk of delamination. Therefore the potential and benefit of directly machining steel with monocrystalline diamond is exceptionally high.

Though diamond machining is conventionally limited to non ferrous, a few crystalline and plastic materials. The affinity between the carbon (diamond) and the iron (workpiece) causes graphitization and leads to excessive tool wear even at very small cutting distances.

One technology that enables the direct manufacturing of steel components with monocrystalline diamond is the ultrasonic assisted diamond turning process. This technology has been investigated over years within the Fraunhofer IPT and has proven its potential. Surface roughness in the range of Ra = 5 nm are reached and the diamond wear is reduced by a factor 100 or higher.

In this publication the most recent investigations in ultrasonic assisted diamond machining of hardened steel at the Fraunhofer IPT will be presented. The results of the worldwide first aspherical steel molds (1.2083, 53 HRC) directly cut with diamond tools will be introduced.

7590-11, Session 2

Rapid mould making for replication of microstructured polymer parts

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Cost effective rapid mould making is a very important requirement for many micro engineering applications, especially when small series of micro structured functional polymer parts have to be fabricated. In this research, a new process chain that integrates model based design, Stereo Lithography Apparatus (SLA) rapid prototyping, electroforming of a nickel mould insert and replication by micro injection moulding has been investigated. In particular, shark skin like features, with a width of 50 µm and high aspect ratio on top of a 3D meso-scale freeform surface were manufactured. The special focus of this research was on the optimisation of the micro SLA process by investigating different combinations of materials, orientation and lens systems. The produced positive masters by micro-SLA were inspected employing a SEM system and the best parts were chosen to undergo metallisation, and then transferred by means of electroforming into a nickel mould suitable for micro injection moulding. The replication results show a good reproducibility within the limitations of the micro SLA processes. The completed experimental study demonstrates clearly the feasibility of the proposed process chain for a cost effective fabrication of small and medium batches of polymer parts.

7590-12, Session 2

Alternative technology for fabrication of nano- or microstructured mould inserts used for optical components

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For mass production of multiscale optical components, micro- and nanostructured moulding tools are needed. Metal tools are used for hot embossing or injection moulding of micro components in plastics. Tools are typically produced by classical forming processes such as mechanical manufacturing e.g. turning or milling, laser manufacturing or electrical discharge machining (EDM).

Microstructures with extremely tight specifications, e.g. in low side wall roughness and high aspect ratios are generally made by lithographic procedures such as LIGA or DPW technology. However, these processes are unsuitable for low-cost mass production. They are limited by the exposure area and structure design.

In cooperation with international partners alternative manufacturing methods of moulding tools have been developed.

In a new replication procedure, mould inserts are fabricated using micro- and nano-scale optics. The multiscale structured prototypes, either in plastics, glass, metal or material combinations, are used as sacrificial parts. Using joining, electroforming and EDM technology, a negative copy of a prototype is transferred into metal to be used as a moulding tool.

The benefits of this replication technique are rapid and economical production of moulding tools with extremely precise micro- and nanostructures, large structured area and long service life. Low-cost mass replication is possible with these moulding tools.

In this submission, an established manufacturing chain will be presented. Demonstrating multiscale and multimaterial optical prototypes e.g. out-of-plane coupler or microinterferometer, made by DPW or laser technology; the mould insert fabrication of each individual manufacturing step will be shown. The process reliability and suitability for mass production was tested by hot embossing.

7590-13, Session 2

Development of a micro-incandescent light source on silicon substrate

A. H. Gollub, D. O. Carvalho, G. P. Rehder, M. I. Alayo, Univ. de São Paulo (Brazil)

In the last years, a great interest in full incorporation of light sources, optical processing devices and detectors in a common silicon substrate has been observed (Huang et al., 2006). The motivation for developing optical devices using the well established silicon technology is fundamentally due to the fact that this technology could lead to better reproducibility and high degree of precision in the fabrication of optical systems. Furthermore, the use of silicon technology offers the possibility of integrating electronic circuits and optical devices in the same chip. However, researches to fabricate integrated light sources are still incipient, mostly because silicon is not an efficient light emitting

material due to its indirect bandgap (Reed 2004). An alternative to solve this problem is the utilization of thermal emission microlamps based on incandescence phenomenon.

In this work we present the simulation, fabrication and characterization of a microscale incandescent light source. The main purpose is to demonstrate the viability of a straightforward microlamp fabrication process on a single crystal silicon substrate. Silicon microtips were used for mechanical support and to improve light coupling from lamp to waveguide. This vertical tips are obtained by controlled anisotropic etch of silicon substrate in KOH solution. Afterwards, the metallic filament is deposited and etched by conventional photolithographic techniques. Finally, a PECVD silicon oxynitride is deposited over the filament to protect it from oxygen, moisture and particles present in the atmosphere. Such protection provides the same functionality of the sealed-cavity devices proposed in previous works (Alayo et al., 2008), but it is simpler and less sensitive to pressure changes. The characterization demonstrated that this microlamp presents appropriate light emission which could be used as light source in optical devices.

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7590-14, Session 3

Optimizing galvanic pulse plating parameters to improve indium bump to bump bonding

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The plating characteristics of a commercially available indium bath are examined and optimized to help meet the increasing performance demands of integrated circuits (IC) that require a substantial number of bond locations over large areas. Current fabrication techniques rely on evaporation of soft metals, such as indium, into lift-off resist profiles that becomes difficult at higher aspect ratios with smaller pitches. Pulse electrodeposition of indium offers a means for producing high aspect ratios with relatively small pitches that can be used in large area device hybridization. Electrochemistry experimentation coupled with state-of-the-art photolithography techniques allow for large areas of bumps to be formed for low temperature indium to indium bonds. The paper will describe electroplating properties of indium that can be altered to control the shape of each bump, making them concave, convex or flat. The galvanic profile also determines the grain size of the indium deposited as well as the macro uniformity of the array, both of which will be detailed in the paper. The plated indium bumps are bonded together using infrared alignment and diffusion bonding and the plating pulse is manipulated to produce optimal bonding properties. The physical properties of the indium bump arrays were examined using a white light interferometer, an SEM, as well as pull test information post-bonding. This paper provides details from the electroplating processes as well as conclusions that led to optimized plating conditions. Sandia is a multi program laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

7590-15, Session 3

Advances in photonic MOEMS-MEMS device thinning and polishing

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As devices continue to increase in density and complexity, ever more stringent specifications are placed on the wafer scale equipment manufacturers to produce higher quality and higher output. This results in greater investment and more resource being diverted into producing tools and processes which can meet the latest demanding criteria. Substrate materials employed in the fabrication process range from Silicon through InP and include GaAs, InSb and other optical networking or waveguide materials. With this diversity of substrate materials presented, controlling the geometries and surfaces grows progressively more challenging. This article highlights the key parameters which require close monitoring and control in order to produce highly precise wafers as part of the fabrication process. Several as cut and commercially available standard polished wafer materials were used in empirical trials to test tooling options in generating high levels of geometric control over the dimensions while producing high quality surface finishes. Specific attention was given to the measurement and control of: flatness; parallelism/TTV; surface roughness and final target thickness as common specifications required by the industry. By combining the process variables of: plate speed, download pressure, slurry flow rate and concentration, pad type and wafer travel path across the polish pad, the effect of altering these variables was recorded and analysed to realize the optimum process conditions for the materials under test. The results being then used to design improved methods and tooling for the thinning and polishing of photonic materials applied to MOEMS-MEMS device fabrication.

7590-16, Session 3

Anti-stiction and wear-resistant coatings based on self-assembled monolayers of phosphonates (SAMP) for MEMS and MOEMS

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Self-Assembled Monolayer of Phosphonates (SAMP) technology enables the commercialization of treatments for anti-stiction and wear-resistant coatings. These coatings can be classified into three functional areas; non-stick, pro-stick/adhesion, and anti-corrosion.

These specialized coatings outperform all known alternatives in characteristics such as adhesion, stability, and scratch resistance.

For surface treatments to be effective, they must be mechanically and chemically stable under conditions experienced in the intended area of use. Self-Assembled Monolayer of Phosphonates can impart any of these properties as desired to metals, metal oxides and even some polymer surfaces by drawing on a library of structurally tailored phosphonic acids.

Enabling the commercialization is covalent bonding, which creates a uniquely strong attachment between the SAMP and the substrate. Because the SAMP is one approximately 1.5 nm thick, it completely covers the material to which it is applied, and assures total surface coverage regardless of the type or texture of that material. The composition of the SAMP determines the properties that it imparts to its substrate.

Durable SAMP non-stick coatings having water contact angles between 115-120 were prepared on silicon, aluminum silicon nitride, and gold. The coatings withstood 10,000 linear abrasion cycles with an applied force of 200g/cm^2. Anti-stiction results demonstrated SAMP technology as a viable alternative for MEMs and MOEMs.

Commercialization of SAMPs proves that such surface-bound phosphonates can dictate control of the surface properties of myriad substrates and that they can be implemented using well-known industrial techniques and conditions. These processes can be scaled to meet the needs of large or small facilities, and can be applied to surfaces of nearly any size or shape without special needs. Based on the needs of the producer, surface modification can be completed during the time of manufacturing or can be performed as a post-production step.

7590-17, Session 3

Kinetic investigations on TiO2 nanoparticles as photo initiators for UV-polymerization in acrylic matrix

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TiO2 nanoparticles of anatase, useful as photosensitive initiators to induce free radical polymerisation in acrylic monomer systems have been prepared by chemical synthesis. Appropriate surface modification of the TiO2 nanoparticles has been achieved to compatibilise the particles with the acrylic monomers to obtain an almost homogeneous distribution down to the primary particle size. The surface modification has been additionally fine tuned in such a way, that an efficient transfer of the electrons generated on TiO2 during UV exposure towards the monomer mixture could be achieved in order to start the polymerisation reaction. In this direction, particles have been synthesized in-situ and ex-situ with the acrylic matrix using different precursors and surface modifiers. Ex-situ produced particles had to be dispersed finally into the acrylate monomer mixture. Residual solvent has been removed by distillation. The formation of anatase modification could be shown by XRD (X-ray diffraction). Particle size was determined by PCS (photon correlation spectroscopy), which showed a distribution between 1-10 nm depending on the used preparation method. Transmission electron microscopy investigations on ultramicrotomed specimen prepared from the UV-polymerised coating layers proved the homogeneous distribution of the anatase nanoparticles. Kinetic investigations on the photo-polymerisation behaviour have been accomplished by photo-DSC (photo differential scanning calorimetry) and IR (infrared spectrometry). Curing time was determined in dependence on the coating thickness and the material composition. It could be shown that by appropriate surface modification the propagation of the UV induced photo-polymerisation is in a similar rangecompared to commercially available organic photo initiators.

7590-18, Session 3

Investigation on particle generation by micro-electro discharge machining

M. ., S. Mitra, N. J. Vasa, S. Makaram, Indian Institute of Technology Madras (India)

There is an increasing interest in generation of nano-particles. Nanometer sized particles suspended in liquids show a significant increase in thermal conductivity as compared to base fluid. In the present work the scope of using micro-electro discharge machining (micro-EDM) technique to generate metal-nanoparticles is studied. Further, thermal conductivity of the fluid with particles generated using micro-EDM is characterized. When a very low energy discharge is applied between a tool and workpiece material, the spark melts and evaporates the workpiece material; the metal vapor changes its current phase by nucleation and solidification and the nucleated particles coagulate to form bigger particles. The dielectric medium acts as a coolant in the whole process. In the experiment, aluminum workpiece is machined with an aluminum tool electrode in deionized water. 40 to 96 V is applied for machining with pulse-on duration being varied between 10 and 100 microseconds. The particle count analysis reveals that low voltage and high pulse-on duration favors formation of smaller sized particles, as predicted by the developed model. A thermal conductivity measurement setup based on steady state approach is built and the experiments reveal that the sample (0.004% by wt. in deionized water) produced by micro-EDM setup shows a maximum of 4% rise in thermal conductivity.

7590-19, Session 3

Estimation of tool wear compensation during micro-electro-discharge machining of silicon using process simulation

M. ., N. J. Vasa, S. Makaram, Indian Institute of Technology Madras (India)

Micro-Electro-Discharge Machining (micro-EDM) is an alternative micromachining technology for the fabrication of three dimensional (3D) micro-features on conducting and semi-conducting materials. Micro-EDM of silicon wafers is gaining importance because of some of its advantages compared to other micro fabrication processes. The process time and the equipment cost is comparatively less, and some of the curved 3D structures can be easily machined on silicon wafers using micro-EDM. Tool and workpiece which are immersed in a dielectric medium are used as two electrodes in an electrical circuit and high frequency square voltage pulses with a specified duty cycle are applied to the electrodes. When the gap between the tool and workpiece is sufficiently small, dielectric breakdown occurs resulting in high temperature sparks. Tool and workpiece materials are removed during Micro EDM process which demand for a tool wear compensation technique to reach the specified depth of machining on silicon. A prototype micro-electro-discharge machine (micro-EDM) is developed incorporating a piezoactuated direct drive tool feed mechanism for micromachining of Silicon using a copper tool. An in-situ axial tool wear and machining depth measurement system is developed to investigate axial wear ratio variations with machining depth. Stepwise micromachining experiments on silicon wafer were performed to investigate the axial wear ratio variations during silicon micromachining. Based on experimental axial wear ratio, a micro-EDM process simulation model has been developed to estimate the required tool wear compensation. Micromachining experiments are performed with the proposed tool wear compensation method and a maximum machining depth variation of 6% is observed.

7590-20, Poster Session

Alternative method for steam generation for thermal oxidation of silicon

J. Spiegelman, RASIRC (United States)

Thermal oxidation of silicon is an important process step in MEMS device fabrication. Thicker oxide layers are often used as structural components and can take days or weeks to grow, causing high gas costs, maintenance issues, and a process bottleneck.

Pyrolytic steam (generated from hydrogen and oxygen combustion) was the default process, but has serious drawbacks: cost, safety, particles, permitting, reduced growth rate, rapid hydrogen consumption, component breakdown and limited steam flow rates.

RASIRC will present results collected by a MEMS manufacturer over 14 months to support replacement of pyrolytic torches with new RASIRC Steamer technology in order to reduce process cycle time and enable expansion previously limited by local hydrogen permitting. Data was gathered to determine whether steamers can meet or exceed pyrolytic torch performance.

The RASIRC Steamer uses de-ionized water as its steam source, eliminating dependence on hydrogen and oxygen. A non-porous hydrophilic membrane selectively allows water vapor to pass. All other molecules are greatly restricted, so contaminants in water such as dissolved gases, ions, TOCs, particles, and metals can be removed in the steam phase.

The MEMS manufacturer improved growth rate by 7% over the growth range from 1µm to 3.5µm. Total cycle time at 3.5µm decreased from 27.9 hours to 26 hours or 7.3%, including ramp up and ramp down. Wafer uniformity was tracked without significant difference found over four months.

The elimination of hydrogen generated a four-month ROI. MTBF was

increased from 3 weeks to 32 weeks based on 3 steamers operating over eight months.

7590-21, Poster Session

Manufacturability of zinc oxide gas sensor with nanoparticles suspension deposited by ink jet printing

P. Menini, V. Conedera, P. Yoboue, F. Mesnilgrente, N. Fabre, CNRS-LAAS (France) and Univ. of Toulouse (France)

Zinc oxide is used in many applications thanks to its various characteristics as well as photoresistivity, piezoelectricity, wide band gap for optical and power components but also its capability for gas detection. In this last field, some experiments were made with ZnO obtained either by standard PVD methods (thin and compact layers) or by electrochemistry or by sol-gel technique deposited by ink jet printing. In this article, we first present new process obtained with ZnO nanoparticles from Sigma Aldrich manufacturer; a stable ink was obtained by mixing 10% weight of commercial powder with ethylene glycol to be deposited by ink jet printing on a silicon oxide substrate covered by platinum interdigitated electrodes. To obtain homogeneous deposits of nanoparticles, the working area of the sensor was bounded by a surface functionnalisation with n-Octadecyltrichlorosilane. These deposits were optimized at low temperature (65°C) and only need a low annealing temperature (400°C).

Then, the study was focused on the correlation between parameters of deposit and gas sensitivity: conductivity for different operating temperatures under methane and isopropyl alcohol vapours. The best results have been obtained for thicknesses in the range of 0.75 and 2.75 µm. The ZnO resistance is stable under air from 225°C and the relative sensitivity to methane and isopropyl alcohol are maximum and opposite at 250°C (76% and 25% respectively). The use of ink jet printing technique offers some advantages as low operating temperature, homogeneous and stable nanoparticle suspensions. It is promising result to manufacture new generation of low cost gas sensors.

7590-22, Poster Session

Electrodes micropatterning by microcontact printing method to large area substrates using nickel mold

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Microcontact printing (CP) was successfully used to micropattern electrode on large area substrates. An A4-size (210 mm - 297 mm) polydimethylsiloxane (PDMS) elastomer stamp was easily fabricated using an electroformed nickel mold. The micropatterns of poly(3,4-ethylenedioxythiophene)/poly(4-stylenesulfonate) (PEDOT/PSS) and silver (Ag) thin films with widths under 10 m were fabricated by transferring the thin films on the PDMS elastomer stamp to another substrate by CP. Bottom contact (BC) organic thin film transistors (OTFTs) with PEDOT/PSS were fabricated as source and drain electrodes. The successful operation of fabricated OTFTs with a channel length of 10 m was demonstrated. Results show that CP is a promising process for use with various devices that require micropatterning on large area substrates.

7590-23, Poster Session

Laser microstructuring of sapphire wafer and fiber

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Currently, sapphire is widely used in the field of optoelectronic devices and micro-mechanical components, such as substrate of GaN based LED, watch bearing and so on. One of the problems in using sapphire is the difficulty in cutting and micro-structuring due to the differences in the crystal orientation and the hardness of sapphire itself. Since sapphire is inert to most wet chemical and dry etching, laser ablation is considered as an alternative method.

In this paper, a 157nm DUV laser micro-ablation system is conducted in micro-structuring of sapphire wafer and fiber. Laser micromachining characteristics of sapphire are investigated by varying the laser process parameters. Because of the large photon energy of 7.9-eV, 157nm laser can destroy the chemical bonding of sapphire crystal. Photo-chemical reaction plays an important role during the 157nm laser process. Under laser fluence of 3 J/cm2, the maximum ablation rate could reach to 400nm/s. For 3D micromachining, laser scanning process is usually used. For demonstration of 157nm laser micromachining technique, several three-dimensional micro-structures are produced in sapphire wafers and sapphire fibers, respectively. As a whole, 157nm laser ablation is a good approach for 3D structuring of sapphire.

7590-24, Poster Session

Colossal room-temperature magnetoresistance in thin La1-xAgyMnO3 epitaxial films

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The first thin La1 - xAgyMnO3 epitaxial films (y . x) were grown on SrTiO3 (110) substrates with silver present in the ionized state (Ag+) only. The Curie temperatures TC of the compositions with x = y = 0.05, x = y = 0.1, and x = 0.3 and y = 0.27 crystallizing in the hexagonal structure R3c lie above or close to room temperature. The temperature dependences of electrical resistivity . and of magnetoresistance pass through maxima near TC, with the magnetoresistance being negative and reaching colossal values of ~7-20% in a magnetic field H = 8.2 kOe not only at TC but also at room temperature. The magnetic moment per formula unit as derived from the saturation magnetization at T = 5 K is substantially smaller than expected for complete ferromagnetic ordering. The magnetization in fields of up to 6 kOe depends on the actual sample cooling conditions, and the hysteresis loop of a field-cooled sample is displaced along the H axis by ΔH.

The above properties can be accounted for by the fact that the films are in a two-phase magnetic (ferromagnetic-antiferromagnetic) state induced by strong s-d exchange. The maximum value of ΔH was used to calculate the energy of exchange coupling between the ferromagnetic and antiferromagnetic parts of a sample.

7590-25, Poster Session

Selective laser sintering of magnesium powder for fabrication of compact structures

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In past decades, considerable research effort has been reported in the area of direct metal laser sintering (DMLS). However, rarely work has previously been found on the laser sintering of magnesium powder. Magnesium possesses of low density, good mechanical properties and high degree of biocompatibility, making it become a potential candidate for the fabrication of structural parts in transportation industries and biological implants in medical industries. The novelty of the present research lies in the fabrication of compact structures by laser sintering of magnesium powder using a Nd:YAG laser. The laser sintering of single tracks and single layers of magnesium powder were carried out for demonstrating the process feasibility and for examining the influences of several processing parameters in terms of laser power, scan speed and repetition rates on microstructural characteristics and mechanical properties of the final sintered structures. The experimental results demonstrated that compact structures of magnesium have

been successfully fabricated by selective laser sintering technique. The results also give valuable information about geometrical features and microstructural evolution of magnesium powder under a Nd:YAG laser irradiation, which would facilitate the fabrication and controllability of compact structures by deliberating the associated effect of different processing parameters, whilst achieving superior quality for the laser sintered parts using this rapid one step laser sintering technique.

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7591-01, Session 1

Two-color photo-initiation/inhibition lithography

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Two-photon photoinitiation or multi-photon absorption by glass at the focus of a Ti:Sapphire laser can produce structures smaller than the linear diffraction limit at the expense of low throughput. Additionally, these methods provide no direct control of the axial exposure profile when used for 3D nanofabrication. We demonstrate a new form of single-photon nanolithography which creates structures well below the linear diffraction limit while providing direct control over the 3D shape of the exposed region.

The process is based on two single-photon absorbers which act in opposition. Initiating species are generated by single-photon absorption at one wavelength while inhibiting species are generated by single-photon absorption at a second color. The absorption spectra of the photo-initiator and photo-inhibitor are designed to provide independent control over the two processes. To lowest order, the polymerization rate is locally proportional to the difference of the two intensity patterns.

Sub-diffraction structures are thus created by shaping the inhibition beam into a Gauss-Laguerre donut mode (for transverse confinement) or a bottle beam (for primarily axial confinement), limiting polymerization at the periphery of the initiating intensity pattern. Increased intensity of the inhibitory pattern reduces the polymerized volume without changing the polymerization rate on axis, allowing independent control over peak conversion and feature size.

We demonstrate fabrication of 65 nm structures with 473 nm (initiation) and 364 nm (inhibition) focused at 1.4 NA, violating the diffraction limit by a factor of 3. Preliminary 3D fabrication is demonstrated by moving the material to write similarly-sized polymer structures.

7591-02, Session 1

Toward diffraction-unlimited 3D laser lithography

J. Fischer, G. von Freymann, M. Wegener, Univ. Karlsruhe (Germany)

In contrast to electron-beam lithography, direct laser writing (DLW) based on two-photon absorption allows for the fabrication of nearly arbitrary three-dimensional polymer structures in a single processing step. While the resolution of DLW is fundamentally limited by diffraction, lateral feature sizes down to 100 nm (/8) are achievable without compromising structure quality if a photoresist with a strong chemical nonlinearity is used.

The resolution of stimulated emission depletion (STED) microscopy [1] is essentially diffraction-unlimited. Inspired by this breakthrough in microscopy, Refs. [2] and [3] have recently demonstrated feature-size reductions with lithography setups using two lasers. Therein the radical species are deactivated before polymerization occurs - a mechanism distinct from stimulated emission.

Here, we present a different, potentially advantageous approach for diffraction-unlimited laser lithography. In close analogy to STED [4], we use a continuous-wave laser for depletion, operating at the long-wavelength end of the photo-initiator's fluorescence spectrum, whereas a femtosecond laser is used for excitation *via* two-photon absorption. When switching on the depletion laser, we observe reduced fluorescence and simultaneous partial or even complete suppression of the local polymerization. Using a vortex phase plate to generate a doughnut-shaped depletion focus, we have achieved reproducible line-width reduction down to 70 nm. This effect works for two-dimensional line patterns, and - more importantly - also for lines inside three-dimensional structures.

We suspect stimulated emission to be the responsible depletion mechanism. Thus deactivation would occur even before reactive radicals are generated, allowing for stronger confinement and ultimately for a spatial resolution significantly higher than current state-of-the-art DLW.

[1] T. A. Klar, S. Jakobs, M. Dyba, A. Egner, and S. W. Hell, PNAS 97, 8206-8210 (2000)

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[3] T. F. Scott, B. A. Kowalski, A. C. Sullivan, C. N. Bowman, and R. R. McLeod, Science 324, 913-917 (2009)

[4] K. I. Willig, B. Harke, R. Medda, and S. W. Hell, Nature Methods 4, 915-918 (2007)

7591-03, Session 1

Pushing the limits of optical lithography with resolution augmentation through photo-induced deactivation

J. T. Fourkas, L. Li, R. R. Gattass, Univ. of Maryland, College Park (United States)

We have recently introduced a technique called Resolution Augmentation through Photo-Induced Deactivation (RAPID) lithography. RAPID uses multiphoton absorption to initiate polymerization and a second, phase-masked laser beam to inhibit polymerization. By this method we have demonstrated the creation of lithographic features of 40 nm dimension using 800 nm light. In this presentation we will discuss recent advances in RAPID lithography, including improvements in optics, materials, and implementation.

7591-04, Session 1

Direct laser writing of 3D nanostructures

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Direct laser writing by two photon polymerization (2PP) is a nonlinear optical technique which allows the fabrication of three-dimensional structures with resolution beyond the diffraction limit. When the beam of an ultra-fast infrared laser is tightly focused into the volume of a photosensitive material, the polymerization process can be initiated by non-linear absorption within the focal volume. By moving the laser focus through the material, three-dimensional structures can be fabricated.

Here, investigations into the structuring by two photon polymerization of a series of hybrid organic-inorganic materials are presented. These are:

(i) Zirconium, titanium and germanium sol-gel composites that can be structured accurately without suffering from distortion due to shrinkage during photopolymerization. These materials can be used for the fabrication of three-dimensional photonic nanostructures.

(ii) Silicon oxide-based sol-gels where a nonlinear optical molecule has been incorporated into the photopolymer, enabling the dynamic tuning of the optical properties of the fabricated structures. The sol-gels investigated are materials with second and third-order optical nonlinearity.

(iii) Composite sol-gels with metal binding affinity. These materials can be also structured accurately and, due to metal binding groups, can be

readily metalized with silver and other metals by simple immersion in a metal bath. They can be used for the fabrication of metamaterials, but also for the immobilization of biomolecules.

7591-05, Session 2

Fabrication of top down silicon nanowire photodetector arrays using nanoimprint lithography

H. Kim, A. Zhang, Y. Lo, Univ. of California, San Diego (United States)

Nanoimprint lithography (NIL) is becoming an increasingly attractive method for pattering nano-scale dimensions. NIL allows for the ability to quickly and cheaply pattern a large sized substrate. Although current applications of this technology are limited to patterned magnetic media and optical components, many fabrication areas could benefit from this technology. In this work, application of NIL has been extended to silicon nanowire detector arrays. These detectors are attractive for high sensitivity light detection, while also having very high pixel density, and ability to integrate with CMOS technology. Due to its small dimensions, silicon nanowire arrays have high photo current gain as well as low dark current. Additionally, the geometry of these vertical devices guide incident light into the structures, leading to enhanced absorption efficiency. NIL using UV curing is used to make nano sized dot patterns on a silicon substrate. A silicon substrate is first coated with a double layer photoresist which increases the etch selectivity of the pattern. A quartz plate mold is then used to imprint a nano-scale dot pattern from the mold onto the substrate, and the residue and the under-layer photoresist of the imprinted pattern etched to expose the substrate in the patterned areas. Metal is then deposited, transferring the pattern to a metal etch mask, and the nanowires formed using a deep reactive ion and inductively coupled plasma etch. Fabricated devices show high current gain, linearity by the number of nanowires, and reproducibility of the process. This technology will enable the future of fabricating high density, addressable imager arrays.

7591-06, Session 2

Critical nanofabrication parameters for the e-beam assisted design of a subwavelength aluminum mesh

C. Mazuir, W. V. Schoenfeld, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States)

We report the improvement of a fabrication process for a relatively thick subwavelength aluminum mesh on top of sapphire. Previously we reported an e-beam lithography assisted technique using a single layer of polymethylmethacrylate (PMMA) and involving a metal lift-off. The 100 nm thick mesh consisted of two perpendicularly oriented sets of 100 nm wide parallel metal lines with a center to center distance as low as 260 nm. Rough metallic sidewalls were observed. Here we report a back-etching technique: after e-beam patterning of a monolayer of ZEP 520 on top of an aluminum film we used a chlorine plasma to etch the aluminum mesh. The ZEP 520 photoresist was chosen due to its higher resistance to chlorine based dry etch. A 500 nm thick photoresist layer was patterned with a good control over the features sizes and the edge sharpness. The proximity effect was calibrated and was found higher than with PMMA due to the higher sensitivity of ZEP 520 to electrons. The benefits of the ZEP process on the sidewall roughness will be presented along with spectral transmission comparing the optical properties of the metallic meshes formed by the two e-beam lithography methods. Finally, the e-beam evaporation of aluminum on a cold temperature controlled substrate was performed and will be compared to typical thermal evaporation, highlighting its improvement to the metal surface smoothness and average grain size. Despite the benefits to mesh smoothness, the low temperature metal deposition was not found to dramatically change the spectral transmission properties.

7591-07, Session 2

Low-cost optical microstructures fabricated by imprinting porous silicon

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We report direct-to-device pattern transfer in a non-polymeric porous substrate based on a low-cost and high throughput planar stamping process. Multi-use aluminum and silicon stamps, applied in the 500-1500 psi range, are found to readily deform mesoporous silicon films to produce the desired microstructure. The quality of the pattern transfer depends on film porosity and thickness, stamping material, and applied pressure. Porous silicon diffraction gratings with grating periods down to 5 microns are demonstrated. Based on the quality of the pattern transfer in these structures, further testing is expected to enable the replication of submicron features. Fabricated structures are characterized by scanning electron microscopy (SEM), optical microscopy, and profilometry. Evaluation of the step profile and surface roughness for different stamping conditions will be discussed. The optical quality of the gratings is verified by observing the resulting diffraction pattern when the gratings are illuminated by a HeNe laser. When infiltrated with various analytes, a change in the diffraction efficiency of the porous gratings results, suggesting that these stamped gratings may be utilized as cost-effective sensors for chemical and biological materials. Calculations suggest that porous diffraction gratings can be up to an order of magnitude more sensitive than traditional diffraction-based biosensors. This is due to the higher diffraction efficiency and to the larger surface available for the analyte bonding. A similar stamping procedure is expected to prove successful in patterning other porous materials, including porous alumina, titania, and silica.

7591-08, Session 2

Hollow ARROW waveguides on self-aligned pedestals for high-sensitivity optical sensing

E. J. Lunt, B. S. Phillips, J. M. Keeley, Brigham Young Univ. (United States); P. Measor, B. Wu, H. Schmidt, Univ. of California Santa Cruz (United States); A. R. Hawkins, Brigham Young Univ. (United States)

Antiresonant reflecting optical waveguides (ARROWs) provide a promising approach to realizing high-sensitivity sensing platforms on planar substrates. We have previously developed ARROW platforms that guide light in hollow cores filled with liquid and gas media. These platforms include integrated traditional solid waveguides to direct light into and out of sensing media. To improve the sensitivity of these platforms for optical sensing, hollow waveguide loss must be reduced. We are working towards this by using anisotropic plasma etching to create near-ideal hollow ARROW geometries. These structures rely on an etching mask that also serves as the sacrificial core for the waveguide. This self-aligned process creates a hollow waveguide on a pedestal which is surrounded by a terminal layer of air in three directions. We previously produced ARROWs by pre-etching the silicon substrate and aligning the sacrificial core to the pedestal. However, this necessitates using a pedestal which is wider than the core, leading to higher loss and poor reproducibility. We have also increased the hollow to solid waveguide transmission efficiency by using a design that coats the sides and top of the hollow core with a single layer of silicon dioxide. Using this design, we have demonstrated an interface transmission improvement of more than two times. A much improved optical sensor platform will incorporate both of these features, using the self-aligned pedestal process for most of the length of the hollow waveguides to decrease loss, and employing the single layer design only at the interfaces to improve hollow-solid waveguide coupling.

7591-09, Session 2

Inkjet printing techniques for the fabrication of polymer optical waveguides

N. A. Vacirca, Drexel Univ. (United States)

A great deal of attention in recent years has been given to inkjet printing as an alternative to traditional lithographic techniques due to its potential for low cost and rapid turnaround fabrication. Several obstacles must be overcome for the technology to be feasible on a large scale including the development of capable print devices, suitable materials for printing, and the ability to print high-aspect-ratio geometries.

A Dimatix DMP-2831 materials printer with piezo-electrically actuated inkjet nozzles has been used to print polymer optical waveguides. SU-8, a UV-curable photoresist polymer, was selected as the printing material for its excellent optical clarity, easily compatible refractive index, and multiple readily available formulations which ensure compatibility with the Dimatix inkjet printer. The effects of printing waveguide geometries with varied drop spacing from 5-25μm using both 1pL and 10pL nozzle sizes are examined. Printed structures are then physically characterized in three dimensions with a profilometer, allowing exact measurement of the dimensions, cross-sectional geometry, and smoothness of the waveguides. The optical performance, specifically the optical power loss incurred per unit length of light traversing the wavelength is measured and the results are compared to the losses reported for traditional glass optical fibers and other polymer optical interconnect and waveguide structures.

7591-10, Session 3

Sub-5-nanometer electron-beam lithography for nano-optics

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Nano-optics requires control of metallic and insulating structure at the few-nanometer length scale. Current approaches to this fabrication frequently make use of focused-ion-beam and electron-beam lithographies. While these techniques each have their strengths and weaknesses, neither method is suitable at present for routine sub-10-nanometer device development. In this presentation, we will discuss methods of resist-based electron-beam lithography capable of patterning at the few-nanometer length scale. In particular, we will review a salt-based development process for hydrogen silsesquioxane resist that is able to yield complex structures with sub-10-nanometer feature pitch (sub-5-nm dimensions). We will also show detailed studies of the point-spread function in this system, including studies using transmission-electron-microscopy of few-nanometer-length-scale lithographically-defined structures. We will then review results on nanooptical devices that take advantage of the processing methods presented, and will discuss the relative advantages of electrons and helium-ion beams for resist patterning.

7591-11, Session 3

Fabrication and scanning control of nanoprobe for NSOM applications

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We report on the fabrication and the scanning operation of the Nanoprobe integrated with a fully customized Near-field Scanning Microscope (NSOM) system.

The Nanoprobe is a silicon cantilever with a hollow pyramidal tip, where the shape of the tip was formed through anisotropic wet-etching process. A 1.7 μm silicon dioxide layer was thermally grown to define the shape of the probe. A 100 nm aluminum layer was then e-beam evaporated onto the released probe. Subsequently, a 500 nm diameter aperture was milled with the Focus Ion Beam (FIB).

The nanoprobe was fully integrated with a customized Near-field Scanning Microscope(NSOM), with build-in scanning control of the probe-sample distance using a force sensing tuning fork. A tapered optical fiber, connected to 410 nm wavelength laser source, was aligned with the probe tip to transmit the light and expose the photoresist(AZ5209E). The photoresist was spun on a cover glass, which was attached on the tuning fork. The nanoprobe was controlled for near-field scanning of samples. A series of 15 exposures, varied from 0 to 8 minutes, were carried out on photoresist stepwise at 5 μm separation with subsequent 60 seconds development time.

The lithography patterns were evaluated by an AFM measurement, and compared to the finite difference time domain (FDTD) simulations. The depths and widths of the developed pattern are linearly correlated with increasing exposure time, showing slopes of 760 nm/second and 3.5 nm/second respectively.

7591-12, Session 3

Fabrication techniques of high aspect ratio vertical light pipes using a dielectric photomask

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CMOS image sensors are increasingly being used in commercial imaging applications due to their ease of integration, low cost and reduced power consumption. However, as the pixel size decreases, the imager's sensitivity is reduced and the crosstalk is increased. To alleviate these problems, we form "light pipe" features in the thick SiO2 dielectric layer where the electrical circuits are implemented. The vertical light pipes will serve to guide light directly down to the photodiodes on the Si substrate, significantly improving the light collection efficiency and reducing the scattering and crosstalk losses in the SiO2 layer. In this paper, we report the development of new techniques for fabricating high aspect ratio vertical light pipes in a 10um thick SiO2 layer on a Si substrate. A dielectric photo mask made of amorphous silicon (a-Si) was used for deep reactive ion etching process. A hard contact lithography step transferred the etching pattern on the photo mask. Our experiments show that CF4-based reaction gases were best for deep etching with high selectivity and etch rate. Light pipes with diameters of 1.5um were demonstrated, with an aspect ratio of 6.7:1 and a sidewall angle of 87.4 degrees. We also present the lift-off process of the etch masks by introducing a sacrificial layer of SiN underneath the etch mask. Finally we discuss the via-filling procedures for the light pipes. These vertical pipe structures are not only useful for image sensors, they are also valuable for vertical interconnect and waveguiding applications.

7591-13, Session 3

Fabrication of photonic crystal cavity laser using a combined lithography of laser holography and focused ion beam

S. Ahn, S. Kim, H. Jeon, Seoul National Univ. (Korea, Republic of)

To enable a large scale and high throughput fabrication of photonic crystal (PC) cavity lasers, we combined laser holography and focused ion beam(FIB). FIB-assisted Pt deposition method was used to define local defects in holographically-generated background PC that is perfectly periodic. So-fabricated single-defect cavity on square-lattice PC slab of InGaAsP quantum-well materials shows a clear laser emission around 1.5um. Also the lasing modes are characterized by measuring the polarizations under micro-photoluminescence system. The resultant lasers exhibited threshold and output powers comparable to those of electron-beam generated ones. We expect that this type of combination

lithography can be a highly time-saving and cost-effective fabrication method for the fabrication of defect-containing PC devices, such as PCCLs, PC waveguides, and other essential elements required for photonic integrated circuits

7591-14, Session 4

Silk as a new platform for nanobiophotonics

F. G. Omenetto, Tufts Univ. (United States)

We introduce the use of silk fibroin as an innovative material platform for optics and biophotonics. We demonstrate the fabrication of purified silk into high quality, nanostructured optical elements composed entirely of the organic, biocompatible and implantable protein matrix.

Combined with all water-based, room temperature processing, and the mechanical stability and robustness of silk set this material apart from glasses, polymers or plastics and from other biopolymers. Most notably, however, the ambient processing environment allows for the simple entrainment of biological components into the optical devices while preserving their function which can lead to new opportunities in nanophotonics.

7591-15, Session 4

Micro-patternable hybrid nanocomposites with tailor-able mechanical and thermomechanical properties

C. Becker-Willinger, P. Kalmes, P. Herbeck-Engel, M. Veith, Leibniz - Institute for New Materials (Germany)

A new type of cationically polymerisable organic-inorganic hybrid nanocomposite with micro-pattern ability by photo lithographic techniques has been developed. The matrix material has been built by co-condensation of 3-glycidyloxypropyl-triethoxysilane and phenyl-triethoxysilane and subsequent mixing with oligomeric cycloaliphatic multifunctional epoxy resin as organic co-monomer. Nanocomposite mixtures have been formed by dispersing sol-gel derived silica nanoparticles with 15 nm particle size into the preformed matrix sol. In order to achieve an almost homogeneous distribution of the nanoparticles over the matrix different surface modifiers have been applied on the silica surface. The resulting transparent mixtures have been applied on silicon and glass substrates and have been UV polymerised using a cationic photo initiator. The mechanical and thermo mechanical properties as well as the resolution of photo patterns have been followed in dependence on the nanoparticulate filler content and the type of surface modification. It could be shown that by appropriate synthesis of the matrix the intrinsic stresses in the reactively cured layers could be reduced by about 50 % compared to conventional organic photo resists. Photo patterns could be created with an aspect ratio of $\geq$ 1 and high edge steepness even for highly filled systems. The universal hardness derived from indentation measurements increased from 115 MPa for the unfilled hybrid resin to 256 MPa for the system containing 50 wt.-% silica. The same nanocomposite system showed an elastic modulus of about 7600 MPa after only UV curing which indicates the high potential of these materials for mechanically stable patterns.

7591-16, Session 4

Scalable polymer-roll metamaterials

N. Gibbons, J. J. Baumberg, C. L. Bower, M. Kolle, U. Steiner, Univ. of Cambridge (United Kingdom)

Metallodielectric multilayers are appealing nanostructures due to their potential for sub-wavelength focussing and also their highly non-linear response. Current metallodielectric multilayer fabrication relies on layer-by-layer deposition techniques such as sputtering and is slow and costly. We demonstrate here a novel and scalable approach to fabricate such multilayers which utilises a floating and rolling technique in order to create metamaterials from a single flexible metallodielectric bi-layer. [1] A layer of polystyrene (170nm) is coated with gold (10nm) and the bi-layer is then floated from the substrate onto a water meniscus where it is rolled up around a thin glass rod to create the final nano-structure. The film is rolled around the rod in a helical fashion which allows optical access to different numbers of layers. Both cylindrical and square rods are demonstrated successfully. Being Bragg-arranged by design, our structures demonstrate strong resonances in reflection and transmission and due to their high sensitivity we are able to accurately quantify layer thicknesses. The origin of these Bragg resonances is discussed in detail and their shape is explained with transfer matrix simulations of the field distribution within the nanostructure which clearly show how the field is trapped in particular configurations. These multilayers are easily fabricated from a wide range of materials and with varying layer thicknesses, making them uniquely flexible in terms of applications. As we show, they can transmit up to 50% on resonance, a hundred-fold enhancement over the non-layered films. We show that they act as enhanced non-linear composite materials.

[1] N Gibbons et al., Adv. Mat. (2009)

7591-17, Session 5

Flexible tailoring of femtosecond laser-written Bragg grating waveguides

J. R. Grenier, Univ. of Toronto (Canada); L. A. Fernandes, Univ. of Toronto (Canada) and Univ. de Porto (Portugal); M. Esfahani, J. S. Aitchison, Univ. of Toronto (Canada); P. V. S. Marques, Univ. do Porto (Portugal); P. R. Herman, Univ. of Toronto (Canada)

New laser methods for integrating Bragg gratings inside laser-written waveguides are essential for opening future three-dimensional optical circuits into optical telecom, sensing and biophotonic applications. To this end, we have developed a programmable electronic control that provides flexible and precise control of an acousto-optic modulator to tailor laser burst trains for writing of Bragg grating waveguides (BGW).

Various modulation profiles were applied to the frequency-doubled output of a fiber femtosecond laser (1044 nm, 300 fs), with a repetition rate set to 500 kHz. We thus have extended the burst writing method for fabrication of a much broader range of Bragg Grating Waveguides (BGW) devices in the bulk of fused silica glass. Precise phase shifts introduced into the grating period resulted in narrow transmission band `defects` (< 0.1 nm) which could be tailored into the stop-band for new high resolution and tailored spectrum devices. Electronic frequency chirps provided chirped BGWs with controllable bandwidths from 0.2 to 25 nm. Analogue modulation profiles eliminated the radiation mode loss thereby permitting more efficient cascading of Bragg grating segments with a compromise of a reduced reflection peak. We also introduce edge filters and birefringent BGW devices. The advanced modulation control offers new dimensions to optimizing and generating new types of BGWs which promise to expand the component toolkit for fabricating highly functional three-dimensional integrated optical circuits.

7591-18, Session 5

Fabrication of micro- and nanostructures in thin metallic films by femtosecond laser ablation

V. Mizeikis, Shizuoka Univ. (Japan); S. Juodkazis, H. Misawa, Hokkaido Univ. (Japan)

Films of metals patterned to contain periodic arrays of metallic patches find applications in photonics, biology, and chemistry as spectral filters, frequency-selective surfaces, plasmonic substrates , etc. Their peculiar electromagnetic response is due to size and shape of the constituent features as well as their periodic arrangement. For such structures to

work at infrared and visible wavelengths, their average feature size must be scaled down below 1 micrometer, which requires application of high-resolution structuring techniques, such as lithography, lift-off, or ion-beam milling. Although capable of delivering excellent structural and optical quality, these techniques are less suited for rapid prototyping and high-throughput mass fabrication. Here we demonstrate that laser ablation may offer a route for faster, essentially single-step procedure for micro- and nano-structuring of metals. Ordered triangul ararrays of circular apertures with diameter of 600-800 nm were fabricated by laser ablation of thin gold films (thickness of 30-40 nm) deposited on glass substrates by sputtering. The ablation was achieved by single pulses of a femtosecond Ti:Sapphire laser (pulse duration of 130 fs, wavelength of 800 nm, pulse energy of 15 nJ), tightly focused by a microscope lens with numerical aperture of 0.9. Optical properties of the fabricated samples as well as their possible applications will be discussed.

7591-19, Session 5

Femtosecond laser photopolymerization of photonic and free-movable microstructures in sol-gel hybrid resist

Q. Sun, S. Juodkazis, N. Murazawa, Hokkaido Univ. (Japan); V. Mizeikis, Shizuoka Univ. (Japan); H. Misawa, Hokkaido Univ. (Japan)

We present the fabrication of microstructures for photonic and micro-/opto-fluidic applications using femtosecond laser 3D direct writing technique in zirconium-based sol-gel hybrid resist. The laser source is an amplified Ti: Sapphire femtosecond laser (Hurricane, Spectra Physics), which delivers 1 kHz, 150 fs pulses centered at 800nm. The laser beam is guided into an optical microscope (Olympus IX71) and tightly focused by an oil-immersion objective lens. 3D writing is accomplished by mounting the samples on a piezoelectric transducer-controlled 3D translation stage. The hybrid resist is a 20/80 zirconium-silicon/methacrylate sol-gel, containing 4,4'-bis (diethylaminobenzophenone) as a photoinitiator.

The advantages and mechanism of photo-polymerization of this new material under fs-pulsed laser exposure are discussed. The use of SZ2080 resist exhibits many advantages, such as straightforward cast-preparation, simple post-exposure procedure, low losses at visible and telecommunication wavelengths, and good optical properties. Almost linear dependence of the lateral cross-section of a polymerized lines on incident laser power indicates importance of the avalanche process in photopolymerization. The laser power dependent transmission measurements support this conjecture. We discuss the mechanism of photopolymerization at high pre-breakdown irradiances.

We also present a novel method to fabricate free-standing and movable photonic microstructures potentially useful in micro-fluidic applications. That is, we fabricated microstructures inside designated enclosure cages which were also produced through photo-polymerization. Fabrication of free movable structures allowed to quantitatively study the shrinkage of photoresist and to improve the structured resolution.

7591-20, Session 5

Waveguides written with femtosecond double pulses in the volume of glass materials

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By using ultra short focused femtosecond laser pulses refractive index modifications in the volume of transparent dielectrics can be produced. The laser radiation interacts with the material only in the focal volume. By translating the sample in relation to the laser beam the production of waveguides and other optical components in three dimensions is possible. Thus, the use of ultrashort laser pulses allows a precise and specific fabrication of devices for applications in optical systems.

Laser radiation from an Yb-fiber laser (tau=500fs, lambda=1045nm, f=0.1...5MHz) is used to create refractive index changes in the volume of fused silica and the borosilicate glass D263. Femtosecond double pulses are produced using a Michelson interferometer to create pulses with a maximum time difference of Delta t=10ns with an accuracy of 33fs. The sample is irradiated with femtosecond double pulses focused by a microscope objective.

The written waveguides are investigated using quantitative phase microscopy and interference microscopy to determine a two dimensional refractive index distribution of waveguide cross sections. Furthermore, the numerical aperture of the waveguides is determined by far field measurements in which the intensity distribution of guided and non-guided light through the waveguide is observed on a screen in the far field.

At a specific time delay of the two pulses an increase of the numerical aperture compared to single pulses is observed. This maximum is considered to be due to changes in the electronic structure because of the formation of color centers and self trapped excitons.

7591-21, Session 5

Laser direct writing of submicron lines using micro- and nanofiber pens

T. Feng, G. Yang, J. Bai, X. Jianfeng, Z. Qiaofen, Zhejiang Univ. (China)

Direct writing techniques allow maskless definition of surface micro- and nanostructures. The laser direct writing is a mature and reliable technique, but it is very difficult to reach subwavelength-resolution. The electron beam direct writing can fabricate high-resolution structures, but its processes tend to be costly and inconvenient. Direct writing using micro- and nanofiber pens can provide a feasible way to achieve subwavelength-resolution without requiring complicated and expensive equipment.

Optical submicron-diameter fibers have attracted much attention on account of their favorable properties, such as tight optical confinement, low optical loss, high fraction of evanescent fields, strong field enhancement. All these excellent properties make the submicron-diameter fiber suitable for maskless lithography. First, tight optical confinement can provide high exposure resolution. Second, low optical loss and strong field enhancement ensure exposure power. Third, high fraction of evanescent fields can be easily coupled into photoresist layer. Based on these, this letter presents a novel direct writing technique utilizing the submicron-diameter fibers. These fiber probes are used like an inked pen, transferring a laser "ink" from the probe tip to a photoresist layer through direct contact.

The experiments of direct writing using micro- and nanofiber pens have been completed. The submicron lines with different width can be obtained by altering writing speed. The thinnest line is 300 nm in width, which is smaller than the exposure wavelength (442 nm). In addition, using this technique, the chinese name of author has been written.

7591-22, Session 6

Challenges and opportunities of manufacturing next generation of integrated photonics

R. Singh, N. Gupta, K. F. Poole, Clemson Univ. (United States)

Integrated photonics has the potential of fabricating diverse set of photonic systems (e.g. computing, sensing, detection, image processing, and energy conversion etc.) on a single substrate. Unlike silicon, fabrication of compound semiconductor (two or more elements) based integrated photonics poses a number of intellectual challenges for inventing processes that can lead to low-cost manufacturing. The key factors that control low-cost of manufacturing are following: low cost of ownership of manufacturing tools, low production cost, prospects for further cost reduction and green manufacturing. At nanoscales (< 100

nm) the properties of material depend on the quantum-confinements. The challenge is to integrate these unique properties of nanostructures into low-cost manufacturing and enhance the performance, reliability and yield of related devices and systems. The “top down” (current lithography techniques used to reduce material dimension < 100 nm) approach is currently used for manufacturing silicon nanoelectronics and has potential to manufacture 15 nm feature size products. Based on fundamental considerations and process induced defects of directed self assembly (DSL), it is highly unlikely that “bottom up” (atom by atom approach to build the required < 100 nm dimension) will ever enter mainstream manufacturing. For material deposition, photo-assisted monolayer deposition technique can provide nanomaterials with ultra low defects density. Epitaxial dielectrics offer the possibility of growing defect free compound semiconductors on silicon substrates. In this paper we will provide manufacturing directions that must be incorporated in basic research for developing next generation of integrated photonics.

7591-23, Session 6

Multiwavelength rolled-up InGaAs/GaAs quantum dot microtube lasers

F. Li, Z. Mi, McGill Univ. (Canada)

Rolled-up semiconductor tubes, formed when a coherently strained thin film is selectively released from its host substrate, have emerged as a promising technique for realizing a new generation of nanophotonic devices. Although optical resonance modes have been observed from rolled-up microtubes, the achievement of a rolled up microtube laser has remained elusive. In this context, we have performed a detailed investigation of the design and fabrication of InGaAs/GaAs quantum dot microtubes and demonstrated, for the first time, multi-wavelength ultra-low threshold lasing in rolled-up microtubes. In this experiment, InGaAs/GaAs quantum dot heterostructures were grown on a 50 nm AlAs layer on GaAs substrates by molecular beam epitaxy. Rolled-up microtubes, with a diameter of ~ 5 μm and wall thicknesses of 50 - 200 nm, were fabricated using standard photolithography and wet etching techniques. The emission characteristics are investigated using micro-photoluminescence spectroscopy at room temperature. Rolled-up InGaAs quantum dot lasers can generate upto 20 wavelengths in the range of 1.1 - 1.3 μm, with an ultralow threshold of ~ 10 μW and an intrinsic linewidth of ~ 0.3 nm. We have further demonstrated that the wavelength spacing can be readily tuned from ~ 2 nm to 10 nm by varying the tube surface geometry using a single photolithograph step. The emission characteristics of rolled-up quantum dot lasers with various tube diameters, wall thicknesses, and surface geometry, as well as the achievement of electrically injected microtube lasers will be presented.

7591-24, Session 6

Controlling thermal emissions: large and sub-millimeter surfaces and their atypical thermal emissions

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We describe the fabrication and test results of passive large devices (15 millimeters on the side) and sub-millimeter paint chips (100 to 500 microns on the side) for thermal emission control at longwave infrared (8 to 12 microns). The large parts are ideal for planar devices and can be added to their fabrication process as an extra set of fabrication steps. The paint chips are intended for application to non-planar surfaces using a thermally neutral paint that carry the chips. All the devices consist of a central gold structural layer covered with silicon nitride/gold posts or lines, 0.5 microns tall. The posts or lines are sub-wavelength (0.9 micron or 0.3 micron features respectively) on a 3 micron pitch patterns on one side for the large device and both sides for the paint chips. The paint chips are too small to be diced or scribed and we fashioned a method to release and float them. We will describe this approach. Both types of devices were tested for their spectral and angular thermal emission distribution. We will describe the way these parts can be applied to a surface.

7591-25, Session 6

Experimental observation of Raman enhancement from a grating-antenna hybrid structure

M. Hu, J. Li, D. A. Fattal, Z. Li, Hewlett-Packard Labs. (United States)

In this work, we present a novel grating-antenna structure for Surface Enhancement of Raman Scattering (SERS) study. A dielectric silicon nitride (Si3N4) grating was created via e-beam lithography and etching process based on a theoretical design which predicted that an enhanced near-field can be achieved after incorporating plasmonic metal nano-antennas periodically on the grating at certain locations. To validate our theoretical design, we fabricated the grating-antenna hybrid structure by depositing small metal nanoparticles randomly on the as-fabricated grating and investigated the Raman scattering of the BPE (trans-1,2-bis(4-pyridyl)-ethylene) molecules adsorbed on the metal antennas. A variety of grating-antenna structures with different optical properties were studied. Our experimental results revealed that an additional Raman enhancement can be realized when we tuned either the excitation wavelengths or emission wavelengths to overlap with the so called guided mode resonance (GMR) of the grating. This experimental observation demonstrated that the grating can be utilized as a cascaded field amplifier to enhance the strong near-field of the plasmonic nano-antenna for SERS and other photon emission process.

7591-26, Session 6

Dry etching of TiO2/SiO2 DBR mirrors for tunable optical sensor arrays

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The fabrication of a tunable optical sensor array consisting of Fabry-Pérot filters depends on various process steps, e.g. deposition of DBR mirrors and cavity material, patterning and structuring of the filters. High-index-contrast DBR mirrors, composed of multiple layers of TiO2/SiO2 have been designed to obtain high reflectivity and large tuning range of the filters.

In this work we focus on the etch processes for filter structuring, which were performed in an inductively coupled plasma reactive ion etcher (ICP RIE). Etch rate and etch selectivity as function of varying etch parameters (gas flow rates, RF/ICP power, pressure and temperature) were investigated. TiO2/SiO2 - DBR mirrors were sputtered by Ion Beam Sputter Deposition (IBSD) on glass substrates. Chrome and aluminum etch masks were deposited by means of electron beam evaporation and patterned with lift-off. Different photoresists were tested in order to obtain good etch mask profiles. Indium Tin Oxide (ITO) as etch mask was introduced for this etching process. Depth of etched structures was measured using a mechanical profilemeter. The surface and sidewall profiles were observed using an optical microscope and a SEM (scanning electron microscope). Smooth surfaces and relatively vertical sidewalls were obtained with etch rates of approximately 800 Å/min at 6 mTorr and 20oC (300W RF/500W ICP), using a combination of SF6/Ar gases and ITO mask. Applying higher temperature results in a better etch profile, but higher pressure gives lower etch rate. Based on these results tunable

optical sensor arrays with multiple layers of TiO2/SiO2 /air gap structures will be developed.

7591-36, Poster Session

Fabrication of corrugated long-period fiber gratings by wet bulk micromachining

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Long-period fiber gratings (LPFG) filter plays an important role in the sensing system of intensity modulation fiber gratings. Several methods have been used for the fabrication of long-period fiber gratings (LPFG). However, LPFG has not been widely utilized in the industrial applications because most of the methods are complicated and expensive. In this paper, we built up a new process of corrugated LPFG by using wet buck micromachining to reduce the cost, and also for mass production. In order to fabricate corrugated long-period fiber gratings, a wet buck micromachining method with the SU8 photoresist and BOE wet etching was used to form the grating pattern precisely. The SU8 photoresist serves as the barrier of etching. Our LPFGs were fabricated with 600 nm periods with resonant-attenuation wavelengths of 1545nm. The maximum resonance-attenuation of the LPFG is 23dB. Eventually, the temperature calibration of corrugated LPFG was performed to obtain 60 pm/ of sensitivity, 0.994254 of R-squared, and 1 of resolution.

7591-37, Poster Session

Dynamics of percolation phenomena in electroluminescent colloidal thin films for roll-to-roll printing

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

The potential realization of single particle organic light emitting devices represents a research field of considerable promise, motivated by commercial interest in the possibility of large-scale printing fabrication routes. Fabrication methods can have a noticeable effect on OLED efficiency and light output. The drying from colloidal emulsion to thin film, as present in roll-to-roll printing, affects particle packing, which causes percolation and changes in charge transport behavior. Carbazole, oxadiazole polymers and light emitting dyes, attached to polystyrene nanospheres, are synthesized by emulsion polymerization. Each organic component fulfills a specific OLED function, such as electron or hole transport and light emission. Blends of the singularly functionalized particles and alternating copolymer functionalized particles are studied to access percolation phenomena and charge transport as it relates to thin film formation and particle packing densities. The particle packing density of either emulsions or thin films directly affects electron transport between moieties. PL spectra show excimer and exciplex peaks, signaling percolation. Temporal evolution spectra are taken for drying thin films. Changes in drying rate and film thickness affect probability of electron transport between moieties. A polymer blend of functionalized and naked PS particles is made to control the conjugated polymer concentration and illustrate the percolation threshold for these colloidal systems. By controlling particle packing and the parameters of thin film formation, incomplete energy transfers between the conjugated polymers are reduced, providing more efficient devices.

7591-38, Poster Session

Antireflection on plastic substrates using ion etching with discontinuous metallic film

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The reflectance of the plastic substrates affects the observers' vision when they are watching the substrates under highlight. In this research, the discontinuous metallic films were fabricated on the plastic substrates to reduce the reflection of the plastic substrates. Besides, the discontinuous metallic film can also be the mask of the selective ion etching to achieve rough surface of the substrate to reduce the reflection. The reflectance, transmittance, and roughness can be treated with the selective ion beam bombardment. The ion beam bombarded the plastic substrates with the beam voltage 400 V and beam current 500 mA under the working pressure of 2×10-4 Pa after the fabrication without heating. Obviously, the surface became uneven by the ion etching, and the roughness of the plastic substrates can be proportional to the etching time of the ion beam source. The metallic particles can be trapped in the interface layer of plastic substrate after the long etching time. The results show the average reflectance of the plastic substrates has been decreased 5% in visible. The average transmittance has been increased 3%.

7591-39, Poster Session

Quantum dots(QDs) immobilization on silver nanowire end-facet for single photon source application

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In present study, we introduce a top-down approach to locate carboxyl functionalized cadmium selenide (CdSe) QD (emission wave-length: 605nm) immobilization on one end-facet of 50 nm silver nanowire which can be possibly used as a cavity-free unidirectional single photon source of high coupling efficiency. Silver nanowires were fabricated using E-beam evaporation followed by lift-off process on a silicon dioxide (SiO2). First, e-beam resister (ER) was patterned to have a few hundred nanometer wide parallel grooves and 50 nm-thick silver layer was deposited using e-beam evaporator at very low deposit rate of 0.1 nm/sec to acquire smooth surface. After lift-off process, whole wafer area was covered with SiO2 layer deposited with PECVD resulting in 50 nm-high parallel silver nanowires surrounded with SiO2. End-facets of silver nanowires, the target surface for QD immobilization, were formed in the middle of nanowires using two wet etching processes for SiO2 and silver, respectively. Wet etching process defines target surface and also makes nanowire surface smoother resulting in higher coupling efficiency.

QD immobilization on the target surfaces was accomplished through several surface modifications on both silver and QD surfaces. Silver nanowires were coated with carboxyl functionalized mercapto ethylene glycol (MEG, HS-(EG)3-COOH) for a self assembled monolayer (SAM) and amine functionalized 12-mer ssDNA with 6 carbon spacer were then applied to MEG monolayer both to provide binding sites for later ssDNA hybridization and to control distance between QD and target surface on nanowire. Same processes were applied to carboxyl functionalized QD surfaces, but with ssDNA of complementary sequence. MEG monolayer conjugation with QDs showed high selectivity between silver and SiO2.

7591-40, Poster Session

Multi-photon-polymerization of inorganic-organic hybrid polymers using visible or IR ultra-fast laser pulses for optical or (opto-) electronic devices

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Integrated passive and active devices are the key components in current and future information technology. In order to fulfill requirements in miniaturization for (integrated) optical or electronic devices, nano-scaled materials with a good compatibility to high-resolution processing techniques are needed. According to these requirements, multi-photon techniques attract much attention by providing a resolution far beyond the diffraction limit.

The patterning of the inorganic-organic hybrid polymers, which are synthesized by catalytically controlled hydrolysis/polycondensation reactions, will be discussed with respect to the underlying photochemical processes. Emphasis will be on the direct writing of structures using femtosecond laser pulses, making use of two- and three-photon absorption (TPA/3PA) processes with visible or IR light, which also allows one to write arbitrary 3D structures. Due to the very sharp threshold fluence for these processes and its non-linear behavior, features down to 100 nm can be realized by choosing a suitable combination of material formulation and patterning parameters. Voxel arrays were written, and the resulting voxel sizes are compared to a growth model and the influence of radical diffusion and chain propagation is discussed. In order to determine the TPA cross-section and to estimate the role of the photoinitiator, a z-scan experiment was realized. The initiators' cross-sections will be correlated to the resulting voxel sizes.

7591-41, Poster Session

Possible integration of Ti-catalyzed silicon nanowires using APCVD method in silicon based electronics

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The integration of nanowires in practical photonic and photovoltaic devices have been discussed and studied by researchers over the last decade. Chemical vapor deposition (CVD) growth techniques have been seen as possible methods for obtaining device quality nanowires that could solve the problem of obtaining faster, and more efficient devices at smaller geometries. One dimensional metal catalyzed silicon nanowires grown using CVD techniques have been seen as possible ways to increase electron transport and device speeds for silicon based electronics. In this experiment the possibility of integrating titanium catalyzed silicon nanowires grown using an atmospheric pressure based CVD method are investigated for use in silicon electronics. Growth experiments were conducted at various partial pressures of silicon tetrachloride, temperatures, and growth times to determine optimum growth rates and the window for oriented, straight silicon nanowires. Using linear regression analysis on a sample set of the grown nanowires, we are left with the conclusion that nanowires grown using APCVD may provide a cost effective growth procedure at predominantly high temperatures (in the 1000oC range). However, further practical tests maybe needed to show its application in devices.

7591-27, Session 7

Atomic layer deposition (ALD) for optical nanofabrication

J. Maula, Beneq Oy (Finland)

Presentation gives an overview of ALD technology for optical film deposition, highlighting benefits, drawbacks and peculiarities of the ALD, especially compared to PVD. Viewpoint is practical, based on experience gained from tens of different applications over the last few decades. ALD is not competing, but enabling technology to provide coatings, which are difficult for traditional technologies. Examples of such cases are films inside (or both sides) of tubes; double side deposition on the substrate; large area accurate coatings; decorative coating for 3D parts; conformal coatings on high aspect ratio surfaces or inside porous structures. Novel materials can be easily engineered by making modifications on molecular level. Examples of engineered nanoscale films and film deposition methods are included to presentation. ALD coats large surfaces effectively and fast. Opposite to common view, ALD actually provides high throughput (coated area/time), when used with a batch and/or in-line tools. It is possible to use ALD for many micrometers thick films or even produce thin parts with competitive cost. Besides optical films ALD provides large variety of features for nanofabrication. For example pin hole free films for passivation and barrier applications and best available films for conformal coatings like planarization or to improve surface smoothness. High deposition repeatability even with subnanometer film structures helps fabrication. ALD enters to production mostly through new products, not yet existing on the market and so the application IP field is reasonably virgin. ALD is an enabling, but mature technology to fabricate novel optical materials and to open pathways for new applications.

7591-28, Session 7

Modification of conformal-evaporated-film-by-rotation technique to improve replica uniformity on nonplanar biotemplates

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The implementation of concepts from nature in different technoscientific fields is called biomimetics. Motivated by the idea of biomimetic optical devices, the conformal evaporated-film-by-rotation (CEFR) technique was devised to fabricate inorganic replicas of biotemplates with high reliability and fidelity at the micro- and nano-scales. We modified the conformal-evaporated-film-by-rotation (CEFR) technique to improve the uniformity of roughly 500-nm-thick films deposited on nonplanar biological templates to replicate surface features. The biotemplates selected are compound eyes harvested from a common species of blow fly. Bulk chalcogenide glass with composition Ge28 Sb12 Se60 was used as the source material for all films. The modified CEFR technique introduced a second degree of freedom in manipulating the biotemplate with respect to the average direction of the vapor flux. We were thus able to tailor the motion of the biotemplate holder to improve the uniformity of deposited films. Cross sections of the coated biotemplates were obtained using microtomy techniques, and the thicknesses of CEFR-and modified-CEFR films were quantitatively compared.

7591-29, Session 7

Templated growth of and optical emission from single crystal GaAs 3D photonic crystals

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We show that GaAs can be grown epitaxially through a colloidal crystal

template on a GaAs wafer, yielding single crystal 3-D GaAs photonic crystal. First, a silica 3-D photonic crystal template is grown by colloidal self-assembly or multibeam interference lithography on a GaAs substrate. GaAs is then grown via MOCVD using conditions where GaAs nucleation on silica is very low and GaAs growth on the GaAs substrate remains high. GaAs growth initiates at the GaAs substrate and grows up through the photonic crystal template. After removal of the template, the product is a single crystal of GaAs containing a periodic array of pores. The optoelectronic properties of devices created with this architecture will be discussed.

7591-30, Session 7

Three electrode control of the nanodeposition of gold nanoparticles with atomic force controlled capillary electrophoresis

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Controlled deposition of the metallic features such as nanoparticles with high spatial accuracy has a great interest in different applications such as surface plasmons, surface enhanced Raman scattering (SERS), nanophotonics and nano biophysics. Lithography based scanning probe microscopy techniques have been shown as a potential methodology for accurate and localized deposition of material in the nanometer scale. Here we report an accurate deposition of high resolution features of single gold nanoparticles using three electrodes and atomic force microscopy (AFM) controlled capillary based fountain pen nanolithography. In this methodology, three electrodes are attached one on the outside of the metal coated glass probe, one on the inside of the hollow probe in the solution contained in the capillary and a third electrode on the surface on which the writing is to take place. The three electrodes provide electrical pulses for accurate control of the deposition and retraction of the liquid from the surface. We will demonstrate depositing of single gold nanoparticle with size of 1.2nm onto surfaces such as semiconductors.

7591-31, Session 8

Analysis, tolerancing, and fabrication of a two element diffractive beamshaper

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This paper describes the design and analysis of a two-element, deep-UV diffractive beamshaper which converts a collimated Gaussian beam into a collimated flattop beam. This conversion involves a one to one mapping of the beam, so that every part of the incoming beam is precisely mapped to the desired location in the output plane. With a two element design, both the intensity and the phase of the wavefront can be controlled. These shaped beams can be used in a variety of different applications such as laser welding and drilling, and to provide uniform illumination for inspection applications and material testing.

Diffractive beamshapers can be manufactured in most common materials to provide good beam control with very low non-uniformity. They can also be much more compact than comparable refractive beamshapers as well as include additional functionality that cannot be incorporated with a refractive element. However, diffractive beamshapers can suffer from coherent interference from other diffractive orders. To avoid this, an off-axis design is preferable. This type of design separates the orders so that overlap is minimized.

Beamshapers are generally very sensitive to misalignment. In this paper we look at the sensitivity of the beamshaper to misalignment and tilt of the input beam and other phase surfaces, change in collimation of the input beam, and various fabrication errors of the diffractive. We show an off-axis beamshaper that was successfully fabricated and met all specifications. Comparisons with laboratory measurements show excellent agreement with simulation predictions.

7591-32, Session 8

Precision glass molding: an integrative approach for the production of high-precision micro-optics

M. Hünten, Fraunhofer Institute for Production Technology (Germany)

Miniaturization and integration are the dominating factors for the success of multiple optical devices. Conventional manufacturing processes for the fabrication of precise glass optics by means of grinding and polishing cannot cope the increasing demands in terms of precision, volume and costs. Here, precision glass molding is the enabling technology to meet these demands of the future optical products and applications. Since the market requests further miniaturization and integration of the micro optical components the possession of the whole process chain is absolutely essential.

With the accomplished and ongoing developments at the Fraunhofer IPT the replication of double-sided (a)spherical and (a)cylindrical glass lenses with maximum form accuracies of < 150 nm as well as lens arrays and even freeform optics could be realized. Therefore, the a-priori FEM-simulation of the molding process was driven to a point capable to simulate even the molding of freeform optics. The research works focusing on the mold manufacturing led to sophisticated grinding process strategies able to realized complex mold geometries such as lens arrays. With regard to the coating of the molds, proceedings were developed assuring a defect free and uniform coating which enables the longevity of the molds and therewith helps reducing the final costs per lens. Thus, the precision glass molding becomes more and more interesting even for highly complex mid volume lots, characteristic for European or US optics manufacturer.

This paper will provide an insight into the different process steps of precision glass molding emphasizing the importance of the interfaces in between and the integrity of the approach.

7591-33, Session 8

Ion beam figuring of strongly curved aspheres using a 3 axes trimming system

M. Demmler, F. Allenstein, M. Nestler, M. Zeuner, Roth & Rau MicroSystems GmbH (Germany)

High end optical components like lenses and mirrors require a surface accuracy of lambda/80 or better in the deviation of the ideal surface. Conventional polishing methods are not able to aim these requirements.

The author will introduce an ion beam trimming method for high end optics which is based on a trimming system used in semiconductor mass production. During the process, the substrate is moved in front of a focussed broad ion beam. Due to the curved surface of the substrate a technique with 5 axes is already established. However, this technique is not meeting the requirements of perpendicular incident on every surface position for aspheres to get a stable etch rate.

By using a 3 axes system the different incident angles have to be considered because the etch rate depends on them. This is can be reached by doing a calibration before trimming. Arbitrary curved surfaces like asphere can be processed with the knowledge about the etch rate dependency on the incident angle.

The local milling rate is controlled upon the residence time of the ion beam at certain positions. A modulated velocity profile is calculated specifically for each substrate in order to mill the material at the associated positions to the target geometry.

It will be shown that curved spherical or aspherical surfaces with incident angles up to 60° can be corrected down to /80 or better by using a state of the art 3 axis trimming system.

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7591-34, Session 8

High-efficient multilevel phase diffractive elements realized by binary effective medium patterns

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Binary subwavelength structures open up the possibility to create an artificial index material which enables the realization of high efficient diffractive structures. This feature can be used to generate optical elements with nearly arbitrary phase profiles and a high accuracy. Furthermore, undesired stray light of conventional diffractive optical elements can be reduced by orders of magnitudes. In this paper we demonstrate the realization of computer generated holograms (CGHs) based on this effective medium approach. High diffraction efficiencies of diffractive elements require a high number of phase levels and a precise pattern positioning which usually leads to an increasing complexity in fabrication. By using two-dimensional binary subwavelength structures it is possible to obtain a multilevel phase modulation by only one depth of the nanostructures. Thus, the exposure process can be reduced to one lithographical step. The structures are fabricated by means of our high-speed e-beam writer Vistec SB350OS which allows patterning with a high resolution in the nanometer range even on large-scale areas. For first demonstration, the CGHs are fabricated as reflective elements, which halve the required structural depth. A patterned e-beam resist layer on a reflective substrate acts as the refractive (effective) medium. The CGHs are designed and experimentally characterized at 532 nm. The effective phase shift caused by the subwavelength structure is additionally characterized by interferometric measurements. We demonstrate a diffractive element in the visible range which generates customized far field patterns. It is shown that the undesired symmetric diffraction pattern in the far field could be highly suppressed.

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7592-01, Session 1

Nanoengineered surfaces for microfluidic-based thermal management devices

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Recent developments in high performance consumer, military, and space electronics significantly increase the demand for new thermal management solutions. Microfluidic systems offer compact and efficient cooling strategies. In this work, we investigate novel nanostructured surfaces to control fluidic behavior and enhance heat dissipation in microfluidic systems. We fabricated silicon nanopillars with diameters ranging from 200 nm to 800 nm and heights of approximately 5 um. With the incorporation of three-dimensional structures, the liquid (DI water) could separate into varying thicknesses of liquid films and achieve uni-directional liquid spreading. The nanostructures enable new capability to control liquid behavior. Heat dissipation studies were subsequently investigated by utilizing these fabricated nanostructured surfaces with integrated heaters and temperature sensors. The results from this work show great potential for novel nanostructure design to control liquid transport and dissipate high heat fluxes.

7592-02, Session 1

A new method for hermeticity testing of wafer-level packaging

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Until now, the determination of the hermeticity of microelectronic packages is related to the MIL-STD-883 method 1014 which is based on the He leak detection method. But this method is no more suited for small packages due to the resolution limit of the apparatus used conventionally. Indeed the minimum detectable leak rate is of the order of 5.10-11 atm.cm3.s-1. Leaks induced by non hermetic MEMS packages are often one order of magnitude smaller. So, the sensitivity of the He leak detector method is too low and this method can not be applied anymore. , the MEMS packages produced with wafer level encapsulation techniques, require new methodologies to measure hermeticity appropriately and accurately. The purpose of this paper is to present the development of alternative methods for testing the hermeticity of MEMS micro-cavities. Two methods will be investigated in the context of this study: The membrane deflection measurement exposed to different pressures, using optical profilometry, and the measurement of the variation of gas concentration in a sealed silicon cavity by Fourier-transform infrared spectroscopy (FT-IR). The calculated leak rates are compared for samples where standard fine leak test gave no results. The values obtained for the leak rates within optical test and FT-IR test for the same sample are identical, showing the relevance of these two methods. FT-IR spectroscopy is a hopeful method which enhances standard detection limits. It can be used as a reliable process quality control tool.

7592-03, Session 1

Pressure sensing in vacuum hermetic micropackaging for MOEMS-MEMS

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Packaging constitutes one of the most costly steps of MEMS/MOEMS manufacturing. Uncooled IR microbolometers require a vacuum atmosphere below 10 mTorr to operate at their highest sensitivity. The bolometer response is also dependent on the package temperature. In order to minimize cost, real estate and power consumption, temperature stabilization is typically not provided to the package. Hence, long term high sensitivity operation of IR bolometers requires a calibration as function of in package pressure and temperature. A low-cost and accurate means of measuring the pressure in the package without being affected by the operating temperature is therefore needed.

INO has developed a low-cost, low-temperature hybrid vacuum micropackaging technology. An equivalent flow rate of 4x10 14 Torr L/sec for storage at 80 °C has been obtained without getter. Even with such low flow, the long term stabilization of residual pressure variations affect the sensitivity and calibration of the IR bolometers. INO has developed MEMS pressure sensors that allow for real-time measurement of package pressure above 1 mTorr, and can be integrated with the IR bolometers in a die-level packaging process or microfabricated simultaneously on the same die.

In this paper, the typical performance and measurement uncertainty of these pressure sensors will be presented along with a reading method that provides a pressure measurement with a dependence on the package temperature as low as 0.7%/°C. Complex reading circuit or temperature control of the packages are not required, making the pressure sensor well adapted for low-cost high-volume production and integration with IR bolometer arrays.

7592-04, Session 1

Wafer-level vacuum/hermetic packaging technologies for MEMS

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An overview of wafer-level packaging technologies developed at the University of Michigan is presented. Two categories of packaging technologies will be presented: (i) low-temperature wafer-level packaging processes for vacuum/hermeticity sealing, and (ii) an environment-resistant vacuum packaging (ERP) technology with thermal and mechanical isolation used in high-performance microsystems and microinstruments.

Low temperature wafer-level encapsulation processes are implemented using solder or eutectic bond rings which are first patterned on a cap wafer and then mated with a device wafer in order to encapsulate the device at temperatures ranging from 200 to 390 °C. Vacuum levels of below 10 mTorr have been achieved with yields in an optimized process of better than 90%. Package pressure has been monitored for more than 4 years using micromachined integrated Pirani gauges, yielding important information on reliability and process control.

The ERP uses a micromachined isolation platform to provide thermal and mechanical isolation, as well as temperature control using a low-power servo-controlled on-chip heater. The packaging technology utilizes batch flip-chip assembly of a MEMS device onto the isolation platform wafer. The MEMS device and the isolation platform are encapsulated at the wafer-level by a cap wafer with vertical feedthroughs for vacuum/hermetic sealing and electrical signal connections. This generic technology was developed for high performance micromachined gyroscopes, but can be applied to any type of MEMS device.

7592-05, Session 1

Characterization of polymeric getter materials for MEMS/MOEMS and other microelectronic package service

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Various getter materials have been developed over the years to deal with hydrogen and moisture caused problems in MEMS/MOEMS packages. These materials consist of two major families, metal alloy systems and polymeric systems. Both systems have pluses and minuses for the MEMS/MOEMS packaging engineer. In order to determine applicability, careful characterization of these systems is critical.

The advent of a new class of polymeric getter materials originally developed for other industries has brought a need to readdress the issue of how to characterize such materials for MEMS/MOEMS service. While MIL-STD-883 gives a degree of guidance, it is not the complete answer. Characterization of these materials has consequently been clean sheeted to address the key areas of hydrogen and water capacity determination, measurement of outgassed VOCs, and determination of ionics concentrations.

Methods used and the results of this work will be discussed. The methods include gravimetric analysis of water sorption capacity, determination of outgassing rates via mass spectrometry, and chemical analysis for ionics. Example results for each test type will be presented for an example polymeric getter material of a type designed to pump both water and hydrogen from a hermetically sealed system.

7592-06, Session 1

Hermetic vacuum sealing of MEMS devices containing organic components

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Traditionally, the use of organics within a vacuum-sealed hermetic electronics package has been avoided. Organics, including adhesives, outgas and degrade over time, resulting in a rapid reduction in vacuum quality within a sealed device package. However, MEMS device fabrication is now blurring the lines between strictly electronic devices, which contain very few organic components, and electro-mechanical devices, whose secondary assembly steps require the integration of stable organics into sealed electro-mechanical devices. The Chip Scale Atomic Clock (CSAC) device developed and implemented with funding from DARPA by a team from Symmetricom, Sandia Labs, and Draper Labs, is a prime example of a device that integrates organics and chip scale die into an assembly that requires operation within a good vacuum environment over the lifetime of the device. Through the use of analytical chemistry techniques such as TGA, DSC, and IVA, we measured outgassing of assembly materials to be sealed in the package. We have been able to determine the magnitude of initial outgassing and to measure the stable vacuum pressure of complete sealed devices to within a millitorr. Comparison of these results with predictions based on IVA data of specific gas species and getter capacity has allowed us to optimize processing conditions (such as cure schedule for adhesives and bake-out profile before sealing) for minimal outgassing. This information has allowed us to design and build MEMS devices which require an internal vacuum level of < 20 millitorr and seal them in hermetic packages without substantial degradation.

7592-07, Session 2

Predicting reliability of silicon MEMS

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Brittle materials fail when the applied stress at a critically-sized flaw exceeds the fracture toughness of the material. Since the location and sizes of all flaws in a material is essentially unknowable, the failure point of a brittle structure cannot be solved in a deterministic manner. Traditional safety-factor analysis, an approach used for ductile materials that compares the highest modeled stress to material yield strength, is dangerously inaccurate for brittle materials like silicon. Yet safety-factor analysis is often employed in analysis of microelectromechanical systems (MEMS) for lack of a better solution.

We have developed a new failure prediction methodology specifically designed for MEMS devices. The method uses a statistical characterization of the as-fabricated surface conditions, determined by fracture testing of simple test specimens. When this data is combined with finite element modeling in a proprietary algorithm, we are able to predict the fracture probability for any MEMS device fabricated by the same methods, under any type of loading. We demonstrate the accuracy of our method by comparing predicted fracture probabilities against actual fracture test results for a MEMS device in multiaxial loading configurations.

7592-08, Session 2

Stability experiments on MEMS aluminum nitride RF resonators

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We report on long-term stability experiments on a novel MEMS radio frequency (RF) resonator fabricated in Aluminum Nitride technology. The AlN fabrication process allows for the realization of resonators, filters, and resonant sensors operating over the frequency range from 500 kHz to in excess of 1 GHz using CMOS compatible materials. The 100 MHz resonators used in these experiments were a ring design with 140-micron outer diameter and 100-micron inner diameter. Electrodes on the top and bottom of this AlN ring enable measurement of resonance. Wafer sections were stored in air and vacuum and tested daily. We observed a steady degradation in the resonant frequency (600 ppm over the 800 hours) for the devices stored in a vacuum. Small degradation was observed in the air experiment (50 ppm over 1200 hours). Failure analysis using secondary emission microscopy (SEM) revealed no differences between control devices and devices on test. However, subsequent investigation of blank wafer sections by Time-of-Flight secondary ion mass spectrometry (ToF-SIMS) found small levels of silicone surface contamination from vacuum chamber exposure. This contamination added enough mass to shift the resonant frequency. These experiments demonstrate the need for clean environments for future wafer-level testing and also packaging for these small-mass resonators.

7592-09, Session 2

Characterization of Au/Au, Au/Ru and Ru/Ru ohmic contacts in MEMS switches improved by a novel methodology

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Research on contact characterization for microelectromechanical system (MEMS) switches has been driven by the necessity to reach a high-reliability level for micro-switch applications. One of the main failure observed during aging of the devices is the increase of the electrical contact resistance. The key issue is the electromechanical behaviour of the materials used at the contact interface when the current is flowing through the contact asperities. Indeed metal contacting switches have a large and complex set of failure mechanisms driven by the current level. Comparisons between several pairs of contact materials have been done with a new methodology using a commercial nanoindenter coupled

with electrical measurements on test vehicles specially designed to investigate the micro-scale contact physics. Dedicated validation tests and modelling were performed to assess the introduced methodology by analyzing the response of contact with 5 μm² square bump under electromechanical stress. The data provided a better understanding of micro-contact behaviour related to the impact of current at low- to medium-power levels. The stability of the contact resistance, when the contact force increases, was studied for contact pairs of soft material (Au/Au contact), harder material (Ru/Ru contact) and mixed one (Au/Ru contact). Contact temperature rises were measured leading to shifts of the mechanical properties of contact materials and modifications of the contact topology when the softening temperature of the contact material is reached. An enhanced stability of the bimetallic contact Au/Ru was demonstrated considering sensitivity to power increase, related to creep effects and topological modifications of the contact surfaces.

7592-10, Session 2

Novel test fixture for collecting microswitch reliability data

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Microelectromechanical Systems (MEMS) is an important enabling technology for reducing electronic component geometries and lowering device power consumption. An example MEMS technology, used in radio frequency (RF) circuits and systems, is the microswitch. Although microswitch operation is relatively simple, they are plagued by poor reliability. In order for microswitches to gain favor they must demonstrate lifetimes of over 100 million cycles. Attempts by researchers to reach this goal have led to investigations of contact force, contact resistance and mechanical designs in an effort to develop these important devices.

Over the years, Microelectromechanical Systems (MEMS) researchers have used various test fixtures including: MEMS devices, atomic force microscopes (AFM) and nanoindentors, to collect necessary data (i.e. contact resistance) for studying micro-switch electric contacts. MEMS device fixtures allow for lifecycle testing but not direct measurements of contact force which must be inferred through modeling. AFM and nanoindentor fixtures allow direct contact force measurements but are severely limited by low resonance beams and piezoelectric force sensors. The entire fixture will be housed in a dry-box enclosure and isolated from external vibrations to minimize external effects. The majority of the test fixture will be automated using LabView running on a PC. All hardware devices (motion actuator, force sensor, power supply and voltage/current measurements) will be connected directly to the PC for fixture control and optimum data collection. This paper presents a unique high lifecycle test fixture capable of simultaneous measurement of contact resistance and contact force. Preliminary micro-contact reliability data is also presented.

7592-11, Session 2

Reliability study of a MEMS array under varying temperature and humidity conditions

T. E. Dallas, G. Sivakumar, R. Ranganathan, R. Gale, Texas Tech Univ. (United States)

In this work, we quantify and analyze the rate of accrual of stiction and mechanical fatigue in a standard MEMS micro-mirror device to understand its reliability under a set of controlled temperature and humidity splits. An accelerated aging system was employed by using a non-standard actuation procedure to more rapidly induce failure of the micro-mirrors. The array is hermetically packaged with a low surface energy self-assembled-monolayer (SAM) based anti-stiction coating, along with an encapsulated source of this anti-stiction coating that serves as a reservoir. Exposure of the micro-mirror array to the environmental conditions was made possible by drilling two 1 mm holes in the hermetic package. This enabled the retention of the encapsulated SAM source in the package which was vital to understanding the effects of SAM re-deposition on the surface in the operating environment. The fastest accrual of stiction was seen in the 90ºC, 80% RH split with approximately 80% of the micro-mirrors failing within 4.4 × 109 cycles (10 hours) with 2.7x10-14 Joules of Stiction Equivalent Energy while the 60oC, 20% RH showed the least stiction accrual rate with less than 2% failure for 2.26×1012 cycles (1500 hours). The mechanical fatigue in the micro-mirror was modeled as a diffusion process of atoms along the torsional hinge on which the mirrors rests, and the activation energy for the diffusion process was calculated as ~ 0.40 eV using an Arrhenius relationship. The failure data obtained from the experiments were used to do a reliability analysis by utilizing the Weibull distribution.

7592-12, Session 3

The effects of plasma pre-treatment and storage time on silicon fusion bonding

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Silicon fusion substrate bonding has long been a technique that was available for hermetically sealing devices at the wafer level, but its usage has been limited by the high annealing temperatures required to create permanent bonds between the wafers. These temperatures are typically 1,000 °C or higher. This severely limits the materials set that can be used for fabrication to the few materials that can take those temperatures for the several hours required for annealing. Plasma pretreatment of these wafers prior to mating the wafers has shown a dramatic decrease in the required annealing temperatures. However, not all of the details are known about how this process works and how robust is would be in a manufacturing environment. In this work the author explains some of the different effects that plasma pretreatment and annealing at low temperatures (~300 °C) produces and how varying the ionized species in the plasma affects the bond strength and lifetime. The shelf life of plasma activation was also investigated. The bond qualities were examined by infrared imaging for the presence and concentration of voids or unbounded regions. The bond strength of these techniques was measured using tensile pull tests. It was found that the bond strength of plasma activated wafers can match the value of traditionally annealed wafers, and is very close to that of bulk silicon. Wafers were stored for as long as 168 hr and an interesting interplay between oxygen, nitrogen, and silicon chemical bonding and time was found and is explained.

7592-13, Session 3

Lifetime estimation and reliability study of electro-thermal MEMS actuators

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This work will present a detailed reliability and lifetime expectancy study of electrothermal micro-actuators under different actuation scenarios. The devices used in this study are bent-beam (chevron) electrothermal actuators designed and fabricated using Sandia National Laboratories SUMMiT V surface micromachining process. The actuators are designed using the topmost poly-silicon layer that is 2.25 μm thick. The legs of the actuator are ~ 395 μm in length with an offset angle of 5°. A custom made characterization setup was built to conduct the reliability and lifetime testing of the device. The image acquisition of the device is done using a Canon S5 IS digital camera (8 MP), connected to a microscope with a 100 × magnification. To calculate the in-plane displacements of the device, a National Instruments' Vision image analysis software routine was utilized. Raman spectroscopy is used to determine the body temperature of the device under different actuation power levels. An initial study is done to determine the actuator displacement characteristics with respect to the applied power. Based on the results from this study, the region of plastic deformation of the devices is determined. The test involved first identifying key power levels and then a square wave of ~ 300 hz was applied for a period of time until the device shows the onset of plastic deformation. Arrhenius relationships are used to model the

plastic deformation based failure mechanism and allow the activation energy to be calculated.

7592-14, Session 3

Reliability assessment of ceramic column grid array (CCGA) interconnect packages under extreme temperatures for space applications (-185°C to +125°C)

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The CCGA packages have been in use for several applications based on their advantages such as high interconnect density, very good thermal and electrical performance, compatibility with standard surface-mount packaging assembly processes, etc. CCGAs are used in space applications such as in avionics, logics and microprocessor functions, telecommunications, payload electronics, etc. The reliability of CCGA packages is very important for short- and long-term space missions. This paper will describe the experimental test results of CCGA testing under wide temperature extremes.

CCGA interconnect electronic package printed wiring boards have been assembled, inspected non-destructively and subsequently subjected to extreme temperature thermal cycling to assess the reliability for future deep space, long-term, extreme temperature missions. In this preliminary investigation, the employed temperature range covers from -185oC to 125oC. The resistances of daisy-chained, CCGA interconnects were continuously monitored as a function of thermal cycling. Electrical resistance measurements during thermal cycling are reported and the tests to date have shown significant change in daisy chain resistance as a function of thermal cycling. The change in interconnect resistance becomes more noticeable with increasing number of thermal cycles. Adaptation of suitable diagnostic techniques to identify the failure mechanisms is in progress. Standard Weibull analysis tools were used to extract the Weibull parameters to understand the CCGA failures. Optical inspection results clearly indicate the solder joints of columns with the board and the ceramic have failed as a function of thermal cycling. The first failure was observed at 137th thermal cycle and 63.2% failures of daisy chains have occurred at about 664 thermal cycles (eta: scale parameter). The shape parameter (Beta) extracted from Weibull plot was about 1.47 which indicates the failures were related to failures occurred during the flat region or useful life region of bath tub curve. Based on this preliminary test data one can use the CCGAs for the temperature range studied for ~100 thermal cycles (DeltaT = 310°C) with high confidence for high reliability space and other applications.

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7592-15, Session 3

Packaging of miniaturized EISCAP Triglyceride biosensor

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Electrolyte insulator semiconductor capacitor (EISCAP) triglyceride biosensors are basically pH sensors which can work on enzymatic hydrolysis of triglycerides with the lipase enzyme. The EISCAP uses silicon substrate, stacked oxide and nitride as the dielectric with an electrolyte which contain the bio-analytes. EISCAP biosensors for sensing triglycerides and bulk micro-machined miniature EISCAP sensors with immobilized enzyme have been reported. In this paper, we report on two kinds of packaging of the miniaturized EISCAP sensors. The first one, which is more robust, involves glass to silicon anodic bonding. However, since it involves high temperature, the enzyme activity is affected and cannot be used for immobilized enzymes. A second kind of low temperature packaging is described for the samples with immobilized enzyme. The miniaturized sensors are fabricated on 4” p-type silicon (100) and boro-float glass wafers. The silicon wafer is oxidized and then gate oxide is thermally grown after etching the silicon from the patterned oxide windows using KOH etchant. Thereafter, nitride layer is deposited by PECVD on the silicon wafer. In the top glass, Cr and Au layers are evaporated which acts as masking layer while etching through holes in the glass wafer using HF. Chrome gold is then evaporated for top metal electrode. The wafers are anodically bonded at 400o C in 15 kV/cm electric field. Finally, miniaturized EISCAPs are diced after evaporating Al metal as back electrode. The lipase immobilized miniaturized EISCAPs are packaged using Anabond glue at room temperature to safeguard the immobilized enzymes from high temperature bonding.

7592-16, Session 3

MEMS/microfluidics packaging without heating

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Conventional hydrophilic and hydrophobic bonding methods require heating at elevated temperatures as high as 1000 ºC in order to attain high bonding strength. In order to reduce the bonding temperature, plasma activated bonding processes utilizing heating at temperatures as low as 200-300 °C. In practical applications, metalized layers and circuits on wafers may be destroyed even at these low bonding temperatures. A room-temperature plasma bonding process has been developed, called sequential plasma activated bonding (SPAB), utilizing the physical sputtering of oxygen RIE and chemical reactivity of nitrogen MW radical on the same surface one after another. Although high bonding strength is achieved at room temperature in SPAB, the specimens were heated up to 900 C in order to investigate the bonding mechanism of SPAB. While the silicon surfaces in sequential activation show hydrophilic behavior, the bonding mechanism is not identical to the conventional hydrophilic bonding of silicon/silicon. The water rearrangement was found below 150 ºC, which produced hillocks at 225 ºC at the interface, resulting in voids at temperatures higher than 400 ºC in order to absorb the gas, likely to be hydrogen, produced from the desorbed water. Further heating at higher temperatures results in bubbles due to the accumulation of hydrogen gas induced voids at the preferential sites. The EELS measurements showed no nitrogen existence either in Si or SiO2 with oxygen deficiency at the interfacial amorphous SiO2. This article reports the details of the bonding mechanism of SPAB as well as some applications in MEMS and microfluidic packaging.

7592-17, Session 3

Use of conductive adhesive for MEMS interconnection in military fuze applications

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Connecting a MEMS chip directly to a PCB using conductive adhesive can increase packaging density and reliability, and reduce cost in medium caliber ammunition fuzes. The fuze environment is very demanding with operating temperatures spanning from -46°C to 71°C, a setback acceleration exceeding 60 000 g and a centripetal acceleration increasing radially with 9000 g/mm.

The conductive adhesive consists of epoxy and uniformly sized polymer particles coated with a thin layer of gold or silver. In our experiments we have used gold coated polymer particles with a diameter of either 10 um or 4 um and silver coated polymer particles with 30 um diameter.

For electrical and mechanical testing of the adhesive, dummy MEMS chips have been designed with size of 3.5x3.5 mm. These chips are identical to the real MEMS device, but they have no movable parts. The contact pads are covered with a thin layer of gold.

The adhesive shows excellent mechanical and thermal properties. All

samples passed more than 100 temperature cycles between -46 and +70 deg C, some samples passed more than 700 cycles. Performed shear test shows that the shear strength is approximately 60% higher then specified in MIL-STD 883 for a chip of this size. The contact resistance compared to the initial value changed less than 15 % after performing both 127 temperature cycles and test firing, where the chips have been exposed to an acceleration of more than 60 000 g.

7592-18, Session 4

Modeling time-dependent dielectric breakdown with and without barriers

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A model was developed to simulate time dependent dielectric breakdown of interlayer dielectrics when a metallic barrier material is present. The barrier serves to separate the copper metallization layer from the dielectric. This paper summarizes the behavior of the model for a generic barrier system and then for the specific barriers, TaN and Ru(P). A comparison with experimental data for SiO2 without a barrier and for SiO2 with TaN and Ru(P) barrier systems showed excellent agreement with the experimental data of Hwang et al [1] and Henderson and Ekerdt [2]. The model was able to simulate the data for all three systems using the same set of physical parameters with one exception. The parameter, g, outlining the dependence of the time-to-failure on the applied electric field was larger for the barrier system than the no-barrier case. This is believed to reflect the barrier properties for Cu as well as the oxidizing agent necessary to form the Cu ion required to break down the dielectric.

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7592-19, Session 4

Remotely accessible laboratory for MEMS testing

T. E. Dallas, G. Sivakumar, M. Mulsow, A. Melinger, S. Lacouture, Texas Tech Univ. (United States)

We report on the construction of a remotely accessible and interactive laboratory for testing microdevices (aka: MicroElectroMechancial Systems - MEMS). Enabling expanded utilization of microdevices for research, commercial, and educational purposes is very important for driving the creation of future MEMS devices and applications. Unfortunately, sometimes prohibitively high costs associated with MEMS devices and testing infrastructure makes widespread access to the world of MEMS difficult. The creation of a virtual lab to control and actuate MEMS devices over the internet helps spread knowledge to a larger audience. A host laboratory has been established that contains microscope, microdevices, controllers, and computers that can be logged into through the internet. The overall layout of the tele-operated MEMS laboratory system can be divided into two major parts: the server side and the client side. The server-side is present at Texas Tech University, and hosts a server machine that runs the Linux operating system and is used for interfacing the MEMS lab with the outside world via internet. The controls from the clients are transferred to the lab side through the server interface. The server interacts with the electronics required to drive the MEMS devices using a range of National Instruments hardware and LabView Virtual Instruments. An optical microscope (100 ×) with a CCD video camera is used to capture images of the operating MEMS. The server broadcasts the live video stream over the internet to the clients through the website. When the button is pressed on the website, the MEMS device responds and the video stream shows the movement in close to real time.

7592-20, Session 4

Optical inspection of MOEMS devices using a configurable and suitable for production image processing system

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In addition to electrical characterization, MEMS and MOEMS typically require additional testing in order to guarantee fulfilment of specification before they can be delivered to customers. Especially, optical testing is required for several reasons. Firstly, exact manufacturing of mechanical structures and right dimensions can only by checked optically. Secondly, optical performance depends on quality of surfaces, so that they have to be checked for homogeneity and absence of scratches and particles.

Fraunhofer IPMS has developed a fully automated system for optical testing and characterization of MEMS and MOEMS that can be used for the purpose described above. It uses modified versions of commercially available tools for device handling, since the system shall be capable of testing not only rigid standard wafers but also thinned, vaulted, bonded and diced wafers. Changing of wafers happens automatically. Using a fast, high-resolution digital camera equipped with a telecentric lens allows coping with different device sizes and topologies. The implemented image processing algorithm is generic and can be adapted to different device geometries and variable requirements concerning accuracy of image analysis by a graphical front-end, so that swapping from one type of device to another happens quickly. Wafer handling and image processing are coupled via standard computer communication means so that the entire testing can be carried out unsupervised. Results are stored in wafer maps which can be directly used for wafer inking. The usability of the system for production purposes has been verified using micro scanning mirrors fabricated at Fraunhofer IPMS in large volume.

7592-21, Session 4

Low-cost system for testing MEMS for research and educational applications

T. E. Dallas, G. G. Ramirez, G. Sivakumar, S. Lacouture, Texas Tech Univ. (United States)

General access to MEMS is hampered by the expense of probe stations. We report on the construction of a low-cost system for utilizing MEMS devices for research and educational purposes. The system includes a driver-board, packaged MEMS chip, and LabView virtual instruments. The overall system is designed around MEMS arrays fabricated using Sandia National Laboratories’ SUMMiT V surface micromachining MEMS process. Typically, 20-40 separate devices are fabricated within the standard SUMMiT chip footprint (6.3 mm x 2.8 mm). These devices include electrothermal and electrostatic actuators, micromirrors, and micro-positioners. The chip is electrically packaged in a 48 pin DIP with a sealed or removable glass window. The chip plugs into a ZIF socket on the driver-board. The current board utilizes eight analog supplies that can be used to drive single or multiple devices simultaneously. The board is controlled through various device specific LabView virtual instrument panels and also displays still and video images generated using a digital microscope and camera. National Instruments’ Vision software is used to analyze the images from the digital microscope to quantify displacements and other device parameters. Experiments ranging from basic tests (displacement versus voltage) to longer and more complex lifetime studies can be readily carried out. Data files are generated in standard formats (Excel, .dat), readily allowing further analysis. Educators can use the system to carry out labs for a variety of education levels. Researchers can use the system for prototyping new devices, developing better models for computer simulations, and utilizing devices for new applications.

7592-22, Session 5

Engineered carbon nanotube and graphene for nanoelectronics, sensors, and actuator systems

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Invited paper: Next generation electronics will significantly increase the capabilities of high-throughput information systems, while simultaneously decreasing their size, weight, cost, and assembly complexity. The outstanding electrical properties of both carbon nanotubes (CNTs) [1] and graphene [2] make them exceptional candidates for the development of novel devices with orders-of-magnitude increases in functionality and efficiency in comparison to the current state-of-the-art. However, despite the promise of vastly superior performance of CNT and graphene-based devices, several fundamental issues in the fabrication and characterization of such devices need to be researched and resolved to realize their full potential. In this regard we are investigating nanodevices based on CNT and graphene nanostructures aimed at developing nanoelectronic devices, nanoactuator systems and nanosensors for cross-disciplinary applications.

For example, for nanoelectronics applications we are pursuing nano-segmented, in-plane CNT structures and investigating their quantized electron energy properties. Here in-plane CNTs are formed via chemical vapor deposition between catalyst patterns and subsequently segmented using a voltage-applied AFM process [3] to form CNT-based quantum dots (QDs). During the segmentation process an AFM tip is used to apply a negative voltage (on the order of 5 volts) to create defects at specified locations along the MWNT. Whereas other researcher are also pursuing the development of CNT-based QDs [4], our fabrication technique is directly compatible with forming arrays of these CNT-QDs, which will enable single electron memory states with high electron charging energies stable up to room temperature, which are critical for future high-speed, ultra-low power electronics and highly sensitive nanosensor applications.

In other work, we are investigating the field emission properties of graphene nanostructures for vacuum electronics applications. Graphene is a two-dimensional honeycomb-structured single crystal showing ballistic transport, zero band gap and electric spin transport characteristics. To measure field emission from graphene, graphene sheets were prepared by mechanical exfoliation and placed on an insulation layer, with the resulting field emission behavior investigated using a Zyvex Nanomanipulator operating inside an SEM. We are currently investigating the field emission properties for different numbers of graphene layers and the directions of the atomic crystal. A triode with a gate electrode will be further studied.

Lastly, a nanoscale actuator or an array of such actuators can be used for many potential applications; for example, to investigate how external forces applied to a cell membrane affects mechanisms such as inter-cell signaling, cell growth, and cell adhesion. For such studies it is important be able to produce a large number of such actuators with repeatable and controllable nanoactuator properties and performance. As an early stage of this project, we have fabricated thermal bimorph nanoactuators based on MWNTs coated with a thin metal film on one side using pulsed laser deposition (PLD) [5]. Thermal actuation and characterization of the resulting nanoactuators was conducted using a temperature stage operating within an SEM. As the temperature was increased from 300K to 550K, the measured displacement of the nanoactuators was 500 ± 100 nm. Using Lateral Force Microscopy (LFM), the forces generated from the tip were found to be on the order of microNewtons. To extend this work we are currently seeking to develop vertical nanoactuator arrays with various actuation modes.

In summary, we are pursuing the fabrication, assembly and manipulation of carbon nanotube and graphene nanostructures for nanosensors/actuators and nanoelectronics device applications. Overcoming the technical challenges of working with these materials will enable one to leverage their outstanding electrical properties in the development of next-generation devices with unrivaled functionality for use in applications such as sensors, detectors, system-on-a-chip, system-in-a-package, programmable logic controls, energy storage systems and future electronic systems.

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7592-23, Session 5

Optimal design of SAW-based gyroscope to improve the sensitivity

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In this paper, we present a novel MEMS-IDT surface acoustic wave (SAW) gyroscope with an 80 MHz central frequency on a 128o YX LiNbO3 wafer. The developed MEMS-IDT gyroscope is composed of a two-port SAW resonator, a dual delay line oscillator, and metallic dots. The SAW resonator provides a stable standing wave, and the vibrating metallic dot at an antinode of the standing wave induces the second SAW in the normal direction of its vibrating axis. The dual delay line oscillator detects the Coriolis force by comparing the resonant frequencies between two oscillators through the interference effect. The coupling of mode (COM) modeling was used to extract the optimal design parameters prior to fabrication. In the electrical testing by the network analyzer, the fabricated SAW resonator and delay lines showed low insertion loss and resonance frequency matching between a resonator and delay lines. When the device was rotated, the resonant frequency differences between two oscillators linearly varied owing to the Coriolis force. As the rotation speed increases, the frequency difference also increased. The obtained sensitivity were approximately 55.5 kHz deg-1 s-1 in the angular rate range of 0~300 deg/s. The measured sensitivity is ~100 times larger than other reported SAW gyroscope with similar configuration. The cross-sensitivity test was carried out by rotating the PCB around y-axis and z-axis. Very small frequency deviations about the y- and z-axis rotation were observed. Superior single sensing directivity about x-axis was observed.

7592-24, Session 5

Temperature measurement on MOEMS micromirror plates under illumination

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The Fraunhofer Institute for Photonic Microsystems (IPMS) develops and fabricates MOEMS micromirror arrays for a variety of applications in image generation, wavefront correction and pulse shaping. In an effort to extent the application range, mirrors are being developed that can withstand higher light intensities.

The absorbed part of the light generates heat. Due to being suspended on thin hinges, and isolated from the bulk by an air gap, the mirrors heat up. Their temperature can be significantly higher than that of their substrate.

In this paper we describe an experiment carried out to verify simulations on the temperature within the mirror plates during irradiation. We created a structure out of electrically connected mirror plates forming a four-point electrical resistor. The mirror plates were connected only in the mirror

layer, so that the temperature-dependent resistance change reflects only the temperature of the mirrors. We calibrated the thermal coefficient of the resistor in a temperature chamber. Then, we irradiated the area of the resistor and calculated the true mirror temperature.

In the experiment, the temperature in the mirror plates increased by up to 180 °C, which agrees very well with our simulations. The mirrors did not show significant damage despite the high temperatures. Also, the experiment confirms the choice of heat transport mechanisms used in the simulations, namely conduction along the hinges and across the air gap. The experiment was done on 48µm x 48µm mirrors suspended over a 5µm air gap, using a 355nm solid-state laser (4W, up to 500W/cm²).

7592-25, Session 5

Development and testing of a multi-level chevron actuator-based positioning system

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This paper presents the design, fabrication, and testing of a micro-scale positioning system. The SUMMiT V processed design allows in-plane, bi-directional, linear motion of a shuttle using a counter ratcheting mechanism and chevron actuators. The design is intended to reduce the footprint and number of electrical connections needed, compared to similar devices. In this work, a single latching system with oppositely faced ratchet teeth on either side of the shuttle is used for achieving the actuation. The actuators were modeled using finite-element analysis software (ANSYS) using a coupled structural-thermal model. The fabricated device consists of shuttle and ratchet pawls on the Poly2 layer, an actuator on the Poly4 layer that holds the pawls and is responsible for movement of the shuttle, and two actuators at the Poly3 layer on either side of the shuttle for engaging/disengaging the pawls from the shuttle teeth. The pawls are coupled to the side actuators using a pin like structure using Poly3, Dimple1, interlocking the pawls. The forward motion of the shuttle is attained by powering the drive actuator, engaging the pawls on the right and disengaging the pawls on left, whereas for backward motion the reverse is done. The system was tested using a custom built optical characterization setup at a driving frequency ranging from 5 to 25 Hz. A success rate of ~70% was observed for the ~9µm long steps. Possible applications for this system are micro-positioning, biological cell probing or any other system requiring mechanical power and micro-scale displacement in discrete steps.

7592-26, Session 5

Development of a microlens array (MLA) for maskless photolithography application

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Most of the reported MLAs based on polymer materials require complicating fabrication process and expensive equipments, and are unstable in a harsh environment. In this work, we suggest simple and inexpensive fabrication of a quartz-based MLA using wet etching method. The negative hemispheres were patterned on a quartz substrate by a lithographic process. The substrate was isotropically wet etched by using BOE (buffered oxide etch), and then UV adhesive was coated on the substrate. The formed curvature and difference of refractive index between quartz (1.47) and UV adhesive (1.58) induced focusing of light. The measured spot size of the MLA was ~1.5µm. Depending on the etching time and the thickness of UV adhesive, the focal length was changed. When the etching time was 85min and 95min and spin speed of UV adhesive was 1200rpm, the focal length of the MLA was 85.6µm and 105.6µm, respectively. The focal length was linearly increased with increase of spin speed (it means decreasing the thickness of UV adhesive). The developed MLA was applied to photolithography process in order to produce arrays of micropatterns on photoresist. The fabricated patterns on photoresist were very uniform and excellent UV focusing was demonstrated. Its testing results were well matched with simulation results. Depending on the distance between MLA and photoresist, various spot sizes were formed. The MLA was placed into oven over 1 week for aging test. The patterns were almost same as patterns from untreated MLA.

7592-27, Session 5

A 2-DOF MEMS positioning system

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We report on the design, fabrication, and testing of a 2 degree of freedom MEMS positioning system. Sandia National Laboratories' MEMS foundry process was utilized for the fabrication of the device; this process incorporates five layers of polysilicon and four sacrificial layers of silicon dioxide. The actuation was achieved by identical comb-drives on both axes. The comb drives produce a displacement of ~ 4 µm which was amplified to ~ 30 µm by the use of a distance multiplier. A pin and track arrangement in the X and Y arms, extending from the actuator assembly, allows bi-axis motion. The stage is connected to the central pin. For testing the performance of the fabricated design a custom made optical characterization setup was assembled. To provide the actuation signals to the stage, a Keithley 2400 source meter was programmed using LabView to provide actuation voltages from 0-100 V at a 2 volt step. An optical microscope, interfaced with a Canon S5 IS digital camera, was used to record the actuation events for the measurement of in-plane displacement. Displacement at the various actuation voltages was obtained using a National Instruments' Vision image analysis software routine. The device has been tested and demonstrates a useful design for realizing a bi-directional 2-D positioning system. The positioning system is capable of 0 - 30 µm of motion in both the X and Y axes, with displacement showing a quadratic relationship with the applied voltage.

7592-28, Session 5

The influence of the arrangement and spacing of CNT column array on the characteristic of field emission

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Carbon nanotubes(CNTs) are known to have excellent field emission properties because of the structure with a high aspect ratio. But it is likely that CNTs having a form of films are not as efficient as desired because of the field screening effect due to the peripheral CNTs.

To overcome the problem, we used VACNT column array having different spacing and arrangement. In the electric field simulation using FEMLAB-based three-dimensional simulations, the cathode was modeled as an array of cylindrical conductors on a conducting substrate with two different types of the VACNT-column array having three different pitch-to-height ratios.

The simulation showed that arrangement of VACNT columns affects the electric field distribution at the surface of the cathodes. The degree of the field screening and the variation in the electric field strength at the cathode surfaces depended on the number of neighboring CNT columns and pitch-to-height ratios. The strongest field occurred at the corner of each VACNT columns like U-shape and outer VACNT columns experienced a stronger electric field compared to the inner columns.

We fabricated VACNT column array using the hot-filament chemical vapor deposition(HFCVD). We measured the field emission characteristic of the VACNT column array cathodes. In the case of triangular VACNT column array with the pitch-to-height ratio of 1, the threshold field and emission current are about 1.3V/ and 2.8 / , respectively. This type has the lowest threshold voltage and higher emission current in comparison with other types. We verified that the tendency of measurement results was consistent with the electric field simulation.

7592-29, Session 5

Self-aligned mask less process for etching cavities in SOI wafers to enhance the quality factor of MEMS resonators

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We present a low cost, self-aligned, process to etch cavities under movable structures, in commercially available SOI wafers. The cavity is formed by electrochemically etching the substrate through the openings in the structural wafer. The process works on devices fabricated with standard DRIE process. First, the buried oxide layer is removed with concentrated HF solution. Next, a 10-μm thick porous silicon layer is formed by electrochemical etching the structural wafer through the DRIE openings (10% HF solution, current density 3.0 mA/cm2 for 20 minutes). Finally, the sacrificial porous silicon layer is removed by a 40 second etch with room temperature KOH, leaving the 10-μm deep cavity under the movable structures. A tuning fork structure fabricated with above process has the resonant frequency of 247 kHz and the measured intrinsic was Q = 82,000 at 35 mTorr. Comparing the measured quality factor as function of pressure, for devices with and without the cavity, the device with cavity showed a consistent improvement in the quality factor by 2-3x except for very low pressures where the mechanical quality factor dominates. As the distance between the device and substrate is increased from 2 μm (of buried oxide thickness) to 10 μm (of electrochemically etched cavity), the parasitic capacitance to the substrate is reduced by 5x, along with reduction in air damping. The problem of stiction between the device and substrate is eliminated with the cavity. We find that with the 10-μm cavity, even long and slender structures never make a contact with the substrate.

7592-30, Session 6

Thermal actuator performance as a function of mechanical stress

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We will report on the effects of tensile mechanical stress on the performance of thermal microactuators. Packaging processes such as die attach and lid sealing usually result in the stresses on the die containing microsystems devices. While this phenomenon is known, quantifying the effects systematically is difficult due to challenges in controlling the resultant stress resulting from packaging. In this study, we are using a four-point bending stage capable of applying up to 12,500 MPa of tensile stress to 11.5 mm by 2.9 mm samples. Thermal microactuators and stress gauges were fabricated using the Sandia 5-layer SUMMiT surface micromaching process and diced to fit in the bending stage. Parts have been fabricated and testing is commencing. At each stress level, the vernier scales on the thermal microactuator and stress gauge are imaged in order to calculate the displacments. Thermal actuator displacements will be reported as a function of voltage at varying stress levels. The results will be compared to simulations of thermal microactuator displacement versus voltage. Modeling results predict a reduction in the thermal microactuator displacement when subject to tensile stresses. Quantitative information on the reduction in thermal microactuator performance as a function of stress will provide validation for MEMS models and guide future designs so that they will be more robust to stresses resulting from packaging processes.

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7592-31, Session 6

Mitigating the irreversible deformation with pressure in silicon / porous silicon composite membranes

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Porous Silicon (PS) has a low Young's Modulus which reduces with increasing porosity and hence deformation in Si/PS composite membranes is more than in silicon membranes. We have earlier reported the higher sensitivity obtained on pressure sensors with Si/PS composite membranes when compared to single crystalline silicon membranes. But the Si/PS composite membranes exhibit a smaller range of linear response with applied pressure than silicon membranes, with the deformation being irreversible once it saturates. The linear range is smaller for microPS as compared to macroPS. Even though Si pressure sensors show saturation in deformation at higher pressures, the effect is not irreversible. The irreversibility seen in composite membranes can be due to the adhesion (stiction) of the pore walls at high pressures. This will also explain the enhanced linear range in the case of macroPS with larger pore size. Self-assembled monolayers (SAMs) are well known in the field of MEMS and a monolayer on the PS membrane can reduce this stiction of pore walls, increasing the linear range. In this paper we discuss the effect of monolayer formation on the PS layer on the linear range of Si/PS composite membranes. The monolayer has been formed by immersing the samples in 5mM solution of 1-Octadecanethiol in ethanol for 24 hours. The deformations obtained on Si/macroPS composite membranes with porosity of 50% and 70% before and after the monolayer formation show an improvement in the linear range of operation. But the Si/microPS composite membranes collapsed after the formation of the SAM.

7592-32, Session 6

Experimental investigation into metamaterial structures operating at infrared wavelength

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Our investigation addresses the fabrication and testing of artificial structures, commonly called metamaterials. Metamaterials enable electromagnetic properties which do not naturally exist from basic structural symmetry. This investigation focuses on the modeling, fabrication and testing of metamaterials at infrared wavelengths. This research utilizes a foundry fabrication process called PolyMUMPs to construct the metamaterial array. The PolyMUMPS process is commonly used for MEMS devices and consists of three polysilicon and two oxide layers. An array of split ring resonators consisting of the polysilicon and silicon dioxide layers was constructed. The split ring resonators are an important aspect to the metamaterial because it allows us to take advantage of structural properties such as scaling, resonant frequency response, and magnetic flux. The metamaterial structure obtains it symmetry from the etching process used to isolate the individual patterns. This array is then tested using a Fourier Transform Infrared Spectrometer (FTIR) to obtain the transmission and reflectance data. This data is then compared to analytical and FEM models to identify key limitations of the "as-built" figure of merit (FOM) structures. The FOM is defined as the ratio of the real component to the imaginary component of the refractive index. By gaining a higher ratio to the FOM, this improves the overall performance of the metamaterial structure at the selected wavelength. Through the understanding obtained from the experimental and modeling data comparison, changes to key parameters which limit the FOM can lead to metamaterial array improvements and ultimately to better components suitable for infrared applications.

7592-34, Poster Session

Physical characterization and dissolution enhancement of Simvastatin by preparing solid dispersion with Gelucire 44/14

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INTRODUCTION:

Simvastatin, a HMG Coenzyme reductase inhibitor mainly used as a hypolipidemic agent. One of the major problems with this drug is, it poorly absorbed from the gastrointestinal (GI) tract because it is practically insoluble in water (0.003mg/ml) and according to the BCS classification simvastatin comes under class II (Low Solubility and High Permeability) thus, dissolution is a rate-limiting step for its absorption. Therefore, it is very important to introduce effective methods to enhance the dissolution rate of the drug, substantially leading to its bioavailability.

In the light of above fact, the present study has been undertaken with following objectives.

1. To improve the dissolution of simvastatin by preparing solid dispersion Gelucire 44/14

2. The Most promising batch was compare with simvastatin plain tablet and market tablet.

EXPERIMENTAL WORK:

Dissolution enhancement by preparing Solid dispersion: Gelucire 44/14 was used as carrier for preparing solid dispersion. Solid dispersions were prepared using fusion method in the ratio from 1:1 to 1:3 (Drug to Polymer).

In vitro dissolution of most promising batch was compared with simvastatin plain tablet and simvastatin market tablet. In vitro Dissolution performed in Phosphate buffer pH 7.0 containing 0.1% SLS at 50 RPM, 37+ 0.50C. Most promising batch was characterized by XRD, DSC, SEM and FT-IR study.

RESULT AND DISCUSSION: Tablet containing solid dispersion with gelucire 44/14 in the ratio of 1:3 (drug: polymer) exhibited fastest drug release (100 % drug release in 20 minute) that's why it considered as a most promising batch. At higher ratio of 1:4 (drug: polymer), compressibility problem started due to waxy nature of polymer used. The most promising batch was compare with simvastatin plain tablet and simvastatin market tablet for f1 (dissimilarity factor) and f2 (similarity factor) statistics. Value indicated there is a significant difference in dissolution profile of most promising batch with simvastatin plain tablet and simvastatin market tablet.

Physical Characterization:

(1) XRD Spectra

Comparison of XRD spectra indicated that reduction of peak height (50 %) and presence of background peak showed in most promising batch. It indicated crystallanity of simvastatin reduce which responsible for dissolution enhancement

(2) DSC thermogram

Simvastatin showed a melting endotherm at 138.230C. In thermogram of solid dispersion with Gelucire 44/14, a characteristics sharp endothermic peak of simvastatin in the range of 1300C - 1390C was absent. It indicated solubilisation of simvastatin in molted carrier or partial amorphization of simvastatin.

(3) SEM study

SEM revealed effective formation of solid dispersion of simvastatin with gelucire 44/14 because well defined difference in morphology of simvastatin and solid dispersion.

(4) FT-IR study

The main simvastatin absorption band at 3546, 1718, 1459, 1267, 870 cm-1 (attributed to the Free O-H stretching, Lactone C= O stretch, Methylene C-H symmetric bend, lactone C-O-C stretch, Trisubstituted olefienic wag respectively) were remain unchanged in prepared solid dispersion, it indicated there is no chemical interaction between simvastatin and Gelucire 44/14.

CONCLUSION: Solid dispersion is promising formulation strategy for dissolution enhancement of simvastatin. Prepared solid dispersion gave 3.49 times and 1.72 times faster dissolution as compared to simvastatin plain tablet & market tablet respectively. The mechanism behind such fast dissolution is gelucire 44/14 has surfactant property & reduced crystalline nature of simvastatin which improve dissolution.

7592-36, Poster Session

Performance and reliability assessment of a dielectric charging guard in MEMS optical switch systems

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Optical MEMS switching technology has attracted attention in managing data flow due to its compactness and robustness. It allows hundreds of optical channels to be switched by micro-mirrors with very low power consumption. The capabilities of switching signals independent of data rates, formats, wavelengths and protocols facilitate and secure many applications such as internet peering exchanges, undersea cables and data centers. All of these applications require a highly reliable and stable switching system.

Dielectric isolation has a huge impact on major failure modes of capacitive MEMS devices such as breakdown and charging. This issue becomes more challenging in electrostatic MEMS optical switches since they usually operate at relatively high voltages. The charges trapped in this dielectric layer could cause interference in the electric field, resulting in erratic responses of the steering mirrors and instability of pointing accuracy over temperature and time, which greatly degrades the system performance.

Aiming at reducing charging and preventing high voltage breakdown, a dielectric charging guard has been developed by using an oxide "fence" with extended breakdown path length and shielded by conductive sidewalls of the silicon interposer. In this paper, the reliability tests as well as the performance impact to the optical switch will be presented, including characterizations of breakdown voltage, leakage current, and charging verses temperature. The test results demonstrate highly repeatable switching accuracy of micro-mirrors with very low drift at varied temperature. Failures induced by fabrication will also be discussed.

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7593-01, Session 1

SERS measurements in microfluidic devices: a promising way for online-monitoring of lowest agent concentrations

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The observation of agent concentrations is in a lot of areas such as medicine, process and environmental analysis of major importance. The aim of this research work is the development of an analytical tool with the potential to online-monitor concentration changes. For this purpose the combination of surface enhanced Raman spectroscopy and a microfluidic device seems to be a promising approach.

For the detection of lowest additive concentrations in aqueous systems surface enhanced Raman spectroscopy (SERS) is a suitable technique. SERS is a sensitive detection method down to even a single molecule level. It is capable for qualitative as well as quantitative analysis. To afford online-monitoring of different drugs like promethazine and mitoxantrone SERS was implemented into a microfluidic device. To guarantee the detection of reproducible SERS spectra a liquid/liquid segmented flow prevents depositions at the channel walls. A problem concerning quantitative analysis is the SERS activity which depends on the properties of the used nanoparticles. To avoid a daily calibration and compensate the influence of the colloid an internal standard is implemented.

In summary the great potential of surface enhanced Raman spectroscopy in combination with a microfluidic device for quantitative analysis will be shown.

7593-02, Session 1

Investigating fast enzyme-DNA kinetics using multidimensional fluorescence imaging and microfluidics

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To image fast kinetics we used a microfluidic device which exploits hydrodynamic focusing to achieve rapid mixing times. The device was simulated using computational fluid dynamic (CFD) techniques and the results were directly compared to experimental results obtained using fluorescence lifetime imaging (FLIM). Experimental images were obtained using a line-scanning FLIM microscope (Robinson et al, 2008). The mixing times of the device were found to be in excellent agreement over a range of flow rates.

The aim of the project is to understand the fast kinetics involved when uracil DNA glycosylase (UDG), binds to DNA and repairs a damaged base. Before the enzyme was introduced into the mixer, a labelled oligonucleotide was studied in a multidimensional spectrofluorometer to measure the changes in fluorescence when it binds to UDG. It was found that the fluorescence lifetime increased from 3.5 ns to 4.2 ns along with an increase in the polarisation anisotropy and rotational correlation time.

The CFD was used to simulate the mixing of UDG and the DNA strand within the device. This allowed us to predict the mixing time to be 46 µs, more 20 times faster than current stopped-flow techniques. Finally, we demonstrate that it is possible to extract fast transient kinetics from UDG within the micromixer using the signal changes observed from the multidimensional spectrofluorometer.

T Robinson et al, “Three-dimensional molecular mapping in a microfluidic mixing device using fluorescence lifetime imaging” Optics Letters, Vol. 33, Issue 16, pp. 1887-1889 (2008).

7593-03, Session 1

Optofluidic generation of color and shape encoded microparticle for multiplexed bioassay

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Precursor for synthesis multifunctional particle is composed of superparamagnetic CNCs, solvation liquid, and photocurable prepolymer. Under external magnetic field, CNCs form to chain-like structure along the magnetic field line in liquid phase, and diffracted color result from the periodicity of chain-like structure. Thus, diffracted color can be tuned through entire visible range simply by varying field intensity. Once desired diffracted color is obtained, corresponding chain-like ordered CNCs structures can be immobilized to the arbitrary morphology by solidifying the photocurable prepolymer through instantaneous exposure of UV whose illumination pattern can be modulated with digital micromirror device (DMD). By virtue of oxygen inhibition layer inside the PDMS channel, generated particles can move along the flow stream without being stuck to the channel walls. Using this property, color/shape coded particles can be produced under distinct levels of magnetic field intensity with multiple patterned UV light. Various color/shape encoded particles are demonstrated by this sequential color tuning and fixing process. Note that only a single material was used for the generation of various color/shape coded particles, which greatly simplifies manufacturing process.

Also, synthesized color/shape coded magnetic supraparticles show magnetic property so that magnetic separation from carrier liquid can be easily applicable via application of external magnetic field. Magnetic separation of produced encoded particle is completed within seconds from carrier fluid due to the large effective magnetization of the coded particle. By combining novel material system and special instrument enables generation of limitless number of codes and greatly simplify the manufacturing process of encoded particles, and allows magnetic separation from carrier fluid effectively. We believe that the novel material system with special instrumentation open a new door to the multiplexed biochemical assay platform.

7593-04, Session 1

Feasibility study of micro-optical diffusion sensor based on laser-induced dielectrophoresis

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A real-time monitoring of the diffusion coefficient using a micro sensing device is valuable for analyzing the dynamic change of protein-protein interactions and the protein conformation, such as the molecular size and the higher order structure. In the present study, we have developed a novel micro optical diffusion sensor (MODS) based on a laser induced dielectrophoresis (LIDEP) enabling small sample volume and high-speed measurement. This paper reports the measurement principle, chip design, and the validity of the proposed method. MODS consists of a pair of transparent electrodes and a photoconductive layer sealing the liquid sample. AC voltage is applied between transparent electrodes, and two excitation lasers are intersected on the photoconductive layer. The electrical conductivity distribution of the a-Si:H layer due to the photoconductive effect generates a non-uniform electric field followed

by the dielectrophoresis (DEP), and then the concentration distribution is induced by LIDEP force. After cutting the AC voltage, the mass diffusion is occurred, and the diffusion coefficient can be obtained by observing the one dimensional diffusion process along with the interference fringe pattern. In the preliminary measurement, the prototype of the DEP cell was fabricated by the micro electro mechanical systems (MEMS) technique in order to verify the applicability of MODS, and we confirmed the lattice-shaped concentration distribution of polystyrene beads in distilled water. The decay time of the diffusion of the concentration distribution agreed well with the theoretical calculation. As a result, the applicability of MODS as the diffusion coefficient measurement method was verified.

7593-05, Session 1

Two complementary tomographic techniques for micromixer characterization

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The micromixer is one of the common components in a micro total analysis system. Since mixing is hardly achieved in microchannels due to a low Reynolds number, periodic temporal and/or spatial perturbations are often applied to the micromixer to induce chaotic advection. Then, characterization of the micromixer becomes an important step but is not always easy due to two aspects: 1) the lack of visualization techniques that are able to show velocity field and lamella structure simultaneously with a high-resolution in a non-invasive and tomographic manner, and 2) the lack of computational methods that can catch precise interfaces between fluid streams overcoming numerical diffusion, even with a complex deformation of the interface and/or a long channel compared with the height or width. Spectral-domain Doppler optical coherence tomography (SDDOCT) and the colored particle tracking method (CPTM) are emerging tomographic technologies for micromixer characterization and show superior performance over conventional techniques. SDDOCT has high-speed, high-resolution, non-invasive, cross-sectional imaging capability that is able to discriminate layered lamella micro-structures in three-dimensional space and allows simultaneous real-time visualization of mixing pattern and flow. CPTM is a systematic numerical method to analyze any micromixer characterized by a periodic mixing protocol. CPTM consists of three steps: 1) obtaining a periodic velocity field by the Galerkin/least-square method, 2) tracking color-labelled particles using the velocity field, 3) quantifying mixing efficiency based on information entropy. We characterized two chaotic micromixers (Kenics micromixer and barrier-embedded Kenics micromixer) by quantifying mixing performance, velocity field, lamella structure, and Poincáre section.

7593-06, Session 1

Capillary electrophoresis in a femtosecond laser written 3-D optofluidic microsystem

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A high repetition rate (1 MHz) femtosecond (fs) laser (IMRA µJewel D-400-VR) with a wavelength of 522 nm was employed to integrate optical waveguide with wet-chemical etched laser patterned micro-channels in fused silica glass (Corning 7980) for a fully integrated three-dimensional (3D) optofluidic system for capillary electrophoresis fluorescence detection. Selective chemical etching of laser irradiated glass with diluted hydrofluoric acid (5% HF) enabled microfabrication of high aspect-ratio micro-channels permitting high density lab-on-a-chip integration of flow channels and optical sensing circuits. In this paper, we present optofluidic systems integrated with waveguides and embedded micro-channels, formed over any arbitrary length in a two-step process for capillary electrophoresis. Waveguides, reservoirs and micro-channels were first laser patterned and followed by selective wet etching of reservoirs and micro-channels. Multi-tracks were laser scanned with perpendicular polarization, producing nanogratings aligning parallel to scanning direction, to create two crossing rectangular shaped micro-channels with smooth side-wall surfaces and terminated with open reservoirs. An array of vertical access holes spaced 100 µm apart facilitate etching of continuous and highly uniform channels of unrestricted length. Short flow plugs of various analytes from the open reservoirs were electrically generated from crossed channels. Monolithically integrated waveguides were positioned to cross the micro-channels to guide excitation light for low-limit detection of fluorescent plugs formed from capillary electrophoresis. Fs-laser processing thus enables rapid patterning of fully integrated 3D optofluidic systems in bulk fused silica glasses for capillary electrophoresis, and more generally opens new 3D design approaches and rapid prototyping methodology for advanced cytometry microsystems.

7593-07, Session 1

Pressure mediated tunable elastomeric optofluidic devices

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We introduce a novel tuning mechanism based on pressure actuating force, which can enable a broad spectrum of tunable elastomeric optofluidic devices. Thanks to the flexibility of the Polydimethylsiloxane (PDMS) material, the local deformation inside PDMS chip can be generated by filling the compressed air/liquid into the embedded channels. Such tuning method turns out to be very simple for fabrication and control, also being compatible with microfluidic chips. To this end, we have demonstrated the pressure mediated tunable optofluidic laser, tunable in-plane liquid lens, tunable optofluidic gratings and microfluidic 2×2 optical switch.

7593-08, Session 2

A research factory for polymer microdevices: muFac

B. W. Anthony, D. E. Hardt, Massachusetts Institute of Technology (United States)

As part of our research on the manufacturing science of micron scale polymer-based devices, an automated production cell has been developed to explore its use in a volume manufacturing environment. This “micro-factory” allows the testing of models and hardware that have resulted from research on material characterization and simulation, tooling and equipment design and control, and process control and metrology. More importantly it has allowed us to identify the problems that exist between as well as within unit-processes. This paper details our efforts to produce basic micro-fluidic products in high volume at acceptable production rates and quality levels. The device chosen for our first product is a simple binary micromixer with 40x50 micron channel cross section manufactured by embossing of PMMA. The processes in the cell include laser cutting and drilling, hot embossing, thermal bonding and high-speed inspection of the components. Our goal is to create a “lights-out” factory that can make long production runs (e.g. an 8 hour shift) at high rates (Takt time of less than 3 minutes) with consistent quality. This contrasts with device foundries where prototypes in limited quantities but with high variety are the goal. Accordingly, rate and yield are dominant factors in this work, along with the need to precise and novel material handling strategies. Production data will be presented to include process run charts, sampled functional testing of the products and measure of the overall system throughput.

7593-09, Session 2

Hybrid tooling technologies for injection molded polymeric microfluidic devices

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In recent years, the growing demand for the commercial manufacturing of microfluidic devices has led to the adaptation of several industrial fabrication processes, namely injection molding for polymeric components. The crucial process step in this technology is the manufacturing of a suitable mold insert which contains the geometrical inverse of the desired structure. This mold insert has to cover a large dynamic range of structural elements, with typical outer dimensions of a microfluidic device in the range of up to 127 mm (SBS titerplate format) in length while containing microchannels with dimensions typically in the range of several 10 to 100 µm. Specific structures (e.g. obstacles to support mixing, cell or bead capture, passive valves) and the general tolerances are often one order of magnitude smaller (e.g. 1-10 µm), while structures influencing the surface properties (e.g. wetting) are in the submicron range. A single microfluidic device will incorporate structures in all these size ranges in all three spatial dimensions, which are generally not accessible with a single structuring technology. We therefore have utlilized a combination of several tooling technologies to generate mold inserts which cover this range of dimensions. Namely the combination of precision mechanical machining either with single point diamond turning (SPDT) or with inserts generated from electroplated photoresist structures (SU-8) has been investigated. Several devices e.g. for diagnostic applications molded in various thermoplastic polymers from such inserts will be presented.

7593-10, Session 2

LABONFOIL: Investigations regarding microfluidic skin patches for drug detection using flexible OLEDs

M. Scholles, L. Kroker, U. Vogel, Fraunhofer-Institut für Photonische Mikrosysteme (Germany); J. Krüger, Biosensia Ltd. (Ireland); R. Walczak, Wroclaw Univ. of Technology (Poland); J. Ruano, Ikerlan (Spain)

One of the goals of the LabOnFoil project, which includes 15 partners from 8 different European countries, is the development of a microfluidic solution for a low cost and point-of-care detection of Cocaine in sweat samples. The overall system design was influenced by analysis of end-user requirements. The skin patch consists of a polymer housing, which integrates hypoallergenic skin adhesive, an absorbent swab for sweat collection, a nitrocellulose membrane strip with a test and a control line for drug analyte detection. The determination of drug concentration is based on a competitive immuno assay approach, where the Cocaine analyte competes with a fluorescently labeled conjugate, which uses a fluorescence marker Dylight 649. The detection and processing of the fluorescent test and control line signals is done via an external read out device

The skin patch also uses integrated Organic Light Emitting Diodes (OLEDs) as a large area, flexible light source for on-chip fluorescence excitation. First optical tests have proven the feasibility of OLEDs for this application. The test and control lines are excited from underneath by the OLEDs whose spectral emission was adjusted by means of a 650 nm short-pass interference filter, which cuts off undesired wavelengths, while ensuring good spectral overlap with the maximum absorbance of the Dylight 649 fluorophores.A conventional CCD camera with a bandpass filter at 670nm has been placed above this configuration, Images produced by fluorescent scans showed that the system is sensitive enough to discriminate between zero, 15 ng/ml, 30 ng/ml and 60 ng/ml cocaine concentration.

7593-11, Session 2

Electrode patterning within a microfluidic channel utilizing an ion-implanted process

J. Choi, Ecole Polytechnique Federale de Lausanne (Switzerland) and California Institute of Technology (United States); S. Rosset, M. Niklaus, J. R. Adleman, H. R. Shea, D. Psaltis, Ecole Polytechnique Federale de Lausanne (Switzerland)

The application of electrical fields within a microfluidic channel has enabled many forms of manipulations necessary for lab-on-a-chip devices. Patterning these electrodes inside the microfluidic channel generally requires multi-step optical lithography. Here, we utilize an ion-implanted process to pattern electrodes within a fluidic channel made of a polydimethylsiloxane (PDMS) chip. Electrode structuring within the channel is achieved by ion implantation at an angle with a metal shadow mask. The advantages of three-dimensional structuring of electrodes within a fluidic channel over traditional planar electrode designs are discussed. Two possible applications of electrodes are alignment through electro-orientation and dielectrophoretic concentration. Asymmetric particles can be aligned in any of the three axial dimensions with electro-orientation. Colloidal focusing and concentration within a fluidic channel can be achieved through dielectorphoresis. Demonstrations are shown with E. coli, a rod shaped bacteria, and indicate the potential that ion-implanted microfluidic channels have for manipulations in the context of lab-on-a-chip devices.

7593-12, Session 2

Patterning of PMMA microfluidic parts using screen printing process

A. Ahari Kaleibar, M. Rahbar, A. M. Parameswaran, Simon Fraser Univ. (Canada)

The microfluidic devices are inevitable building blocks of biosensors that find lots of applications in biological assays detection and point-of-care diagnostic tools. Nonetheless, their fabrication process requires precise and expensive equipments, and highly trained technicians that make their mass manufacturing expensive and time consuming; therefore, developing rapid and inexpensive micro-fabrication process is in high demand.

This paper describes a novel micro-fabrication process that takes advantages of cheaper technologies such as silk screen printing and UV opaqueness of the printing-ink to directly expose fluidic channel patterns on Poly Methyl Meth Acrylate (PMMA) substrates. First, the microfluidic device design is created using a CAD program and a negative emulsion image is created. Using this emulsion a silk-screen is created through a local screen-printing shop. Using a squeegee the printing ink is applied on a PMMA substrate. The printing ink shows excellent UV-Opaqueness. After the ink has dried on the PMMA substrate the sample is exposed using deep-UV, =254nm. This process breaks the long chains of PMMA. Shorted PMMA can be easily dissolved using IPA-water mixture [1]. Interestingly enough, IPA also dissolves the ink; therefore, we need not employ a separate processing step to remove the ink. The development step, PMMA etching step as well as the ink removal step are combined into one single processing step.

We have fabricated a set of microchannels using this technique to verify the proof of concept. We are in the processing of characterizing this process systematically. Our presentation will outline the technique, limits of microfluidic channel width, the 254 nm exposure system and the functional performance of a microfluidic experimental system This novel PMMA microfluidic devices fabrication process will offer an ultra economical way of producing plastic microfluidic devices and systems for various analytical chemical experiments and clinical diagnostic systems.

Reference:

[1] M.Haiducu et al “Deep-UV patterning of commercial grade PMMA for low-cost, large-scale microfluidics” Journal of Micromechanics and Microengineering, 2008

7593-13, Session 2

Effect of surface treatments/coatings and soft bake on surface uniformity and adhesion of SU-8 on a glass substrate

S. M. Grist, M. Haq, J. N. Patel, B. L. Gray, B. Kaminska, Simon Fraser Univ. (Canada)

We present the effect of surface treatments/coatings and soft bake temperatures aimed at improving adhesion and surface uniformity of SU-8 on a glass substrate. While the adhesion strength of SU-8 to metal layers on glass and silicon has been previously investigated, our research examines the influence of additional surface treatments (RCA, Acetone/IPA rinse) and coatings (fresh/one-day-aged Ti, fresh/one-day-aged Cr, SU-8 2005®, OmniCoat®) on adhesion strength as well as surface uniformity for 100 µm thick SU-8 films. Additionally, we vary the soft bake time and temperature while keeping all other process parameters constant, to correlate adhesion strength with surface uniformity of SU-8 films for each surface modification.

We have found that for all surface treatments/coatings, a soft bake temperature of 65oC for a 90 minutes yielded a more uniform SU-8 film (= 4.97 µm) as compared to the traditional soft bake temperature of 95oC (= 12.57 µm) for 30 minutes. Consequently, a more uniform SU-8 film provided excellent adhesion strength (> 2 MPa, as determined by stress testing using an Instron® microtester) for both metallic seed layers while the adhesion strength of films baked at 95oC was determined to be < 0.5 MPa. Moreover, we discovered that OmniCoat® had an adverse effect on adhesion strength, with SU-8 films delaminating off of it during development and hard bake. This study, for the first time, has been able to quantitatively determine the adhesion strength of SU-8 films on different seed layers deposited on glass substrates, for varying soft bake temperatures.

7593-14, Session 3

From bioseparation to 'artificial micro-organs': microfluidic chip based particle manipulation techniques

M. Stelzle, Naturwissenschaftliches und Medizinisches Institut an der Univ. Tübingen (Germany)

Microfluidic device technology provides physical phenomena which are not available in the macroscopic world. They may be exploited towards a diverse array of applications in biotechnology and biomedicine ranging from bioseparation of particulate samples to the assembly of cells into structures that resemble the smallest functional units of an organ.

The talk will provide an overview of basic principles and the state of the art of such technology including electric, magnetic field effects as well as optical means to manipulate particles. Three applications employing dielectrophoretic forces for particle manipulation will be discussed in detail:

Firstly, a virus assay based on antibody-loaded microbeads will be presented. Beads are retrieved from a sample into a pico-liter sized aggregate located at a predefined position in the chip thus enabling highly sensitive fluorescence detection.

Secondly, subcellular fractionation of mitochondria from cell homogenate employing our microPrep system yields pure samples of mitochondria as was demonstrated by Western Blot and mass spectrometry analysis. Finally, a chip intended for the dielectrophoretic assembly of hepatocytes and endothelial cells into a structure resembling a liver sinusoid is presented. Such "Artificial Micro Organs" are envisioned as substance screening test systems and are expected to provide significantly higher precision with respect to the in vivo response towards a substance under test.

7593-15, Session 3

New device for in vivo study of the tumor microenvironment

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In-vivo cancer cells create a unique microenvironment which helps them to spread to other organs. To understand the tumor microenvironment, special tools and devices are required to monitor the interaction among different cell types as well as the effects of particular chemical gradients. We are reporting on the status of a new device (the NANIVID) that will collect chemotactic cells from the tumor environment. Due to the transparency of this implantable device, direct in-vivo cell imaging both inside and outside the device is possible. The cell collection chamber of the device consists of a micro-electrode system based on patterning of transparent, conducting films that delivers real time data cell density and dynamics. The current development and testing status of the device will be presented. This will include fluidic simulation results (benchmarked against experimental data) to predict and visualize the time development of the ligand gradient profile produced from the device. Further, a design run was completed for a series of electrode array configurations and cells were cultured on these arrays at selected degrees of confluence to measure the device sensitivity. The development path of the NANIVID will be integrated with an existing animal model protocol for in-vivo testing. This will result in a clearer understanding of the dynamics of a tumor's metastatic progression.

7593-17, Session 3

Gravity-assisted capillary flow of buffer with microbeads

P. R. Waghmare, S. Mitra, Univ. of Alberta (Canada)

In most of the Bio-MEMS applications, the cells are being transported by non-mechanical pumping in a microfluidic device. In such applications, microbeads are often used to mimic the cell transport. In the present study, theoretical and experimental investigation of gravity assisted capillary flow of fluid with microbeads is proposed. In the theoretical model, the capillary flow of a buffer fluid containing microbeads is presented. The reservoir containing the buffer is placed at the top of the capillary and an additional varying gravitational head is achieved by changing the orientation of the capillary. The non-dimensional governing equation in terms of entrance, viscous, gravity and inertia forces of capillary and reservoir is derived. Pressure field distribution at the entrance of capillary with an additional gravitational head and inertia of fluid in the reservoir is proposed. The numerical solution is achieved to depict the flow front movement in the capillary. The numerical and experimental studies are performed to explore the effects of several operating parameters. It is observed that, the vertical orientation provides an added advantage to capillary flow front. The dimensions of the capillary and the reservoir play a vital role in depicting the magnitude of gravitational, viscous and inertia forces. The volume fraction of the microbead present in the buffer solution also has important influence on the capillary flow. The model suggests that, the inertial effect of the reservoir of finite dimensions cannot be neglected and an added advantage of gravitational head has a significant role in the transport of fluid within the capillary.

7593-18, Session 3

Mesoscale to microscale manipulation using haptic interface and MEMS microgripper

T. E. Dallas, A. P. Vijayasai, Texas Tech Univ. (United States); A. Holness, Univ. of Maryland (United States); M. Mulsow, S. Lacouture, G. Sivakumar, Texas Tech Univ. (United States)

In this work, we describe the development and testing of a three degree of freedom (DOF) meso/micro manipulation system for handling micro-specimens. Three axis control is obtained using three stepper motors coupled to micromanipulator. One motor is coupled to a linear X-stage which holds the test specimen. The remaining two stepper motors are coupled to Y and Z axis micromanipulators. The stepper motor - micromanipulator arrangement has a step size of ~1.5µm with a total travel of 10mm and the stepper motor- X-stage arrangement has a size of 1.25±0.5µm. The shaft end of the micromanipulator has a commercially available electrostatic MEMS microgripper from Femtotools which has a gripping range of 0 - 100µm. As the gripping action is performed, the microgripper senses the gripping force and produces an output voltage (0-5V), which is sent to a commercially available 3 DOF haptic device (Novint Falcon), to give force feedback to the user. Both mesoscale and microscale control are important, as mesoscale control is required for the travel motion of the test object whereas microscale control is required for the gripping action. A LabView-based system is used to control the position of the microgripper, to control the opening of the microgripper, and to provide force feedback through the haptic. The positioning and manipulation of test specimens are observed using a CCD camera integrated with National Instruments IMAQ system.

7593-20, Session 4

Microfluidic diagnostics for low resource settings

B. H. Weigl, PATH (United States)

Diagnostics for Global Health, and specifically microfluidics-based low resource diagnostics, has become a very active research area over the last five years, thanks in part to new funding that became available from the Bill and Melinda Gates Foundation, the National Institutes of Health, and other sources. This has led to a number of interesting prototype devices that are now in advanced development or clinical validation. These devices include disposables and instruments that perform multiplexed PCR-based lab-on-a-chips for enteric, febrile, and vaginal diseases, as well as immunoassays for diseases such as malaria, HIV, and various sexually transmitted diseases. More recently, instrument-free diagnostic disposables based on isothermal nucleic acid amplification have been developed as well.

Regardless of platform, however, the search for truly low-cost manufacturing methods that would result in cost of goods per disposable of around US$1/unit at volume remains a big challenge.

This talk will give an overview over existing platform development efforts as well as present some original research in this area at PATH.

7593-21, Session 4

High-speed high-throughput microfluidic system for whole blood analysis

M. G. Grafton, M. D. Zordan, H. Chuang, P. Rajdev, P. P. Irazoqui, S. T. Wereley, Purdue Univ. (United States); A. L. Jones, R. Byrnes, P. W. Todd, Techshot, Inc. (United States); J. F. Leary, Purdue Univ. (United States)

Lab-on-a-chip systems allow for complex laboratory assays to be carried out on a single chip using less time, reagents, and manpower than traditional methods. There are many chips addressing PCR and other DNA assays, but few that address blood analysis at the single cell level. Blood contains massive amounts of information regarding overall health, including disease states as well as tissue function. Therefore blood analysis, particularly of the cellular component, is highly important in both medical and scientific fields. Traditionally blood samples require a vial of blood, then several processing steps to separate the various components, followed by the preparations for each specific assay to be performed. A lab-on-a-chip for both red and white blood cell analysis and sorting would be ideal. The microfluidic-based system we have developed requires a mere drop of blood to be introduced onto the chip. Once on chip, the blood is mixed with both fluorescent and magnetic labels. The lab-on-a-chip device then uses a syringe drive to push the cells through the chip, while a permanent magnet is positioned to pull the magnetically labeled white blood cells to a separate channel. The white blood cells are analyzed and counted, while a sampling of red blood cells is also counted. This device is capable of processing the information in a matter of minutes and displaying the cell count. This portable blood analysis device, with no moving parts, will be of use in space medicine and neonatal applications.

7593-22, Session 4

Integration of an ELISA assay for breast cancer analysis into disposable, microfluidic chips for automatic diagnostics

K. S. Drese, D. Latta, T. E. Hansen-Hagge, Institut für Mikrotechnik Mainz GmbH (Germany); A. Fragoso, Univ. Rovira i Virgili (Spain); M. Bertschi, S. Dasen, Ctr. Suisse d'Electronique et de Microtechnique SA (Switzerland); L. Cognolato, Olivetti I-Jet SpA (Italy); C. Gärtner, microfluidic ChipShop GmbH (Germany); C. K. O'Sullivan, Univ. Rovira i Virgili (Spain)

In the framework of the EU funded project SmartHEALTH, a series of devices are developed that will allow the early diagnosis of cancer, such as colon, breast and cervix cancer, and that will support the monitoring of the course of respective diseases. With the SmartHEALTH devices the entire analysis shall be automatically performed from the sample injection via marker preparation and analysis to the subsequent data interpretation. Independent from the position of the device, the result of the analysis shall be wirelessly transmitted to the physician in charge.

The presented chip is designed for the detection of protein tumour markers from blood serum by an electrochemical detection cell integrated into the chip. The chip lay-out comprises of fluid storage of all required reagents, manual intake of sample (blood serum) and reference molecules, and fluid transport to a detection zone with the help of a syringe pump. In the detection zone, the ELISA assay is performed on a 2-dimensional electrode array. 16 working electrodes are individually labelled with primary antibodies in a self assembled monolayer.

Mechanical interfaces between chip and instrument contain tappets to actuate disposable valves by stepper motors, light barriers to monitor the position of all fluids and a pogo-pin array that connect the chip-integrated electrodes with the potentiostat of the instrument.

The sensitivity of the electrochemical sensor has reached a limit of 5 ng/ml of protein which is sufficient for a wide range of markers that are not only restricted to breast cancer analysis. Ongoing development will expand and include all steps from sample preparation to detection and data handling.

7593-23, Session 4

Development of a lab-on-a-chip for detection of vitamin A and D

T. Hossain, S. Mitra, Univ. of Alberta (Canada)

It has been estimated that approximately, 1 billion people of the world are vitamin D deficient or insufficient. To improve public health and prevent vitamin D deficient related diseases a low-cost vitamin detection device

is needed. Up till now vitamin D is measured indirectly by detecting 25-hydroxyvitamin D and 1,25 -dihydroxyvitamin D since it has not been possible to measure Vitamin D directly due to its low concentration and short life. The available Vitamin detection techniques used in clinical application at present are also expensive and time consuming. Here, we report a low-cost microfluidic device for detection of Vitamin A and D. Detection of Vitamin A and Vitamin D in our device is executed either by direct fluorescence or through immunoassay based detection technique. Vitamin A is auto-fluorescence in the near UV but Vitamin D does not auto-fluoresce notably. Thus, to detect Vitamin D, we have immobilized Vitamin D to affinity region of microbeads and the active sites of Vitamin D are attached to Fluorescein isothiocyanate (FITC) that amplified the optical signal. Fluid flow operation in our devices is governed by gravitational and capillary effects and consequently gets rid of expensive micropumps and microvalves. The reported device is a few square centimeters in size and is capable of handling low fluid volumes down to a few microliters which help performing the detection process in few minutes.

7593-24, Session 5

Microfluidic cell separation: applications & challenges in tissue engineering

S. Murthy, Northeastern Univ. (United States)

In tissue engineering, the enrichment of a particular cell type typically precedes in vitro culture on scaffolds. Another separation challenge that has emerged recently in tissue engineering is the need to isolate stem or progenitor cells that are naturally present in certain tissue types and have the ability to differentiate into functional cells. In both contexts, the ability of microfluidic systems to handle small sample volumes and achieve highly selective separation presents an attractive alternative to traditional techniques such as pre-plating and cell straining. This presentation will describe applications of size- and adhesion-based separation in cardiac tissue engineering and the challenges associated with each approach. Size-based separation is utilized to enrich cardiac muscle cells (cardiomyocytes) prior to in vitro culturing on scaffolds and adhesion-based separation techniques can be applied to isolate rare cardiac progenitor cells. The objective of the size-based separation approach is to enrich cardiomyocytes from a heterogeneous suspension of digested tissue. Examples of our approaches will include designs based on sieves and deterministic displacement around obstacles. Adhesion-based separation is generally preferred when cell subpopulations of interest are of the same size and density as other cells in a heterogeneous suspension and requires knowledge of cell surface markers. As a step toward negative selection isolation of cardiac progenitor cells, we have developed a 3-stage system to systematically deplete a heterogeneous suspension of endothelial cells, smooth muscle cells, and fibroblasts. Using this 3-stage depletion system, we can demonstrate successful isolation of a fourth cell type.

7593-25, Session 5

Development and fabrication of a micro-chip based multiplex immunoassay

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Immunoassay is a technique that utilizes antibody and antigen complexes as a means of generating a measurable signal to detect various pathogenic agents. Multiplex immunoassay can be used to simultaneously detect several target agents in a single assay. Comparing to conventional immunoassay, microchip based immunoassay has several advantages. It consumes much smaller amount of expensive reagent, requires much shorter analysis time, and the resulting device can be made portable. Development of polymer microfabrication technology in recent years has made it possible to make inexpensive multilayer micro fluidic chips with complex geometry design and different integrated functional units. In this paper, we report a microchip based multiplex immunoassay fabricated with PDMS soft lithography. On chip pneumatic micro valves are integrated above the fluidic network layer. By controlling the valve, immune reaction reagents and buffer solutions can flow in the specified micro channels. Immune reaction happens at the intersection of antigen micro flow and antibody micro flow. In our design, flow network consists of a center micro flow channel and four shorter sideway micro channels which are perpendicular to the center channel. Another control layer with pneumatic valves is aligned on top of the flow network so that each channel has its own micro control valve. Valves for the sideway fluidic channels are closed first, so analyte sample with several target antigens can pass through the center flow channel without contaminating the sideway channels. After incubation and washing steps, valves on the center flow channel are closed and reagents with specific antibody pass through each side way flow channels. Immune reactions then occur at the channel intersections and four different antigens can be detected using one microchip immunoassay. Since PDMS is a highly hydrophobic material, its binding to various proteins is fast and strong. This is important for sensitive detection, but can also introduce strong non-specific binding and thus cause higher noise level. Because of this, blocking efficiencies of various blocking reagent were studied and optimized to effectively suppress the non-specific binding on PDMS surface.

7593-26, Session 5

Effectiveness of multiple pulses on degree of electroporation

B. I. Morshed, M. Shams, Carleton Univ. (Canada); T. Mussivand, Ottawa Heart Institute (Canada)

Background: Electroporation (EP) is the formation of reversible pores in cell membranes without rupturing the membrane using a high electric field (EF). EP is an important technique for various biomedical applications, such as drug delivery, gene transfection and therapeutic treatments. A biomedical-Microelectromechanical System (bioMEMS) device was developed to investigate this phenomenon.

Purpose: This paper presents theoretical analysis and experimental results of EP using single and multiple pulses.

Method: The bioMEMS device contained integrated electrodes inside microchannels. Stained cells were introduced inside the microchannels and excitation pulses were applied through the integrated electrodes. Sequences of images were captured using an integrated-camera on an optical microscope in the bright-field mode. Stained pixel data in the sequences of images were extracted through image processing.

Results: Decrease of stained pixels was observed when EF over 2 MV/m was developed. The normalized (wrt initial) stained pixel (NSP) data were compared for various excitation parameters. Higher degree of EP caused greater reduction of NSP. The degree of EP increased with increased pulse energy. Multiple pulses increased the degree of EP when increased energy was delivered, but reduced degree of EP when same amount of energy was delivered. For example, average NSP reduction for 1 pulse of 4 mJ was 13%, 10 pulses of 4 mJ was 32% and 1 pulse of 40 mJ was 52%. These experimental results validate corresponding theoretical analysis.

Conclusion: A single pulse delivering certain amount of energy was found to be more effective to induce EP compared to multiple pulses.

7593-27, Session 5

Sample to answer: a fully integrated nucleic acid identification system for bacteria monitoring

J. Kim, J. Elsnab, M. Johnson, B. K. Gale, The Univ. of Utah (United States)

A fully integrated microfluidic system was developed and incorporates

a multi-walled carbon nanotube(MWCNT) electrochemical(EC) sensor for the detection of bacteria. Sample metering, reagent metering and delivery, and nucleic acid extraction were performed using microchannels controlled using automated microvalves and pumps embedded inside the microfluidic system and a disposable microfluidic silica cartridge. The extracted sample was flown across the MWCNT-EC sensor (built on a silicon chip), which was embedded in a microfluidic cell. The 9-pad sensor was scanned before and after hybridization to measure the quantity of RNA bound to the array surface. A rapid and accurate nucleic acid assay was realized with automated volume metering, microfluidic sample preparation, and integrated nano-biosensors.

This microfluidic system was fabricated by casting PDMS on CNC machined micromolds. A silicone rubber sheet was bonded between the top and bottom castings to form the microvalves and pumps. Each microvalve and pump was sequentially controlled to extract the nucleic acid and deliver the sample to the sensor for EC detection.

Sample preparation, reagent and sample volume metering were accomplished using the microfluidic system to control the chemical reactions required for cell lysis and nucleic acid extraction. A nucleic acid extraction test was performed using E-coli bacteria(approximately 10^6 cells), and approximately 1.4µg of nucleic acid was extracted. Using the integrated microfluidic cell, three differential pulse voltammetry(DPV) scans were consecutively performed before and after hybridization. For the hybridized electrode, the first scan shows a higher current magnitude than the second and third scan due to irreversible guanine oxidation. With this integrated system, nucleic acid was extracted within 30 minutes and detects and identifies bacteria within 2 hours using an EC sensor, compared to several days for current tests. This µTAS system could potentially be used for point-of-care, environment assessment or food analysis.

7593-28, Session 5

A microfluidic platform for characterization of DNA-DNA interactions

M. Javanmard, Stanford Univ. (United States)

In our assay for anti-hCG detection, 10um polystyrene beads are coated with Anti-Rabbit IgG, which has a specific affinity to anti-hCG antibody. The beads are then placed in the test solution for 40 minutes and the target biomarkers are captured if present . The biosensor has anti-Rabbit IgG already immobilized on the surface of the channel. The beads are then injected into the micro-channel occluding the channel and increasing the resistance from the baseline value. They are allowed to come to rest for 1 minute. Beads that have captured the targeted biomarkers will attach to the receptors on the channel surface, forming a sandwich assay. We then flush the channel (50nl/min flow rate), removing unbound beads and reducing the channel's electrical resistance, which depends on the number of beads remaining. The number of attached beads is a function of the biomarker concentration. High concentration of biomarkers results in smaller resistance drop compared to low biomarker concentration. Thus, in addition to biomarker detection at low concentrations, this technique can also be used for biomarker quantification.

7593-29, Session 6

MEMS-based sensing and algorithm development for fall detection and gait analysis

T. E. Dallas, P. Gupta, G. G. Ramirez, D. Felty, D. Lie, R. Banister, A. Dentino, Texas Tech Univ. (United States)

Falls by the elderly are highly detrimental to health, frequently resulting in injury, high medical costs, and even death. Using a MEMS-based sensing system, algorithms are being developed for detecting falls and monitoring the gait of elderly and disabled persons. The wireless sensors, incorporated into planar shoe inserts as well as a waist mounted device, utilize Zigbee protocols. The insole contains four sensors to measure pressure applied by the foot. A MEMS based tri-axial accelerometer is embedded in the insert and a second one is utilized by the waist mounted device. The primary fall detection algorithm is derived from the waist accelerometer. The differential acceleration is calculated from samples received in 1.5s time intervals. This differential acceleration provides the quantification via an energy index. From this index one may ascertain different gait and identify fall events. Once a pre-determined index threshold is exceeded, the algorithm will classify an event as a fall or a stumble. The secondary algorithm is derived from the planar foot insert. The data received from the insert is correlated with the waist data to further classify gait/detect falls. This correlation provides an in-system check for false positives. The analysis consists of wavelet transforms conducted on the insert accelerometer data. The pressure data is used to underline discrepancies in the transforms. The range of the transform amplitude in the fourth iteration of a Daubechies-6 transform was found sufficient to detect and classify fall events. Other transforms were also found to determine different gait states.

7593-30, Session 6

Defect tolerance in microfluidic chambers for capacitive biosensors

G. H. Chapman, B. L. Gray, Simon Fraser Univ. (Canada); V. K. Jain, Univ. of South Florida (United States)

Biomedicial sensors combining microfluidic and electronics involve defect avoidance in both the electronic processing circuits and microfluidic areas. Inserting microchannels between capacitive plates enable the detection of biomaterials by the change in capacitance. Faults occur from blockages in the microfluidic channel, affecting both the flow and the capacitance. We investigate a fault tolerant Cathedral Chamber design, rather than parallel channels, which support the encapsulation while preventing single blockages from stopping fluid flow through the system. Two exposures at 2 different wavelengths are used: an I-line light source to define the channel pillars, while a non-collimated deep-UV (254 nm) light source provides a large energy dose to the top surface SU-8 producing a sealing membrane over the chamber. The dual wavelength method allows SU-8 to be used for the pillars and the encapsulation method is self-limiting avoiding the requirement for precise control over the exposure dose. Faults occur when foreign materials, or fluid bubbles get lodged in the paths blocking a channel.. We discuss the potential causes and effects of such blockages and simulate how the Cathedral Chamber design allows fluid to bypass significant number of blockages. Simulations show this significantly increases lifetime an n channel microfluidic system before full blockage occurs from n-1 for parallel walls, to a median of n(n-2) for the Cathedral Chamber. The impact of these time depended defects, particles or bubbles, on the capacitive measurement also requires fault tolerance in the measurement methods which is analyzed. In addition the capacitive measurement circuits them selves need redundancy.

7593-31, Session 6

Improving electrochemical immunoassay sensitivity via electrode architecture design and focused biomolecule deposition

R. H. Page, C. J. McNeil, Newcastle Univ. (United Kingdom)

The development of an integrated microsystem for the electrochemical measurement of specific antigens associated with coeliac disease (CD) will be discussed. CD is an autoimmune disorder. CD is caused by exposure of a susceptible individual to gluten, this triggers the immune system to produce autoantibodies that trigger an inflammatory response of small-bowel tissue. The primary antibody that is used as an analytical marker for the diagnosis of CD is anti-tissue transglutaminase (t-TG). Electrochemical detection of anti-tTG antibodies was performed via Impedance Spectroscopy (IS) in a low conductivity medium using a

standard sandwich immunoassay. Sample delivery was performed using a flow through microfluidic system. A labelled detection scheme based on the use of anti-human IgG-HRP conjugates and amionethyl carbazole enzyme substrate were performed. The catalytic reduction of this species generated an insoluble product that deposited on the sensor surface and induced an impedance increase of the system. To enhance the detection capabilities of the microsystem a number of differing electrode architectures were designed and simulated using ANSYS modelling. Direct detection of antigens using IS has also been attempted. By modifying interdigitated electrode (IDE) architecture to create areas of high electrical field in conjunction with site specific immunoassay deposition using 3-D biologically activated silane polymer, we have found that increased sensitivity can be attained. Results obtained by the differing IDE set-ups were compared to establish optimum IDE dimensions. It should be stressed that the assays proposed in this work are not exclusive and can be independently suited for a variety of biosensor formats and working conditions, for example we have developed an assay to detect humoral immunogenic responses to Infliximab.

7593-32, Session 6

Compact and fast read-out for wavelength-encoded biosensors

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Many new optical bio sensor concepts rely on the detection of small wavelength changes in response to changes of temperature, strain, adhesion of bio-particles, or change in the chemical environment. Special coatings can sensitize them to specifically bound molecules (e.g., biomarkers). Examples include Fiber Bragg Grating (FBG) sensors, laser cavity sensors, micro-sphere or micro-ring based sensors, surface plasmon resonance sensors as well as photonic crystal sensors. The major advantages of these sensors over electronic sensors are their sensitivity and the possibility of remote and distributed sensing, making them suitable for harsh environments and immune to electromagnetic interferences. However, commercially available interrogation systems that are capable of resolving the small wavelength shifts (sub pm to few nm) produced by these sensors are bulky and expensive.

We will describe a compact and fast wavelength monitor that can resolve sub-pm wavelength changes. It combines a photosensor array or position detector element with a linear variable filter that converts the wavelength information of the incident light into a spatial intensity distribution on the detector. Differential read-out of two adjacent elements of the photosensor array or the position detector is used to determine the centroid of this distribution. A wavelength change of the incident light is detected as a shift of the centroid of the distribution. The wavelength monitor can be used as read-out unit for any optical sensor that produces a wavelength shift in response to a stimulus. The wavelength interrogation unit has been applied to measure temperature and strain with FBG sensors. We could clearly monitor 5 kHz vibrations with amplitude as small as 1 micro strain.

7593-16, Poster Session

Microfluidic sorting system based on optical force switching

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In the field of optical micromanipulation, the ability not solely to trap but to separate or sort micro particles and cells is attracting more attention recently. We report a novel, versatile, and automatic method for sorting cells and particles in a three dimensional PDMS structure consisting of two cross-microchannels. As the microspheres or yeast cells are fed continuously into a lower channel, a line shaped focused laser beam is applied (perpendicular to the direction of flow) at the crossing junction of the two channels. The scattering force of the laser beam was employed to push microparticles matching specific criteria upwards from one channel to another. The force depends on the intrinsic properties of the particles such as their refractive index and size, as well as the laser power and the fluid flowing speed. The combination of these parameters gives a tunable selection criteria for the effective and efficient sorting of the particles. The introduction of the cylindrical lens into the optical train allows simultaneous manipulation of multiple particles which has significantly increased the efficiency and throughput of the sorting. A high aspect ratio microchannel (A.R.=1.6) was found to enhance the sorting performance of the device. By careful control of the microparticle flow rate, near 100% sorting efficiency was achieved. The proposed system provides a simple, low-cost, high-performance solution to isolate, separate or sort a wide variety of suspensions of microscale biological or colloidal particles within a microfluidic system.

7593-39, Poster Session

Properties of conductive micromoldable thermosetting polymer for electronic routing in highly flexible microfluidic systems

A. Khosla, B. L. Gray, Simon Fraser Univ. (Canada)

Integration of conductive tracks in bulk elastomers is important for signal routing, interfacing to signal processing electronics, and to power active devices in elastomer-based microfluidic systems. However, it is difficult to integrate conducting lines on elastomers because of weak adhesion between elastomeric materials and metals/other conducting polymers. We present the preparation, characterization, electrical properties, and micropatterning of a highly flexible and electrically conducting extrinsically conducting nanocomposite polymer prepared by ultrasonic agitation of 80-500 nm silver in PDMS and CLEVIOS . Electrical conductivity of extrinsically conducting polymers depends upon many factors including filler composition. At low filler concentrations particles are separated and conductivity is low. As filler content is increased, a percolation threshold appears and conductivity rises sharply over several orders of magnitude. We have characterized and compared the resistivity of our polymer films as a function of different weight percentages of silver nanoparticles (ranging from 10 to 50nm) and demonstrated a percolation threshold of 32.5 weight percent. The resistivity level achieved is 2.3 x 10-5 Ohm-cm which is better than bulk carbon, yet the material has excellent flexibility unlike other conducting polymers. We also demonstrate microfabrication of our conducting nanocomposite through soft lithography with an example flexible printed circuit board (minimum feature size of 100±10μm, with a height of approximately 200μm). Such flexible microelectronic routing embedded in undoped (insulating) polymer is crucial to further development of elastomer-based microfluidic systems, especially those that must be made highly flexible to be implanted, worn, packaged for curved surfaces, or feature chip-to-chip electronic interconnect.

7593-40, Poster Session

Analysis on the effect of geometrical design parameters on maximum shear stresses in an electromagnetic micropump

A. T. Al-Halhouli, Technische Univ. Braunschweig (Germany)

This work presents analytical and numerical investigations on the effect of circular channel geometrical parameters on shear stress distribution in a newly introduced gentle electromagnetic micropump. The proposed design depends on controlling the rotation of two hard magnets placed in an annular channel in opposing polarity under the influence of a moving electromagnetic field. This magnetic field is produced in a set of coils placed along the annular channel by switching and modulating current flow. This new concept aims at pumping biomedical fluids carrying particles sensitive to shear stresses. The novel design was tested successfully on a mesoscale model and showed attractive concept

suitable for microfluidic applications.

For design purposes, the analytical expression in non-dimensional shear stresses is presented to estimate for a wide range of geometrical parameters at different flow conditions. These expressions enable optimizing compact devices and avoiding geometrical dimensions in which particles damage may occur under simultaneous impose to shear stresses.

The influence of channel aspect ratio (channel width, w, to height, h) on the shear stress in slightly curved microchannels is studied by using the unfolding approximation of the curved microchannels into straight channels under Dean's approximation, and the Navier-Stokes equations is solved at the imposed boundary conditions. The influence of channel radius ratio (inner to outer) is derived for the flow in circular microchannels using Navier-Stokes equations in cylindrical coordinates at high channel aspect ratios. The analytical solution showed good agreement with the numerical simulations with an error less than 15% for radius ratio greater than 0.2.

7593-41, Poster Session

A microfludics and microsensor development environment

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The trend towards creation of microfludic and microsensor on traditional CMOS processes from traditional foundry suppliers is growing. A development environment consisting of a standard pad frame and package, common characterization device patterns, a structured test methodology, and a simulation tool flow that supports the electrical design, postprocessing TCAD, and physics of the sensor element. The tools, while from multiple vendors, are connected into a flow through scripting and standardized file formats.

The use of this development environment has been tested and used for several designs that resulted in functional first silicon of the integrated sensor, with custom IP and process development, from concept to testable prototypes in under 12 weeks. These designs included a specialty deposited film sensor and a microfluidics sensor. This paper will outline the environment and detail some of the key aspects.

7593-42, Poster Session

Fabrication of integrated polymer permanent micromagnets for microfluidic systems

A. Khosla, B. L. Gray, D. B. Leznoff, Simon Fraser Univ. (Canada); J. Herchenroeder, Magnequench International, Inc. (United States); D. Miller, Magnequench International Inc. (United States)

Magnetic microactuation can generate high forces over comparatively long working distances, which is attractive for, among other things, manipulation of fluids in micro total analysis systems that require actuation to facilitate fluid transport and mixing. In this paper we present fabrication of permanent micromagnets which are capable of generating large bi-directional forces with long working lengths. They have the advantages that they can be actuated with external fields, operate in a variety of contaminated or dirty environments, generate large forces over large distances, provide 'latching' action, can be micromolded into complex shapes, and can be remotely actuated. One obstacle to widespread use of micro magnetic actuation is the inclusion or permanent magnetic materials in micro systems that are polymer-based. We present permanent micromagnets developed at Micro-Instrumentation Lab (Simon Fraser University, Canada) by ultrasonically dispersing MQP- Spowder (manufactured by Magnequench International Inc) in a polymer matrix. This powder is composed of spherical particles which have a typical median size of 50 µm. It has a remanent induction (Br) of 0.75 T , a theoretical density of 7.43 g/cm3 and an apparent density of 4.2 g/cm. It is an NdFeB based isotropic powder manufactured by Magnequench Inc. The polymer matrix is PDMS (Sylgard 184). The volume fraction of Spowder in PDMS is 52%V/V. The resulting composite was successfully micromolded against an SU-8 master in a similar way like that of undoped PDMS. The fabricated micromagnets were magnetized with an electromagnetic charger and tested using a Tesla meter and found to have a magnetic field intensity of 0.5mT at the surface of the magnet.

7593-43, Poster Session

PDMS surface modification in the application of waveguide claddings for evanescent field sensing

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In this paper we treat poly(dimethyl siloxane) PDMS thin films with low frequency 40 kHz oxygen plasma to make the surface more hydrophilic. Surface wettability and topography are studied before and after oxygen plasma treatment of varying discharge power and exposure time. Comparing to conventional RF plasma treatment of 13.56 MHz, low frequency plasma provides better uniformity on the surface without overheating PDMS layers. In evanescent field sensing higher sensitivity is obtained by generating stronger penetrating power above the waveguide into the analyte. It can be achieved by reducing the refractive index of the substrate. Comparing to glass substrates which have refractive index of 1.5, PDMS has the refractive index of 1.42 at 633 nm which serves as a good lower cladding material for high sensitivity sensing with evanescent field or claddings in multilayer waveguide applications. In this work we develop a thin film planar waveguide with SU-8 spin coated on the post-treated hydrophilic PDMS lower cladding. The feasibility of the polymer planer waveguide with PDMS lower cladding is also examined by light propagation in the waveguide with prism coupler.

7593-45, Poster Session

Sample preconditioning to enable downstream electrokinetic manipulations

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Sample preconditioning is a critical step for rapid diagnostic tools that involve the detection of biomarkers from complex biological samples. In order for detection to occur, target markers are usually isolated from their sample of origin by means of sample preparation. However, raw samples are not optimized for certain sample preparation processes, such as electrophoresis and dielectrophoresis. In order to address these concerns, a raw sample preconditioning microfluidic chip has been fabricated that can demonstrate selective tuning of key parameters of blood serum in order to enable effective electrokinetic manipulations.

These parameters include pH and conductivity as well as viscosity. Using previous literature related to capillary electrophoresis [1][2][3], a bench-scale pretreatment protocol was developed to tune these parameters to an optimal range. A PDMS device based on a previous active micromixer design [4] was fabricated and used to combine raw sample with specific buffer solutions. Off-chip electrodes were used to induce electroosmotic micromixing in the mixing chamber. Computer-based modeling using COMSOL was used to predict and quantify the amount of mixing occurring in the device which was later compared to the experimental results.

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7593-33, Session 7

Multiplexed Dip Pen Nanolithography® patterning by simple desktop nanolithography platform

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Multiplexed patterning in the micro-scale has been required in order to accomplish functional bio-materials templating on the subcellular length scale. Multiplexed bio-material patterns can be used in several fields: high sensitivity DNA/protein chip development, cell adhesion/differentiation studies, and biological sensor applications. Especially, two or more materials' pattering in subcellular length scale is highly demanding to develop a multi-functional and high-integrated chip device. The multiplexing patterning of two or more materials is challenging because of a difficulty in alignment and a precision of pattering. In this work, we demonstrate that multiplexed dip pen nanolithography® (DPN®) patterning up to four different material inks using recently developed new generation nanolithography platform (NLP 2000TM, NanoInk Inc.). This lithography platform is capable of patterning 12 separate materials within micrometer areas by efficient use of the available MEMs accessories. This number can be scaled up further with development of new accessories. Ink materials were prepared by adding different colored fluorescent dyes to matrix carrier materials, such as poly(ethylene glycol) (PEG) and lipid material (1,2-dioleoyl-sn-glycero-3-phosphocholine, DOPC). Finally, a dot array of four different inks multiplexing pattern was obtained in 50 x 50 μm^2 area.

7593-34, Session 7

Creating well-defined molecular and colloidal assemblies with scanning probe techniques

J. D. Batteas, Texas A&M Univ. (United States)

Scanning probe lithography has been employed to direct the assembly of molecules in confined geometries to explore how spatial confinement influences the assembly of molecules on surfaces in nanoscopic junctions for potential device applications. The influence of local environment, molecular packing density on the types of structures that can be formed will be described. Approaches for creating molecular and colloidal assemblies for electronic and plasmonic devices will be described. In particular, the influence of ligand interactions and local solvent environment for the creating of hierarchical assemblies will be discussed, whereby control of intermolecular forces may be employed to create 3D architectures. Methods for the controlled assembly of metallic nanostructures will also be discussed with an eye toward creating hot optical junctions for SERS and TERS measurements.

7593-35, Session 7

Biomimetic nanolithography and its application for biosensor chip fabrication

H. Matsui, Hunter College (United States)

Various nano-structures and complex patterns have been fabricated by top-down or bottom-up approaches, which have own strength and weakness. Here we combined the top-down and the bottom-up fabrications to take advantages on both strengths. We demonstrated that two different ways of the top-down/bottom-up combination could be very effective for the future nano-fabrications. One way is to assemble nanometer-sized building blocks into the device configurations such as electronics and sensor. Our strategy is to use those functionalized peptide nanowires, which can recognize and selectively bind a well-defined region on antigen-patterned substrates, as building blocks to assemble nanoscale architectures at uniquely defined positions, patterned by AFM-based nanolithography. The second method of the top-down/bottom-up combination is to pattern mineralization peptides with nanolithography and grow metals along the peptide lines. For example, when an Au-mineralizing peptide was written in the line-array, the biomineralization yielded monodisperse Au-NPs along the peptide lines. We were also succeeded to grow and pattern semiconductors at room temperature as precursors were patterned with dip-pen nanolithography. This crystallization was induced by energy gain from the shape change caused by DPN. Then, the peptide nanotube-based pathogen sensor chips will be introduced as another example of peptide nanotube device. Here the peptide nanotubes coated by the antibody of target pathogen were bridged between a pair of electrodes, and the detection was made by the capacitance change via the binding events of viruses on the nanotube.

7593-36, Session 7

Surface assembly of pyridyl-substituted porphyrins on Au(111) investigated in situ using scanning probe lithography

J. C. Garno, Z. M. LeJeune, M. McKenzie, E. Hao, M. G. H. Vicente, B. Chen, Louisiana State Univ. (United States)

The surface assembly of porphyrins is mediated by complex intermolecular interactions, such as pi-pi stacking between macrocycles or by the binding interactions between peripheral groups and surfaces. Scanning probe characterizations provide insight for the molecular orientation and assembly of porphyrins, furnishing highly local views of the assembly of pyridyl-substituted porphyrins on surfaces of Au(111) over time. By imaging in dilute solutions of mixed solvents, high resolution images disclose steps of the solution phase assembly of pyridyl-functionalized porphyrins. The molecules used for these investigations are porphyrins containing pyridyl and phenyl groups. Energy minimized structural models of pyridyl-substituted porphyrins on Au(111) will be presented, computed using Car-Parrinello Molecular Dynamics (CPMD). We are also using scanning probe lithography with n-alkanethiol self-assembled monolayers to provide a molecular ruler for nanoscale height measurements. Nanoshaving can be applied to measure the thickness of molecular layers by referencing uncovered areas of the substrate as a baseline for height measurements. Nanografting can also be used to measure the thickness of porphyrin films by comparing the well-known heights of n-alkanethiol nanopatterns inscribed within a matrix layer of porphyrins. During nanografting, very small areas of freshly exposed gold are produced while scanning with a high force applied to the AFM tip. When nanografted, pyridyl porphyrins assemble directly onto gold with an upright configuration, and surface binding is likely mediated through nitrogen-gold chemisorption. Understanding the self-organization and assembly of designed porphyrins at the molecular level will contribute to rational designs for applications in electronic and photonic devices.

7593-37, Session 7

Self-leveling 2D DPN® probe arrays

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Dip Pen Nanolithography® (DPN®) is a direct write scanning probe-based technique which operates under ambient conditions, making it suitable to deposit a wide range of biological and inorganic materials. Precision nanoscale deposition is a fundamental requirement to advance nanoscale technology in commercial applications, and tailoring chemical

composition and surface structure on the sub-100 nm scale benefits researchers in areas ranging from cell adhesion to cell-signaling and biomimetic membranes. These capabilities naturally suggest a “Desktop Nanofab” concept - a turnkey system that allows a non-expert user to rapidly create high resolution, scalable nanostructures drawing upon well-characterized ink and substrate pairings. In turn, this system is fundamentally supported by a portfolio of MEMS devices tailored for microfluidic ink delivery, directed placement of nanoscale materials, and cm^2 tip arrays for high-throughput nanofabrication. Massively parallel two-dimensional nanopatterning is now commercially available via NanoInk’s 2D nano PrintArray , making DPN a high-throughput (>3x10^7 µm^2 per hour), flexible and versatile method for precision nanoscale pattern formation. However, cm^2 arrays of nanoscopic tips introduce the non-trivial problem of getting them all evenly touching the surface to ensure homogeneous deposition; this requires extremely precise leveling of the array. Herein, we describe how we have made the process simple by way of a self-leveling gimbal attachment, coupled with semi-automated software leveling routines (InkLeveler brings cm^2 chip within 0.007 degrees of co-planarity). We have engineered the devices to be easy to use, wire-free, and fully integrated with both of our patterning tools: the DPN 5000, and the NLP 2000.

Conference 7594: MOEMS and Miniaturized Systems IX

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7594-01, Session 1

In vivo brain imaging using miniaturized one- and two-photon fluorescence microscopes

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An important aim of neuroscience research is to explain mammalian behavior in terms of underlying cellular dynamics. However, there has been a paucity of tools for visualizing the dynamics of individual cells in the brains of awake behaving mammals. I will describe recent progress in the development of miniaturized microscopes (1-4 grams) that are sufficiently small to be borne on the head of a freely behaving adult mouse. High-speed (100 Hz) fiber-optic epi-fluorescence microscopy now permits the visualization of intracellular calcium dynamics and of cerebral microcirculation within the brains of mice that are actively behaving. A complementary approach involves miniaturized, laser-scanning two-photon fluorescence microscopes, which have employed either resonant or non-resonant fiber-scanners, or microelectromechanical systems (MEMS) laser-scanning mirrors. The two approaches to fluorescence excitation have complementary advantages and limitations, and miniaturized microscopes of both types are likely to find key niches in neuroscience research, for studies of healthy animals and animal models of brain disease.

7594-02, Session 1

MEMS-devices for laser camera systems for endoscopic applications

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In 2007 IPMS and MVIS presented the results of a full colour scanned beam imaging system. In this paper we will in addition give an update on the technological development since the last paper. The already small die size of 3000µm x 2300µm was further reduced to less than 2000µm x 2000µm. The new devices consist of a moveable frame oscillating at frequencies in the range of 700 Hz - 900 Hz and 1400 Hz - 1800 Hz carrying a mirror of 350 µm diameter in a gimbal mounting. The mirrors oscillate at frequencies in the range of 13-15 kHz. The characteristic mechanical amplitudes are 21° MSA (mechanical can angle) for the frame and 28° MSA for the mirror respectively. Voltages of less than 50 V for the frame and 100 V for the mirror were necessary to accomplish this. The improved MEMS device design is presented as well as the related measurement results. The images of various objects taken with an optical system using the former devices are presented revealing the excellent resolution of such a system and enabling an outlook on the possibilities of the new device.

7594-03, Session 1

In vivo 3D and Doppler OCT imaging using electrothermal MEMS scanning mirrors

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Most cancers occur inside human body, which requires high-resolution endoscopic imaging modalities. The paper reports in vivo endoscopic optical coherence tomography (OCT) imaging enabled by integrating rapid-scanning MEMS mirrors into a miniature imaging probe. The MEMS mirror has an aperture size of 1mm by 1mm and a chip size of 2mm by 2mm. The optical scan angle exceeds ±25 at 6 Vdc. The outer diameter of the probe is only 5 mm. The axial resolution is about 10 µm and the imaging speed is 2.5 frames per second. Doppler OCT imaging has also been demonstrated.

7594-21, Session 1

Piezoelectric MEMS mirrors for forward-looking endoscopic imaging

S. Grego, K. H. Gilchrist, RTI International (United States); R. P. McNabb, J. A. Izatt, Duke Univ. (United States)

A novel scanning mirror device consisting of a mm-sized microfabricated mirror actuated by a single piezoelectric cantilever is presented. The device was designed to provide wide-range rapid forwarding-looking scanning of a 500 um diameter optical beam at the distal end of a 3 mm catheter. The piezoelectric scanning mirror can be cascaded in a dual mirror system to allow 2D beam steering. Two-dimensional scanning MEMS mirrors are generally used in a side-looking configuration, however, forward-looking MEMS probes could be effectively used in imaging large hollow organs such as stomach, bladder and colon. The MEMS optical scanner provides a large ratio of mirror aperture to device size; optical angular displacements up to ±14 deg were demonstrated and resonance frequencies ranging from hundreds of Hz to kHz were measured for a set of different mirror sizes. The imaging capability of the piezoelectric scanner was demonstrated using a bench-top spectrometer based Fourier-Domain OCT system. The packaging approach to integrate the MEMS devices in a highly compact 2D scanning system will be discussed.

7594-22, Session 1

Dual-axes confocal microendoscopy of gastrointestinal tract

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We demonstrated a Dual-Axes Confocal (DAC) fluorescence microendope (785-nm-light-source) and obtained in vivo images of the human gastrointestinal (GI) tract. All optical components, including a MEMS scanner, are assembled in a 5.5-mm diameter stainless steel package equipped with a micromotor for vertical translation (z-axis). The endomicroscope delivers an excitation wavelength of 785 nm with a maximum laser output of 2.5 mW at the surface mucosa. Confocal images can then be collected at a scan rate of 4 frames/second with a 225 µm × 425 µm FOV. Both axial and transverse resolutions are 5 µm and lamina propria constituents can be visualized to a depth of 130 µm.

While performing standard videocolonoscopy, the confocal images are simultaneously collected from the MEMS based endomicroscope that occupies the instrument channel. An Indocyanine Green (ICG) mixture is topically applied onto the mucosal surface 5 minutes before each image is obtained. Two distinct morphologies have been identified from the endomicroscope based on the in vivo subsurface crypt appearance. Normal crypt architecture is classically represented by ordered and regular crypt openings covered by a homogenous epithelial layer with visible goblet cells within the subcellular matrix. Dysplastic crypt architecture is represented by architectural disorder of the crypts characterized by ridge-lined epithelia.

This novel imaging instrument have potential for major clinical implications as it allows in vivo diagnosis of colonic intra/sub-epithelial neoplasia that can influence ‘on table’ management decisions.

7594-23, Session 1

A surgical confocal microscope utilizing a MEMS scanner and a GRIN relay lens for molecular image-guided brain tumor resection

J. T. C. Liu, M. J. Mandella, Stanford Univ. (United States); N. O. Loewke, Univ. of California, Los Angeles (United States); E. Garai, W. Piyawattanametha, H. Ra, H. Haeberle, O. Solgaard, G. S. Kino, C. H. Contag, Stanford Univ. (United States)

Numerous studies have indicated a correlation between the outcomes of brain tumor patients with the degree of surgical resection. Real-time image guidance is necessary to allow for complete resections in a larger proportion of patients, and to reduce the debilitating effects of over-aggressive resections. Confocal microscopy, if modified for deep tissue imaging, allows one to image sub-surface cells that are in their natural undisturbed tissue microenvironment, where cell-surface proteins may accurately be labeled with exogenous contrast agents.

We have developed a surgical confocal microscope with a 2-mm diameter GRIN relay lens at the distal tip for in vivo histopathological guidance during brain tumor resection. The microscope we have developed utilizes a dual-axis confocal architecture to efficiently reject out-of-focus light for high-contrast optical sectioning within intact tissues. A biaxial MEMS scanning mirror is actuated at resonance along each axis to achieve a large field of view. We have developed a synchronized and calibrated waveform-generation and data-acquisition system to decode the unstable Lissajous pattern that results from actuating the orthogonal axes of the MEMS mirror at highly disparate resonance frequencies.

Imaging studies have been performed with tissues from a transgenic mouse (Ptc+/-p53-/- Math1-GFP) that spontaneously develops medulloblastoma with colocalized GFP expression. We are also developing fluorescent antibody- and peptide-contrast agents for delineating tumor margins in human patients. These techniques will allow surgeons to unambiguously distinguish between normal and cancerous tissues for chemically-specific and spatially-precise tumor debulking.

7594-04, Session 2

MEMS deformable mirrors for focus control in vital microscopy

D. L. Dickensheets, S. J. Lukes, E. Dunbar, J. Lutzenburger, Montana State Univ. (United States)

MEMS deformable mirrors can play an important role in beam focusing and wavefront correction in microscopy systems. The technology is especially well suited to endoscopic microscopy platforms where extreme miniaturization is required and any microscopy system where high speed focus control or focus scanning is necessary. MEMS deformable mirrors designed specifically for focus control and spherical aberration compensation can be made quite small and require only a few actuators, making them attractive for miniaturization for endoscopy applications. With control over primary spherical aberration, these mirrors can correct for depth-dependent spherical aberration that decreases image contrast and resolution when imaging into tissue using high NA. This paper describes recent progress toward our design goal to reach 200 microns of focus adjustment range with an NA=1.0 imaging system, typical of high NA confocal reflectance imaging. The mirrors are constructed as metalized polymer membranes ranging from 1-3 mm in diameter using the photo-cured epoxy SU-8. They are electrostatically actuated using three concentric electrodes to provide large displacement while minimizing mirror-induced aberration. A feedback control system maintains desired surface shape while maximizing the range of stable deflection of the mirror. The mirrors have resonant frequencies of several hundred Hertz, making them suitable for real-time x-z scanning confocal microscopy. Imaging examples will be presented to illustrate the mirror ability as a focusing element. Finally, limitations including residual aberrations that are non-linearly dependent on focus will be discussed in the context of anticipated future performance of this class of deformable mirror for focus control in microscopy.

7594-05, Session 2

High-speed liquid lens with 2-ms response and 80.3-nm root-mean-square wave front error

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High-speed focusing technology has been desired for decades. Here, a liquid lens with a novel structure using a liquid-liquid interface with a pinned contact line that can arbitrarily control the focal length in milliseconds and achieve practical imaging performance is reported.

The interface curvature is dynamically controlled by liquid volume change. The lens includes two immiscible liquids infused in two chambers, but they are interfaced at a circular aperture. One chamber is equipped with a deformable wall that is thrust by a piezostack actuator to change the chamber volume.

The vibrating interface behaves like a damped harmonic oscillator depending on the kinematic viscosity of the infused liquid. Based on the result of preliminary experiment, ultra pure water and poly-dimethyl-siloxane (PDMS) with 5000 cSt were used as immiscible liquids to achieve high-speed response.

The pinned contact line should be a good circle in three dimensions to realize a good spherical interface. The largest deformation of the interface could be limited by the largest contact line deformation. By setting the acceptable vertical deformation of the contact line to be less than the quarter wave length, a machining accuracy of less than 1.95 um is required for the circular edge pinning the contact line.

A prototype achieved a refractive power range of 52 D, a 2 ms step response time and a minimum RMS wavefront error 80.3 nm. The potential applications of this device are axial focus scanning of microscopes, and focusing/zooming of camera lenses and machine vision systems.

7594-24, Session 2

Improved chromatic performance of endomicroscope optics for broadband imaging

G. C. Birch, College of Optical Sciences, The Univ. of Arizona (United States); B. McCall, T. S. Tkaczyk, Rice Univ. (United States); M. R. Descour, College of Optical Sciences, The Univ. of Arizona (United States)

Conventional miniature optical microscope systems are usually made from a single optical material and therefore have poor correction of chromatic focal shift (CFS, a.k.a., axial color). Typical Stokes shifts exceed the limited bandwidth of such single-material optics. This problem is compounded when using multiple fluorophores.

To demonstrate a solution, we have designed, fabricated, and tested an achromatic doublet made from optical polymers. Ten different common optical polymers were analyzed and doublet designs were evaluated for the most promising materials combination. Optical polymers were chosen for the range of available manufacturing options (e.g., diamond turning, milling, or injection molding), their low cost, and their ready availability. The final doublet design employs two common, off-the-shelf optical polymers: PMMA and polystyrene.

The all-polymer achromat doublet was manufactured using diamond milling and single point diamond turning (SPDT). Diamond milling differs from SPDT by employing a shaped diamond tool with the radius of the desired surface and the same semi-diameter as the desired clear aperture (e.g., 1.5 mm in our case). Advantages of this manufacturing technique will be discussed in detail.

The measurement of the doublet's residual CFS was made using a custom designed, multispectral Shack-Hartmann (SH) test setup. The SH test uses a lenslet array to locally sample the wavefront emerging from the test lens. The CFS measurements were simulated in ZEMAX to predict the results of evaluating the achromatic doublet design. The experimental performance of the achromatic doublet, as well as an example miniature microscope design based on doublets, will be presented.

7594-25, Session 2

Focused OCT and LIF endoscope

R. A. Wall, The Univ. of Arizona (United States) and College of Optical Sciences, The Univ. of Arizona (United States); G. T. Bonnema, D4D Technologies, LLC (United States); J. K. Barton, The Univ. of Arizona (United States)

Optical coherence tomography (OCT) is a non-invasive, interferometric imaging technique capable of imaging up to 2 mm deep in highly scattering tissue. Laser-induced fluorescence (LIF) has shown promise as a viable option for diagnostic tests in the gastrointestinal tract. Our in vivo work on the mouse colon with similar LIF techniques has shown high sensitivity and specificity in spectrophotometric analysis of distinguishing normal tissue from adenoma. Combining OCT and LIF in one endoscope shows a heightened sensitivity to early changes in tumor progression when compared to either modality alone.

Previously, we have built ultrahigh resolution (2-5 microns) OCT endoscopes with unfocused LIF and have demonstrated imaging of mouse colon serially over time. Our new design is a high-resolution endoscope 2 mm in diameter that can focus light from 325-1300 nm. A reflective design ball lens is employed that eliminates the difficulty of operating achromatically over a large range, while taking advantage of TIR at two faces and coating a third mirror face internally to focus the beams downwards. It is a 1:1 imaging system that obtains a theoretical diffraction-limited resolution for both the OCT (800-1300 nm) and LIF (greater than 325 nm) channels.

We have built the focused OCT-LIF endoscope and integrated it into an existing arrangement. In vivo and ex vivo images acquired using this focused OCT-LIF system suggest higher lateral resolution in both imaging modalities than those images collected with previous systems, allowing for heightened specificity and sensitivity in the detection of early changes in tumor progression.

7594-26, Session 2

High-resolution axicon based endoscopic FD OCT imaging with a large depth range

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Endoscopic imaging in tubular structures, such as the tracheobronchial tree, could benefit from imaging optics with an extended depth of focus (DOF). These optics could accommodate for varying sizes of tubular structures across patients and along the tree within a single patient. However, most small sized catheters cannot simultaneously achieve high lateral resolution and long depth of focus. In the paper we demonstrate extended DOF without sacrificing resolution showing rotational images in biological tubular samples with arbitrary cross-section through a custom designed axicon. The axicon microoptics (i.e.,<1 mm in diameter) achieves a measured invariant resolution of ~ 8 µm across a 4 mm DOF. The measured DOF and resolutions were compared to theoretical results from the quasi-Bessel beam simulation using parameters of the fabricated axicon and the profile of the incident beam on the axicon. A fabricated gold coated mirror (size: 1.4mm by 2.1mm) attached to a custom 45-degree-wedged ferrule was located after the axicon to put the 4 mm DOF in the tubular sample. To secure the 4 mm imaging depth with the spectral resolution given by the spectrometer and broadband source in the FD OCT, the mirror image is suppressed using a piezoelectric fiber stretcher in the reference arm. In conclusion, a sub millimeter catheter design is presented for high resolution OCT over long DOF demonstrating OCT images of tubular biological samples with 2.5 µm axial resolution and 8 µm lateral resolution over a 4 mm depth range.

7594-06, Session 3

Pixtronix digital micro shutter display technology: a MEMS display for low power mobile multimedia displays

T. J. Brosnihan, Pixtronix, Inc. (United States)

The Pixtronix display technology eliminates the traditional power consumption / performance trade-off, delivering 145% NTSC color gamut (CIE 1976), 24-bit color, 1,000:1 contrast ratio and 170° view angles, all at one quarter the power consumption of competing TFT-LCDs.

At the heart of this technology is a MEMS-based Digital Micro Shutter device that enables the low power, high speed light modulation in the Pixtronix displays. The Digital Micro Shutter is a laterally translating element, which is supported on a patented dual compliant actuator. Each pixel has one shutter, which is used to show all colors in a Field Sequential Color, Time Division Multiplexed driving scheme. The pixel has been demonstrated over a density range of 100 PPI to 300 PPI. The Digital Micro Shutter also supports an optical recycling approach through which 60% of the light from the backlight becomes available to the viewer - compared to only 6% efficiency in liquid crystal based displays.

This talk will highlight some of the design innovations and corresponding display results achieved in the Pixtronix Digital Micro Shutter technology.

7594-07, Session 3

Resonance MEMS mirrors design considerations

S. Sourani, bTendo Ltd. (Israel)

Resonance MEMS mirrors are widely used today for many applications such as bar-scanners and pico-projectors.

bTendo manufactures pico-displays based on two types of mirrors:

Resonance mirrors for horizontal scanning

Linear mirrors for vertical scanning

In this lecture we will discuss the "Energy Balance" and start-up conditions for resonance mirrors.

We will derive the conditions for start-up as well as the predicted curve of (v):

≥V/π √((C_0-C_)/2f×Q/√jk)

We will show simulation results in time domain that prove the validity of the last equation as well as fast finite element simulation to predict the performance of a new structure.

7594-08, Session 3

Evolution of MEMS scanning mirrors for laser projection in compact consumer electronics

J. Tauscher, W. O. Davis, D. Brown, M. Ellis, Y. Ma, M. E. Sherwood, D. Bowman, M. P. Helsel, S. Lee, J. W. Coy, Microvision, Inc. (United States)

The idea of MOEMS scanning mirrors for the creation of "flying spot" scanned laser displays is well established. The extension of this concept towards compact embedded pico-projectors has required an evolution

of scanners and packaging to accommodate the needs of the consumer electronics space. This paper describes the progression of the biaxial MOEMS scanning mirrors developed by Microvision over recent years. Various aspects of the individual designs are compared. Early advances during the development of retinal scanning displays enabled elimination of the combined magnetic quasistatic and resonant electrostatic operation in an evacuated atmosphere and acheived a simpler, more manufacturable component. Subsequent designs have realized further simplification of the actuation scheme through proprietary technical advances. Continued improvements have doubled the scan angle capability and futher miniaturized the MOEMS component while not incurring any increase in power consumption, making it an excellent fit for the consumer pico-projector application.

The simplicity of the scanned laser-based pico-projector optical design enables high resolution and a large effective image size in a thin projection engine, all of which become critical both to the viability of the technology and adoption by consumers. Microvision's first scanned laser pico-projector is built around a MOEMS scanning mirror capable of projecting 16:9 aspect ratio, WVGA display within a 6.6 mm package. Further evolution on this path promises continued improvement in resolution, size, and power.

7594-09, Session 3

Nonlinear mathematical model for a biaxial MOEMS scanning mirror

Y. Ma, W. O. Davis, M. Ellis, D. Brown, Microvision, Inc. (United States)

The pixel placement accuracy requirement for scanned laser spot displays is on the order of 1/10 of a pixel, which translates into a roughly 80dB signal to noise ratio, noise being a departure from the ideal laser spot trajectory. To provide a tool for understanding the subtle phenomena that can contribute to such small deviations from ideal behavior, a detailed nonlinear mathematical model is derived for Microvision's MOEMS scanning mirror. The paper describes the lumped-parameter treatment of a gimbal-suspended scanning mirror as two rigid bodies connected by a flexible member. The Lagrangian is used to derive coupled equations of motion that include several readily observable nonlinearities.

Coefficients in the equations are derived by various means: the geometrically nonlinear electromagnetic actuation forces and torques acting on the MOEMS scanning mirror and used as inputs to the model are analyzed using finite element analysis, while nonlinear damping is accounted using physical principles and experimental data. The MOEMS scanning mirror incorporates integrated position feedback sensors, and the transfer function from rigid body motion to integrated feedback sensor signal output is additionally derived by finite element analysis. The device temperature, influenced by both ambient environment and Joule heating, affects some aspects of the device dynamics and is also handled by the model. Dynamics predicted by the model are compared to the measured performance.

7594-10, Session 4

Synchronized micro scanner array for large aperture receiver optics of LIDAR systems

T. Sandner, M. Wildenhain, H. Schenk, Fraunhofer Institute for Photonic Microsystems (Germany)

Traditional laser scanners for 3D distance measurement involve expensive, heavy and large rotating or vibrating mirrors for light deflection of the scanning TOF (time of flight) distance measurement. Typically, the precision of TOF distance measurements is limited by the amount of signal light available at the detector. Hence, a scanning mirror with large aperture is re¬quired for LIDAR systems to collect small amounts of light reflected or scattered by the measured target. Its replacement by a micromechan¬ical scanning mirror is not straightforward, since a large mirror aperture of the receiver optics must by guaranteed in addition to suf¬ficiently large optical scan angles (> 40°) and high scan frequency of more then 100Hz. Contrary, the aperture of a single MEMS scanning mirror is limited to small values of typically 1...4mm diameter due to the dynamic mirror deformation.

To overcome the mentioned problems, Fraun¬hofer IPMS has designed a scalable 1D-MEMS scanner array composed of 2 x 7 silicon mirror elements each having an identical design with comparatively large aperture of 2.51 x 9.51mm² and ±30° optical scan range. All mirrors are driven electrostatically resonant with identical frequency close to design frequency of 250 Hz around their long symmetry axes by means of separate in-plane comb drives. By driving control all single scanner elements are synchronized to identical phase and amplitude resulting in a large total scanner aperture of 334 mm² and a filling factor of 80 %. To guarantee the synchronized operation the paper discusses the compensation of frequency tolerances caused by fabrication and packaging. The system integration of the MEMS array will be presented also in this conference in a separate paper.

The new concept of using an array of synchronized identical MEMS mirror elements for LIDAR systems permits large reception apertures while preserving the outstanding reliability, high scanning speed, compact size and small system weight that can be expected from MEMS. In comparison to systems with conventional scanner components, the new 1D-MEMS scanner enables 3D-LIDAR systems to become significantly smaller and more robust, higher scan rates can be realized without additional efforts (e.g. air bearings).

7594-11, Session 4

Large aperture MEMS scanner module for 3D distance measurement

T. Sandner, M. Wildenhain, C. Gerwig, H. Schenk, Fraunhofer Institute for Photonic Microsystems (Germany)

In this article we present a new large aperture 1D-MEMS scanner module especially designed for laser radar systems. The scanner module has a resonance frequency of 250 Hz and optical scan range of 60°. It comprises of two separate scanning channels: (a) a single scanning mirror of the collimated transmit¬ted beam oscillates parallel to (b) a scanning mirror array of the receiver optics. Light paths of emitting and receiving optics are separated to reduce crosstalk in the final laser radar system. The receiver optics use an array of 2 x 7 identical mirror elements, each with 2.51x 9.51 mm² per single mirror element, resulting in a total aper¬ture of 334 mm² and filling factor of 80 %. The transmitted beam is sent via a separate emitting master mirror of the same mechani¬cal dimensions as one elements of the mirror array. Since laser energy is emitted in only one direction, all the receiving mirrors are synchro¬nized in phase to the master scanner by the driving control electronics to point in the same direction in order to form a sufficiently large aperture and to maximize the optical signal of the detector system. To realize the mirror synchronization, miniaturized position sensors are integrated into the scanner module for each individual mirror element. Thus, a precise control of the mirror motion is achieved so that all receiving mir¬ror elements can be slaved to the motion of the emission mirror. The 1D-scanner module has a total size of about 40x52x45 mm³, and satisfies at the same time the demand of a com¬paratively large optically active area, while keeping the reso¬nance frequency of 250 Hz at a val¬ue that matches well to current TOF laser distance measurement systems with point measurement rates of typical 250 - 1000 kHz. Thus, the optical scan range of ±30 degrees is split into 500-2000 intervals. First experimental results will be presented also for an entire LIDAR system.

7594-12, Session 4

Surface micro-machined SU8-2002 membrane mirrors for focus control

S. J. Lukes, Montana State Univ. (United States); D. Lämmle, Albert-Ludwigs-Univ. Freiburg (Germany); D. L. Dickensheets, Montana State Univ. (United States)

SU8-2002 deformable membrane mirrors designed for variable-focus control are capable of large stroke and a correspondingly large range of focus adjustment. This paper describes electrostatically actuated SU8 deformable mirrors fabricated using a surface micromachining process that simplifies the fabrication process relative to earlier bonded-wafer techniques and produces mirrors with excellent optical properties. Multiple concentric actuation electrodes improve surface shape control and increase maximum stable range of deflection. Previously, surface micromachined silicon nitride mirrors have proven effective for focus control while also controlling spherical aberration. The primary limitations for electrostatic MEMs deformable mirrors are the snapdown phenomenon and the large voltages required for actuation. Because the Young's modulus of SU8 is two orders of magnitude less than that of silicon nitride and the intrinsic stress is more than one order of magnitude less, the SU8 membrane is capable of greater membrane stroke, thus providing a greater range of focus at a specified maximum voltage. We demonstrate a stroke greater than 15 m for circular membrane mirrors less than 3.0 mm in diameter. The mirrors consist of a single-side-polished silicon wafer, 1 m thick oxide layer, 150 nm psg layer, 2 m SU8-2002 membrane, and 100 nm gold reflective coating. An optimization scheme based on aberration reduction and total stable deflection prior to snapdown was used to determine the radii of three annular gold electrodes for actuation. Range of stable displacement and residual aberration are experimentally verified.

7594-13, Session 4

Deformable silicon membrane for dynamic linear laser beam diffuser

J. Masson, Ecole Polytechnique Fédérale de Lausanne (Switzerland); A. Bich, SUSS MicroOptics SA (Switzerland); W. Noell, Ecole Polytechnique Fédérale de Lausanne (Switzerland); R. Voelkel, K. J. Weible, SUSS MicroOptics SA (Switzerland); N. F. de Rooij, Ecole Polytechnique Fédérale de Lausanne (Switzerland)

A one-dimensional (1D) dynamic linear laser beam diffuser is presented. Dynamic linear diffusers allow one to tune both the angular diffusion range and intensity profile as well as lower the speckle contrast within an application-dependent time frame. It consists of a square single crystal silicon micro-membrane. Two opposite sides of the membrane are fixed to the bulk substrate while the two other sides are free to move. The top of the membrane is flat and smooth, and is used as the reflective optical surface. The mirror is continuous without any air gaps that would cause power loss and diffraction. The bottom is shaped to form beams that run parallel to the fixed ends of the membrane. They are used to stiffen the membrane in one direction and to force a 1D deformation when actuated. These beams are also employed as electrodes for the electrostatic actuators. They can excite any 1D mode of the membrane. When actuated in resonance, the diffuser deforms in an undulating fashion in one dimension. Diffuser resonance mode frequencies between 1-100 kHz were obtained in vacuum. The first prototypes are square membranes measuring between 5-15 mm and 5 um thick. In addition, a metallic or other high-reflectivity dielectric coating can be deposited uniformly on the membrane for specific applications. Due to the large thermal conductivity of silicon, relatively high-power laser beams can be used without damaging the mirror. Target applications include high-power laser-intensity profile shaping, diffusers for polysilicon annealing, and projection and display systems.

7594-15, Session 5

Diffusers for shaping light with a multichannel concept

F. Wyrowski, Friedrich-Schiller-Univ. Jena (Germany); C. Hellmann, LightTrans GmbH (Germany)

Diffusers for spatially shaping of light are of increasing importance for illumination and display applications. The use of the Iterative Fourier Transform Algorithm is a well-established design technique. However for the design of diffusers for non-paraxial and non-monochromatic light, e.g. in case of LED's, this iterative technique causes some problems. (1) The numerical effort for the design can be very high. (2) Also the simulation of its effect for partially coherent light is time consuming. (3) The appearance of vortexes does not allow the reduction of a high wavelength dependency. We suggest a concept, which separates the function of the diffuser in a multichannel concept. Examples are grating cells diffusers and also the use of beam shaping elements in laterally separated channels. We discuss the advantages and disadvantages of such approaches in the context of a general diffuser theory. In particular we discuss and demonstrate its use for illumination and the design of screens for display applications. We show, that this concept allows a smooth transition from ray-tracing design and simulation of diffusers to wave-optical techniques. The theory is illustrated with design and simulation examples on the basis of the VirtualLab optics software technology.

7594-17, Session 5

Design and testing of a rotating out-of-plane micromirror

T. E. Dallas, S. Oak, G. Edmiston, G. Sivakumar, Texas Tech Univ. (United States)

A novel, micro-actuator system for beam steering or optical multiplexing applications has been developed. The system was fabricated using the SUMMiT V polysilicon MEMS process. A rectangular micro-mirror is held at a 45° angle out of plane by serpentine springs attached to a gear which has rotational freedom of 360°. The gear has position specific "catch blocks" to hold the mirror at the desired angle. The out-of-plane assembly is done by a simple post-fabrication step which involves providing a lateral push to the mirror using a micro-probe. Once the mirror slides into catch grooves, it balances the restoring force from the spring and maintains its out-of-plane position. The gear can be driven at rotational frequencies ranging from 1-1000 RPM using an electrostatic rotational drive. The assembled structure was tested for robustness by actuating the micromirror at a range of frequencies (1-1000Hz). As a part of the dynamic analysis of the optical properties, an auto-reflection measurement system was developed and used to quantify the intensity of the reflected light from the mirror in its scan range. An azimuth variation of -8° shows a change in intensity of 65% when compared to the peak intensity obtained at 0°. Furthermore, the effect due to backlash between the TRA and the mirror at low speeds was quantified and was found that in the span of 0.825° of backlash angle there is a change in the intensity of ~9% of the peak intensity.

7594-18, Session 5

CMOS Geiger-mode avalanche photodiode detectors for time and intensity resolved measurements

W. G. Lawrence, T. Tozian, C. Stapels, J. F. Christian, Radiation Monitoring Devices Inc. (United States); G. D. Derderian, Dipole Engineering (United States); J. P. Derderian, Consultant (United States); G. Varadi, Radiation Monitoring Devices Inc. (United States)

Small Geiger-mode avalanche photodiode detector elements and arrays have been produced using standard CMOS fabrication methods. These optical detectors are 10 to 60 microns in diameter and are designed to produce a discrete electrical output pulse for each incident photon. This discrete output pulse is a digital representation of the detected photon. We have produced mixed signal (digital/analog) application specific integrated circuits that include the Geiger-mode photodetector and subsequent digital signal processing circuits. Our current design includes sixteen photon counting detector elements, with bias control, active quenching circuits, and integrated counters at each pixel. The detectors are used to measure low intensity chemiluminescence from horseradish peroxidase conjugated antibodies in sub-microliter samples using an optical waveguide. The discrete signal output of the detector array has been coupled with an external field programmable gate array (FPGA) to perform multi-channel, all digital, time resolved fluorescence measurements. We demonstrate the system performance by measuring the pH dependence of the fluorescence lifetime of fluorescein dye.

7594-19, Session 6

High aspect ratio micromirror array with two degrees of freedom for femtosecond pulse shaping

S. M. Weber, W. Noell, Ecole Polytechnique Federale de Lausanne (Switzerland); D. Kiselev, J. Extermann, Univ. de Genève (Switzerland); S. Waldis, Ecole Polytechnique Federale de Lausanne (Switzerland); L. Bonacina, J. Wolf, Univ. de Genève (Switzerland); N. F. de Rooij, Ecole Polytechnique Federale de Lausanne (Switzerland)

Photochemistry has recently undergone a revolution through the use of modulated femtosecond laser pulses, leading to the new field of femtochemistry. Usually, liquid crystal devices are employed to modulate the phase, amplitude, or polarization of fs-laser pulses though they are limited by their slow switching speeds and bandwidths. With the addition of the UV, fundamental compounds of organic chemistry and biochemistry such as aromatic rings could also be accessed.

Our prototype MEMS pulse shaper has broadband capabilities using reflective micromirrors. The optical setup has a pair of mirrors and gratings to disperse the femtosecond beam into its frequency components and then, at the Fourier plane, retard or diminish the respective frequencies. With two degrees of freedom, rotation and piston movement, one can either perform phase or amplitude modulation, whereby diminishing the amplitude is achieved by the different outgoing beam path of a mirror in a tilted state.

The design implements symmetrical and asymmetrical vertical comb drives, fabricated from SOI wafers. We are now improving the capabilities of our first prototype with a re-design which features a new balanced rotational actuator and a laterally reinforced spring.

7594-20, Session 6

Optical position feedback and phase control of MOEMS-scanner mirrors

A. Tortschanoff, A. Frank, M. Lenzhofer, Carinthian Tech Research AG (Austria); M. Wildenhain, T. Sandner, H. Schenk, Fraunhofer Institute for Photonic Microsystems (Germany); A. Kenda, Carinthian Tech Research AG (Austria)

Resonantly driven oscillating MOEMS mirrors are used in various fields in optics, telecommunications and spectroscopy. Recently, we developed a compact device comprising a resonant MOEMS micro-mirror, optical position sensing, and driver electronics, with closed loop control, which ensures stable resonant operation with well controlled amplitude under varying environmental conditions. In this contribution we present this device and show first experimental results with a 23 kHz MOEMS mirror, which demonstrate its capabilities.

The mirrors, developed at the Fraunhofer IPMS, are driven electrostatically with a pulsed driving voltage. Position feedback is obtained using a trigger signal, generated from a laser beam reflected from the backside of the mirror, combined with a harmonic extrapolation function.

For closed loop control, the time delay between the switching of the driving signal and the zero-deflection of the mirror is minimized by adjusting the frequency. This drives the mirror close to its resonance frequency, thus ensuring stable operation with large amplitude. In our device, which has a size of only ~1cm3, the timing is measured and controlled with a precision of <10 ns. The amplitude is kept constant via the driving voltage.

The experiments indicate the feasibility of our position encoding and feedback scheme. Phase stability better than 1/10.000 can be obtained by this method, sufficient even for demanding display applications. Closed-loop control of MOEMS mirrors will significantly improve the performance of these devices and will be highly relevant e.g. for the development of compact projection devices and MEMS-based spectrometers.

7594-21, Session 6

Development of miniaturized optical viscosity sensor with optical surface tracking system

H. Abe, R. Nagamachi, Y. Taguchi, Y. Nagasaka, Keio Univ. (Japan)

A new viscosity sensor enabling non-contact measurement at high speed, with less sample volume and high stability is required in a broad field. For example, in the industry field, process control by real time monitoring of viscosity can enhance quality and process yield of coating films such as conductive films and optical films. Therefore, we have developed a new miniaturized optical viscosity sensor, namely MOVS (Micro Optical Viscosity Sensor), based on a laser-induced capillary wave (LiCW) method which can meet requirements above. In the MOVS, viscosity is estimated by observing the damping oscillation of LiCW, which is generated by an interference of two excitation laser beams on a liquid surface. By irradiating a probing laser on LiCW, a first order diffracted beam containing information of sample viscosity, is generated. The intensity of the zeroth order diffracted beam (reflected beam) is utilized for the distance control between liquid- and sensor-level. The newly integrated optical surface tracking system makes possible the stable viscosity measurement in the presence of disturbance such as evaporation and external vibration. MOVS consists of five U-grooves fabricated by MEMS (Micro Electro Mechanical Systems) process and optical fibers (photonic crystal fibers and fusion-spliced lensed fibers). In this study, by integrating the optical surface tracking system on the chip, nanosecond order damping oscillation of LiCW is successfully observed in the presence of high speed evaporation (speed of 1 micrometer per second), external forced vibration and drying process of a liquid film (thickness of hundreds micrometer order).

7594-22, Session 6

Tunable optofluidic dye laser with novel cavity

W. Song, A. E. Vasdekis, D. Psaltis, Swiss Federal Institute of Technology Lausanne (Switzerland)

We present a pressured mediated tunable optofluidic dye laser with novel cavity. The dye laser chip was fabricated with Polydimethylsiloxane (PDMS) via replica molding and has none nano-features. It comprises a liquid waveguide and micro-scale air-gap chambers which function as mirrors to provide feedback. The lasing wavelength was determined by the interference of the reflected beams from the two PDMS-air interfaces of the air-gap chamber acting as Fabry-Perot etalon, while the tuning was realized by varying the width of the air-gap by applying air pressure. The lasing with linewidth of 2 nm and tuning range of 10 nm was demonstrated.

7594-14, Poster Session

Design and experimental results for a compact laser printer optical system with MEMS scanning mirror

T. Suzuki, D. Seki, S. Fujii, Y. Mukai, Nalux Co., Ltd. (Japan)

There are many features expected by printer users, which include high resolution, low price, compact size, color, high speed printing and so on. Laser printers generally utilize a polygon mirror as a reflector in their optical configurations, but the usual size of the polygon mirror prevents laser scanning unit from being made much smaller. We have been conducting research on techniques which can contribute to reducing the optical unit size. Although oscillating mirror made with MEMS technology enables the system to be compact, it requires a sophisticated optical design having an increased number of constraints due to the change in angular velocity which varies depending on the orientation of the mirror, while the polygon mirror allows the scanning with constant speed. Using a small MEMS mirror is one of the critical issues concerning the reduction of cost. We have successfully resolved all the challenges listed above by using high-precision free-form optical surfaces and an optical layout making efficient use of 3D space. Our techniques can make the unit size much smaller and reduce the price. The optical path is designed to have a ray passing through a lens twice. We report both theoretical and experimental results for this system.

7594-35, Poster Session

Design and characterization of MEMS interferometric sensing

A. Siahmakoun, R. M. Snyder, Rose-Hulman Institute of Technology (United States)

A MEMS-based interferometric sensor is presented for applications where size is a limiting factor. The micro-scale device is fabricated using MUMPS surface-micromachining and employs tunable-micromirrors placed precisely on a silicon substrate. Mirror displacement in the interferometric scheme is possible using either micro-scale gear shaft assemblies or by thermal actuation. The interferometer is comprised of gold reflection surfaces, polysilicon thermal actuators, hinges, latches and thin-film polarization beam splitters. A polysilicon film of 3.5 microns reflects and transmits incident polarized light from an external laser diode coupled to a multi-mode optical fiber. The input beam is shaped to a diameter of 20 microns for incidence upon the 100 micron mirrors. Losses in the optical path include diffraction effects from etch holes created in the manufacturing process and surface roughness of both gold and polysilicon layers. Numerous optical paths on the chip vary by length, number of reflections, and mirror subsystems employed. Subsystems include thermal actuator batteries producing lateral position displacement, angularly tunable mirrors, double reflection surfaces, and static vertical mirrors. All mirror systems are raised via manual stimulation using two-micron probe tips and some are aligned using electrical signals causing joule heating in thermal actuators. The characterization of thermal actuator batteries includes maximum displacement, deflection, and frequency response that coincides with theoretical thermodynamic simulations using finite-element analysis. Maximum deflection of 35 microns at 400 mW input electrical power is shown for three types of actuator batteries as is deflection dependent frequency response data for electrical input signals up to 10 kHz.

7594-36, Poster Session

A novel free-space MEMS-based variable optical delay line

M. A. Basha, Univ. of Waterloo (Canada); N. Dechev, Univ. of Victoria (Canada); S. Safavi-Naeini, S. Chaudhuri, Univ. of Waterloo (Canada)

In this paper we present a new architecture for a compact free-space variable optical delay line based on a newly developed 3-D rotating inclined micromirrors (3DRIM). The 3DRIM is a rotating micromirror placed at 45 degrees to the rotating plate form assembled on top of a rotary comb-drive actuator to provide rotations of few degrees around the center of the 3DRIM. The MEMS-ODL consists of an input and output ports, two 3DRIMs, and two vertical mirrors parallel to the plane passing through the two 3DRIMs. The input fiber is positioned vertically with respect to the substrate where the input 3DRIM is placed with a common center. The same configuration holds for the output fiber and the output 3DRIM. The optical beam coming from the input fiber will travel to the input 3DRIM and hit the input mirror at 45 degrees. The optical beam will be directed towards one of vertical reflecting mirrors. The incident angle of the optical beam on this vertical reflecting mirror will depend on the orientation of the 3DRIM. The optical beam will propagate in the free space and will encounter several reflections between the two vertical reflecting mirrors until it reaches the output 3DRIM. The output 3DRIM will align with the direction of the coming optical beam to fully capture it and directed toward the output fiber. The MEMS-ODL provides variable delay times based on changing the optical path length using two 3DRIMs attached to the input and output fibers.

7594-37, Poster Session

Design of spectrophotometers and ended-ended systems

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Optical spectrometers are widely used for the highly sensitive and highly selective measurement of the composition of a gas or a fluid, in chemical chromatography for analysing the composition of a sample fluid [1]. Miniaturized systems have been realized formonitoring the ozone in the earth atmosphere from a satellite [2].The fluorescence spectrum is also used in chemistry to identify the composition and concentrations of dissolved ions [3]. Fluorescence signals are also investigated for monitoring of photosynthesis in plants [4].

We have characterised five different kinds of micromirrors and pointed out their repeatability. We can now focus on their possible utilisation in optical systems, compare them, and enhance the problems implied in the fabrication process. Here are presented two different simulations made with OSLO of “4f systems” very useful in telecommunication, as well the “ended-ended” systems and a spectrophotometer setup correspondent. The important parameters are Diameter D = 420 microns, Sagitta s = 8.9 microns, Focal length f = D2 / 16s = 1239 microns.

This system includes a glass layer, which is put directly on the micromirrors. For the simulation, the KF3 glass was chosen, having a refractive index equal to 1.51 at the wavelength chosen (588 nm). A reflective layer must be deposited on a part of the upper edge of this glass layer in order to make the beam reflect on the second micromirror.

We use this system as an infinity-infinity combination, so the image focal point of the mirror M1 (and the object focal point of the mirror M2) must be on the reflective part of the reflective of the glass layer (mirror M3), figure 1.

7594-38, Poster Session

MEMS temperature scanner: principles, advances, and applications

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Contactless measurement of temperatures has gained enormous significance in many application fields, ranging from climate protection over quality control to object recognition. Thereby measurement of linear or spatially temperature distribution is often necessary.

For this purposes mostly thermo cameras or motor driven temperature scanners are used today. Both are relatively expensive and the motor drive devices are limited regarding to the scanning rate additionally.

An economic alternative is a micromirror-based temperature scanner device. The micromirror, combined with standard optical components, reflects the emitted radiation from the observed heat onto an adapted detector. A line scan of the target object is obtained by periodic deflection of the mirror. Planar temperature distribution will be achieved by perpendicularly moving the target object or the scanner device. Using Planck radiation law the temperature of the object is calculated. The device can be adapted to different temperature ranges and resolution by using different detectors - cooled or un-cooled - and parameterized scanner parameter. With the basic configuration 120 spatially distributed measuring points can be determined within in a temperature range from 350°C - 1000°C.

The achieved miniaturization of such scanners permits the employment in complex plants with high building density or in direct proximity to the measuring point. The price advantage enables a lot of applications, especially new applications in the low-price market.This paper shows principle, setup and application of a novel temperature measurement system working in the near infrared range. Advanced packaging issues and measurement results will be discussed as well.

7594-24, Session 7

JWST microshutter array system and beyond

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We have developed the Microshutter Array (MSA) system at NASA GSFC as a multi-object aperture array for the Near Infrared Spectrograph (NIRSpec) instrument on the James Webb Space Telescope (JWST). The MSA system will enable NIRSpec to simultaneously obtain spectra from more than 100 targets, which, in turn, increases instrument efficiency one-hundred fold. Consequently, this system represents one of the three major innovations on the JWST, which has been selected by the National Research Council's 2001 decadal survey as the top-ranked space-based mission and is scheduled to be the successor to the Hubble Space Telescope. Furthermore, the MSA system will be one of the first MEMS devices serving observation missions in space. Microshutters are designed for the selective transmission of light with high efficiency and constrast and feature torsion hinges, light shields, deep-reactive ion-etched silicon windows, magnetic actuation, and electrostatic latching and addressing. Complete MSA quadrant assemblies consisting of 365 x 181 microshutters have been successfully fabricated. The assemblies have passed a series of critical reviews, which include programmable 2-D addressing, life tests, optical contrast tests, and environmental tests, required by the design specifications of JWST. Both the MSA and NIRSpec will be delivered to ESA for final assembly, and JWST is scheduled to launch in 2014. During final assembly and testing of the MSA system, we have begun to develop the Next Generation Microshutter Arrays (NGMSA) for future telescopes. These telescopes will require a much larger field of view than JWST's, and we discuss strategies for fabrication of a proof-of-concept NGMSA which will be modular in design and electrostatically actuated.

7594-25, Session 7

Development of a tilt actuated micromirror for applications in laser interferometry

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A silicon micromirror with 3x3 mm² surface area and 100 µm thickness has been designed and realized for the future space mission LISA (Laser Interferometer Space Antenna). The mirror is electrostatically actuated. The tilt movement of the mirror is provided by torsional load of the mirror suspension. A torsion angle of 2 mrad is achieved at a driving voltage of U = 150 V. 3D FEM simulations have been used for optimization of the layout of the mirror device.

The laser interferometer in the mission LISA will require tilt actuated mirrors in its interferometric beam path and outstanding performance in respect to mechanical stability, noise performance and piston effect, i.e. the requirement that under rotation of the mirror no significant z-movement of the reflection surface occurs [1]. This is ensured by a rotation axis of the micromirror which coincides exactly with the mirror surface - stating an important new aspect compared to previous designs [2]. This is achieved by using a symmetric SOI-wafer with handle and device wafer having exactly the same thickness. The mirror plane is formed by the handle wafer only, the suspending beams are realized from both, the handle and the device wafer of SOI-wafer. Thus the axis of the beams coincides with the reflecting plane. In addition, the bending, i.e. the piston effect of the mirror [3] is minimized by optimization of the beams and the counter electrode using FEM simulation.

The device will be characterized by interferometric optical measurements.

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7594-26, Session 7

Realization and characterization of MEMS-based programmable slit mask for multi-object spectroscopy

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Multi-object spectroscopy is a powerful tool for space and ground-based telescopes for studying the formation of galaxies. This technique requires a programmable slit mask for astronomical object selection. A first sample of MEMS-based programmable reflective slit masks with elements of size 200x100 um2 has been successfully tested in cryogenic conditions at 92 K. In order to achieve a better fabrication yield as well as to increase the reliability, improvements are made on the architecture, the process flow, the assembly and the electronics. Devices of larger size have been microfabricated, the largest chip measures 25x22 mm2 and is composed of 200x100 electrostatic actuated micromirrors each supported and stabilized by 3 pillars. A new process flow is also being evaluated utilizing refill techniques based on BPSG (borophosphosilicate glass) deposition and reflow. A programmable slit mask is made of two wafers which are processed separately and subsequently assembled. Different bonding techniques are under study to determine the method with the highest yield. The electronics, which controls the actuation process, was modified providing a higher number of channels and was implemented with a line-column algorithm allowing actuation of each mirror individually. This algorithm is based on the electrostatic hysteresis of the actuator. Devices are under preparation for the cryogenic experiments and a full characterisation of the large slit masks is underway.

7594-27, Session 8

Carbon nanotube-based digital vacuum electronics and miniature instrumentation for space exploration

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Field emission from carbon nanotube bundles has been applied to develop new class of computational electronics for extreme environments and miniature instrumentation for space exploration. Electron sources are fundamental components of analytical instruments to perform XRD/XRF, mass spectroscopy, and high-resolution microscopy. They are also necessary for high frequency, high-power vacuum tube sources, and for high temperature tolerant vacuum electronics. JPL has developed high performance cold cathodes using arrays of carbon nanotube bundles that produce > 15 A/cm2 at applied fields of 5 to 8 V/μm without any beam focusing. They have exhibited robust operation in poor vacuums of 1E-6 to 1E-4 Torr- a typically achievable range inside hermetically sealed microcavities. Using these CNT cathodes we have developed miniature X-ray tubes capable of delivering sufficient photon flux at acceleration voltages of <20kV to perform definitive mineralogy on planetary surfaces; mass ionizers that offer two orders of magnitude power savings, and S/N ratio better by a factor of five over conventional ionizers. Recently, we have demonstrated a new class of programmable logic gates using CNT vacuum electronics potentially for Venus in situ missions. These gates use carbon nanotube emitters surrounded by three silicon micromachined gate electrodes and function in vacuum. They are inherently high-temperature tolerant and radiation insensitive. We have achieved switching operation at temperatures up to 700° C. The concept, the initial design and operation, and the potential performance in an improved design will be presented in this paper.

7594-28, Session 8

Development of slab waveguide spatial heterodyne spectrometer for remote sensing

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We present development of a compact, robust, waveguide Fourier-transform microspectrometer for high-resolution and high-throughput spectroscopy in space-based applications. The prototype device is being designed to monitor water vapor in the atmosphere from a micro-satellite platform. The instrument is based on a unique slab waveguide spatial heterodyne spectrometer (SHS) chip fabricated at the National Research Council Canada in silicon-on-insulator (SOI) technology. Our SHS is based on an array of waveguide Mach-Zehnder interferometers [1]. The array intercepts input light from an external source into multiple waveguide apertures along the facet of a silicon wafer, which greatly enhances the optical throughput compared to single-input waveguide spectrometers. We discuss progress in the design and calibration and review latest experimental results of the device. We propose using waveguide gratings for coupling the input light into the SHS.

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7594-39, Session 8

MOEMS for space application: The European Space Agency strategy for photonics components

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Miniaturisation of scientific instrumentation for space applications leads to better use of the available resources (e.g. volume, mass and power), and create the potential to integrate more complex functionality. MEMS and in particular MOEMS devices have already a wide range of application in terrestrial industries (beamers, telecom switching, etc). MOEMS are, of course, very promising for future space applications because of their potential to reduce mass, size and consequently launch costs. However, ESA interest in MOEMS is before all generated by their mission enabling capabilities such as for example MEMS shutters or micro-mirrors for MOS (multi -object spectrometers).

The general objective of this presentation is to demonstrate the potential of micro-opto-electro-mechanical system (MOEMS), and the available European sources for MOEMS components with applications in space. The presentation will also give a general overview of ESA strategy for Photonics components with space application in mind. This strategy is expressed in the Photonics dossier currently being drafted to secure future technology needs related to European space activities for the next 5 years.

7594-30, Session 9

Miniaturized tunable integrated Mach-Zehnder MEMS interferometer for spectrometer applications

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In this work we present a novel miniaturized Mach-Zehnder MZ interferometer fabricated by Deep Reactive Ion Etching DRIE technology on an SOI wafer. The new structure is based on the use of two Si/Air beam splitters, and two metallic mirrors fabricated simultaneously in a single lithography step. The Mirrors are actuated by single comb drive actuator to ensure their continuous alignment with the splitters. The complete interferometer structure is integrated in a small footprint measuring 1 mm x 2 mm. The structure is tested using an infrared tunable laser source in the C band and optical fringes are recorded. Moving the mirrors allows to control the optical path difference OPD of the interferometer and thus to control the fringes. The two outputs of the interferometers are then measured using IR detectors and the complementary nature of the outputs is demonstrated. Measuring the output optical intensity of the interferometer as a function of the OPD and then using the Fourier transform technique is then used to get the spectrum of the input source. By this FT spectroscopy technique the structure has been used to successfully identify the two wavelengths 1525 nm and 1575 nm with a comb drive motion of only 20 microns. The structure has many advantages as it allows to obtain the two complementary outputs of the interferometer and thus to cancel the source fluctuation noise and increase the signal to noise ratio. In addition, the integrated nature of the structure opens the door for more complicated structures fabricated self-aligned by simple one step lithography

7594-31, Session 9

Miniaturized MEMS-based spectrometric sensor for process control and analysis of carbonated beverages

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MEMS is an enabling technology to realize compact and reliable NIR and mid-IR analyzers with good spectral properties and outstandingly fast response times. Furthermore the excellent mechanical stability of MEMS has the potential for being used as in-line sensor flanged directly to the main process pipeline. In this context a MEMS based sensor for the measurement of dissolved carbon dioxide for quality control of carbonized beverages and beer is of certain interest. At present dissolved CO2 in beverages is determined mainly by measuring the partial gas pressure. This method is well proven but has several drawbacks e.g. the error of measurement introduced by other dissolved gases, and the need of complex and bulky mechanics leading to high costs especially in applications where in- or on-line measurements are demanded. The spectrometric approach offers an alternative for the measurement of CO2(aq) with the advantage of not being interfered by other gases. A recently developed compact spectrometer based on a micro-electro-mechanical reflective scanning grating has been further developed for mid-IR operation, especially to observe the absorption band of CO2(aq) at 2343cm-1. With a 25µm flow cell in a transmission setup, 3000 single scans were averaged to generate an adequate SNR yielding a repetition time of about 20 seconds. A calibration curve was obtained by measuring different CO2aq absorptions which result from different concentrations of NaHCO3 in a citric acid puffer at pH3. The resulting calibration curve is linear in a very good approximation. However, with this setup the detection limit was determined at 0.5g/l CO2(aq)

7594-32, Session 9

Recent advances in expanding the spectral range of MEMS Fabry-Pérot filters

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We already published our work on FPF for the spectral range of 3-5 µm. The reflectors are made of poly-Si and SiO2 (Bragg reflectors). The filters have a large aperture of 2x2 mm² and a Finesse of 40 up to 60 and are therefore well suited for infrared absorption spectroscopy. However, the limitation to the spectral region of 3-5 µm is unsatisfactory. Our main objective has therefore been to expand the spectral range to higher wavelengths. In gas analysis, the 8-11 µm region is of particular interest, because many gases have strong and well separated absorption bands in this region.

Our first approach is to use an already proven electromechanical design with thick and stiff reflector carriers and electrostatic tuning of the optical resonator gap. The formerly used SiO2 low refractive index material cannot be applied within the Bragg reflectors anymore, because the extinction coefficient increases dramatically above 6µm. For this reason we now make use of the thin-film coating technology, which is established in the fabrication of optical filters and makes it possible to use alternative infrared materials. Besides a state-of-the-art material system a new system is under development, which introduces a new low refractive index material.

Different reflector designs have been developed, fabricated and tested. The results of a standard (LH)x reflector compared to the reflectors made with the new material clearly show that a relatively simple design with a low number of layers results in a broad bandwidth since the refractive index contrast is much higher.

We will also report our new tunable MEMS FPF for the spectral range of 8-11 µm. The half power bandwidth is in the range of 200 - 300 nm and the peak transmittance has been determined to be 35 % to 55 %. Bragg reflectors typically show a dispersion of the phase shift on reflection. It reduces the free spectral range and increases the mechanical travel which is required to spectrally tune the filter. A low number of layers and a high refractive index contrast also reduces the dispersion in case of the alternative reflector.

7594-33, Session 9

Prototyping of SWIR MEMS-based optical filter combined with HgCdTe detector

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In the past decades, there have been several attempts to create a tunable optical detector with operation in the infrared. The drive for creating such a filter is its wide range of applications, from passive night vision to biological and chemical sensors. Such a device would combine a tunable optical filter with a wide-range detector. In this work, we propose using a Fabry-Perot interferometer centered in the short wave infrared (SWIR) spectrum with an HgCdTe detector. Using a MEMS-based interferometer with an integrated Bragg stack will allow in-plane operation over a wide range. Because such devices have a tendency to warp, creating less-than-perfect optical surfaces, the Fabry-Perot interferometer is prototyped using the SOI-MUMPS process to ensure desirable operation. The mechanical design is aimed at optimal optical flatness of the moving membranes and a low operating voltage. The prototype is tested for these requirements. An HgCdTe detector provides greater performance than a pyroelectic detector used in some previous work, allowing for lower noise, greater detection speed and higher sensitivity. Both a custom HgCdTe detector and commercially available pyroelectric detector are tested with commercial optical filter. In previous work, monolithic integration of HgCdTe detectors with optical filters proved to be problematic. Part of this work investigates the best approach to combining these two components, either monolithically in HgCdTe or using a hybrid packaging approach where a silicon MEMS Fabry-Perot filter is bonded at low temperature to a HgCdTe detector.

7594-34, Session 9

Design and fabrication of a micro-mirror for spectroscopy

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A wide variety of MEMS micro-mirrors are being developed for various optical applications. This paper deals with process optimization for fabrication of a micro-mirror and its application in Fourier Transform Spectrometry (FTS). Large, non-tilting displacements of micro-mirrors are required to achieve high FTS resolution. In order to achieve this without using Deep Reactive Ion Etching (DRIE), the micro-mirrors were fabricated on silicon using bulk micromachining techniques. This paper will present results on the process developed for fabrication of a mirror with the required specifications and the FTS experiments conducted with the micro-mirror as part of the interferometer set-up. A Michelson interferometer is used as part of the FTS. As optical frequencies are too high to be detected directly, they are mixed with a lower frequency introduced by a vibrating (MEMS) mirror in one arm of the interferometer. The beat frequency of the optical and the mirror frequencies is then detected by taking the Fourier transform of the interferometer output.

Initially the interferometer was used with a macromirror vibrating at 19 Hz and 1.5 Vpp as characterization of the mirror showed that it traveled maximum distance for these values. Two source inputs were coupled into the interferometer and the FT output as captured by a Digital Oscilloscope (DSO. The source was replaced with a single 1525 nm source and the mirror was replaced with a micro-mirror. An ac voltage of 20 V, 50 Hz was applied to it and the source frequency could be detected from the Fourier transform output.

Conference 7595: MEMS Adaptive Optics IV

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7595-01, Session 1

Interferometric adaptive optics testbed for laser pointing, wave-front control, and phasing

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Implementing the capability to perform fast ignition experiments, as well as, radiography experiments on the National Ignition Facility (NIF) places stringent requirements on the control of each of the beam's pointing, intra-beam phasing and overall wave-front quality. A testbed was constructed to evaluate the ability of an interferometric adaptive optics system to meet these phasing, pointing and higher order beam aberration control requirements. Experimental results are presented from this testbed and include quantification of the reduction in Strehl ratio incurred when using the MEMS device to correct for pointing errors in the system. The interferometric adaptive optics system achieved a Strehl ratio of 0.83 when correcting for a piston, tip/tilt error between two adjacent rectangular apertures, the geometry expected for the Advaced Radiographic Capability(ARC) on the National ignition Facility. The interferometric adaptive optics system also achieved a Strehl ratio of 0.66 when used with a piston-only MEMS device to correct for a phase plate aberration of similar magnitude as expected from simulations on the ARC beam line. All of these corrections included measuring both the upstream and downstream aberrations in the testbed and applying the sum of these two measurements in open-loop to the MEMS deformable mirror.

7595-02, Session 1

Phasing rectangular apertures

K. L. Baker, Lawrence Livermore National Lab. (United States)

Several techniques have been developed to phase apertures in the context of astronomical telescopes with segmented mirrors. Phasing multiple apertures, however, is important in a wide range of optical applications. The application of primary interest in this paper is the phasing of multiple short pulse laser beams for fast ignition fusion experiments. In this paper analytic expressions are derived for parameters such as the far-field distribution, enclosed energy or energy-in-a-bucket and center-of-mass that can then be used to phase two rectangular apertures. Experimental data is taken with a MEMS device to simulate the two apertures and comparisons are made between the analytic parameters and those derived from the measurements. Two methods, fitting the measured far-field distribution to the theoretical distribution and measuring the enclosed energy or energy-in-a-bucket in the far-field, produced overall phase variance between the 100 measurements of less than 0.005 rad2 or an RMS displacement of less than 12 nm.

7595-03, Session 1

Low power MEMS retroreflectors for optical communication

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We report on the design, development and testing of a new low-power, light-weight and low-cost modulating retroreflector system for free-space covert optical communication and remote sensor interrogation. The central component of the system is a MEMS modulator mirror, which is physically similar to a "very low modulation" reflective diffraction grating that has actively controlled groove depth and can operate at frequencies up to 1MHz. One facet of the hollow corner cube retroreflector consists of the MEMS mirror, providing intensity modulation of a reflected interrogating beam by switching from an un-powered flat mirror state to a powered diffractive state. The system is optimized for performance at 1550nm and has a field of view >40 degrees. For covert operation it uses "wake-up" circuitry to control a low-power shutter that remains closed between data transfers. The system's compact driver electronics employs power scavenging and resonant properties for minimal power consumption and extended autonomous operational life. Interrogation field test results for the modulating retroreflector will be presented.

7595-04, Session 1

High-power visible-laser effect on a 37-segment Iris AO deformable mirror

A. P. Norton, Univ. of California, Santa Cruz (United States); D. T. Gavel, D. Dillon, Univ. of California Observatories (United States)

The Laboratory for Adaptive Optics (LAO) is exploring the use of Iris AO's 37-segment micro-electrical mechanical system (MEMS) deformable mirror (DM) for laser uplink correction in Phase II of the Visible light laser guidestar experimental system (Villages). A MEMS DM will be used to correct the Laser Guide Star (LGS), as it is projected from the 40" Nickel telescope, to a diffraction limited spot on the mesosphere. This will reduce the power needed for the LGS while simultaneously increasing the efficiency of wavefront sensing. However, the response of a MEMS DM to high-power incident light, such as the 10 watts required for uplink correction, is not well understood. In an effort to measure and characterize the response of the MEMS DM, the LAO has designed tests to qualify the use of the 37-segment DM for uplink laser correction. Results of the DM's temporal stability and position repeatability will also be presented.

7595-05, Session 1

Fast autonomous holographic adaptive optics

G. P. Andersen, U.S. Air Force Academy (United States)

We have created a new adaptive optics system using a holographic wavefront sensing method incorporating autonomous (computer-free) closed-loop control of a MEMS deformable mirror. The system is compact, lightweight and extremely fast.

Our holographic adaptive optics system consists of a multiplexed hologram for the wavefront sensing. Many holograms are recorded using the maximum and minimum actuator positions on the deformable mirror as the "modes". On reconstruction, an input beam will be diffracted into multiple focal spots - the ratio of particular pairs determines the absolute wavefront phase at a particular actuator location. The phase error can thus be measured using a fast, sensitive photo-detector array such as a multi-pixel photon counter. This information is then used to directly control each actuator in the MEMS DM without the need for any computer in the loop.

We will present results of a 32-actuator prototype device. Our tests show the system, which has a footprint no bigger than a standard sheet of paper, can operate at speed limited only by the driving frequency of the DM and not by the number of actuators Furthermore, being modal in nature the system is largely insensitive to obscuration and scintillation.

7595-06, Session 2

Progress report for visible light laser guidestar experiments at Lick Observatory

D. T. Gavel, Univ. of California Observatories (United States)

We present an update on the Visible Light Laser Guidestar Experiments (ViLLaGEs) taking place at the Lick Observatory. The goal of phase one of these experiments is to demonstrate the practical feasibility of using MEMS deformable mirrors in astronomical adaptive optics systems, including the use of open-loop wavefront sensing and control. The goal of phase two is to incorporate a laser guide star and demonstrate laser up-link correction, again using a MEMS deformable mirror running in open-loop. The overall set of experiments is designed to demonstrate these and various other new concepts leading to feasible and low-cost laser guidestar adaptive optics that can be used for science observing in the visible wavelength bands.

7595-07, Session 2

The MEMS adaptive optics program at the Naval Research Laboratory

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

7595-08, Session 2

Using two MEMS deformable mirrors in an adaptive optics testbed for multi-conjugate correction

J. R. Andrews, T. Martinez, U.S. Naval Research Lab. (United States); S. W. Teare, New Mexico Institute of Mining and Technology (United States); S. R. Restaino, C. C. Wilcox, F. Santiago, U.S. Naval Research Lab. (United States); D. M. Payne, Narrascape, Inc. (United States)

Adaptive optics (AO) systems are well demonstrated in the literature with both laboratory and real-world systems being demonstrated. Some of these systems have employed MEMS deformable mirrors as their active corrective element. More recent work in AO for astronomical applications has focused on providing correction in more than one conjugate plane. This provides challenges for a laboratory system as the aberrations need to be generated and corrected in more than one plane in the optical system. Our work with compact AO systems employing MEMS technology in addition to liquid crystal spatial light modulator (SLM) driven aberration generators has been scaled up to a two conjugate plane testbed. Using two SLM based aberration generators and two separate wavefront sensors, the system can apply correction with two MEMS deformable mirrors. The challenges in such a system are to properly match non-identical components and weight the correction algorithm for correcting in two planes. This paper demonstrates preliminary results with this system.

7595-09, Session 2

Reliability of MEMS deformable mirror technology used in adaptive optics imaging systems

A. L. Hartzell, S. A. Cornelissen, P. A. Bierden, C. V. Lam, D. Davis, Boston Micromachines Corp. (United States)

Deformable mirror (DM) technology based on microelectromechanical systems (MEMS) technology produced by Boston Micromachines Corporation has been demonstrated to be an enabling component in a variety of adaptive optics applications such as high contrast imaging, multi object adaptive optics, free-space laser communication, and microscopy. Many of these applications require DMs with thousands of actuators operating at frame rates up to 10 kHz for many years requiring sufficient device reliability to avoid device failures. In this paper we present improvements in MEMS deformable mirrors for reliability along with test data and device lifetime prediction that show trillions of actuator cycles can be achieved without failures.

7595-10, Session 2

Preliminary results of large-actuator-count MEMS DM development

M. A. Helmbrecht, M. He, P. Rhodes, C. J. Kempf, Iris AO, Inc. (United States)

Large actuator count DMs are necessary for correcting aberrations in applications where the Fried's parameter is small relative to the primary aperture or for extremely high-contrast imaging. In support of these applications, Iris AO has been developing MEMS fabrication processes to scale to 10^3 piston/tip/tilt (PTT) segment DMs. The first short-loop lot, which did not include a wiring layer, started fabrication in May 2008. Preliminary results from this lot were discussed at Photonics West 2009. Since then, a second prototype lot has been completed that includes a dedicated wiring layer. Wafers from this lot contain fully wired 111-actuator, 37-PTT-segment and 489-actuator, 163-PTT-segment DMs. The wafers also contain a 925-segment demonstration array where banks of actuators have been electrically ganged together.

This paper will present an overview of the fabrication process and will present results from the development. Actuator yields and failure modes from the second lot will be presented. Testing methodologies used to ascertain electrical and mechanical yields will be described here as well. Finally, electromechanical test results from 489-actuator, 163-PTT-segment DMs and 925-segment demonstration DMs will be presented.

7595-11, Session 2

Open loop control on large stroke MEMS deformable mirrors

A. Diouf, T. G. Bifano, A. Legendre, Y. Lu, Boston Univ. (United

States); J. B. Stewart, Boston Micromachines Corp. (United States)

BU/BMC MEMS DMs can be shaped predictably in a single step to nanometer-scale precision, enabling open loop AO control. That characteristic has profound implications in new astronomical instruments such as the multi-object adaptive optics (MOAO) and extreme adaptive optics (ExAO). In a recent past, we developed an AO control algorithm routine for limited stroke and simplified shapes. We extend the model to DMs with larger achievable stroke and many more actuators as would be required in MOAO. A significant challenge in extending the algorithm to larger stroke is that large deflection can experience considerable stretching of the actuator membrane in addition to the bending that dominates behavior at small deflection. The stretching non-linearity combined with actuator non-uniformity complicate the calibration step routine, a central part of the algorithm. Fast, efficient calibration of all actuators as opposed to a single actuator, optimized filtering, and a characterization of all intrinsic sources of errors will be presented in evaluating the DM capability for AO control at large strokes (>1 microns).

7595-12, Session 2

Modeling, parameter estimation, and open-loop control for MEMS deformable mirrors

C. R. Vogel, Montana State Univ. (United States)

In this talk we will review a MEMS modeling approach based on continuum mechanics (partial differential equations). We will present a robust, efficient output least squares approach to estimate model parameters, and we will introduce a fast new algorithm for open-loop control based on multigrid solution to the model equations.

7595-13, Session 3

Adaptive optics for microscopy and photonic fabrication

M. J. Booth, A. Jesacher, A. Thayil, T. Wilson, Univ. of Oxford (United Kingdom)

The image resolution and contrast of microscopes are often detrimentally affected by aberrations that are introduced when focusing deep into specimens. These aberrations arise from spatial differences in optical properties of the specimen or refractive index mismatches. This is particularly problematic in multiphoton microscopy, where short pulsed lasers are used to generate contrast through non-linear optical effects, such as two-photon fluorescence or third harmonic generation. The non-linear nature of the signal generation process means that the signal level is strongly affected by changes in the focal spot intensity. We have applied the techniques of adaptive optics to measure and correct the aberrations, restoring image quality. In particular, this has been demonstrated in two-photon fluorescence and harmonic generation microscopy of developing mouse embryos.

Similar aberration problems affect the resolution and efficiency of three-dimensional optical fabrication systems, such those used for the manufacture of photonic crystals or optical waveguides. These systems are based around microscope optics and use short pulsed laser illumination to induce localized multiphoton effects in a fabrication substrate. In this case, significant aberrations are introduced when focusing deep into the substrate. We report on the development of adaptive optics systems for these applications and discuss the specific challenges for wave front sensing and correction that are presented by these systems. We show the benefit of aberration correction in increasing the effective fabrication depth.

7595-14, Session 3

Adaptive optics multiphoton microscopy

E. Gualda, J. M. Bueno, P. Artal, Univ. de Murcia (Spain)

Non-linear microscopy techniques are important tools in medical and biological research. These techniques might be significantly improved when combined with wavefront-assisted approaches and adaptive optics, reducing the required excitation power levels and minimizing phototoxicity side-effects. In this presentation, we will revise the impact of the aberrations of the illuminating laser beam in the quality of the images. In particular some examples of imaging ex-vivo ocular tissues will be presented. We have developed an improved version of a multiphoton microscope with optimized wavefront of the laser beam and adaptive optics control. The multiphoton imaging system combines an ultrafast high-power laser, a scanning unit, a motorized Z-scan device and a photon-counting detector. A Hartmann-Shack wavefront sensor was included in the illumination pathway to measure the aberrations of the incoming beam in real time. These wavefront aberrations were fairly constant over time and the main contribution is due to low order aberrations (defocus and astigmatism). This indicates that simple static correction of low-order aberrations would produce a significant increase in the detected nonlinear signal. The dynamic correction of higher-order aberrations with a MEMS deformable mirror should produce an additional benefit. TPEF and SHG images of ex-vivo corneal and retinal tissues were recorded for different beam wavefronts. Results show that an accurate control of the illuminating beam wavefront increases the contrast and resolution in nonlinear microscope images of ocular tissues. This indicated the potential of this approach for the development of new clinical tools for diagnosis of ocular pathologies.

7595-15, Session 3

Femtosecond NIR pulse shaping with push pull deformable mirror

S. Bonora, D. Brida, C. Manzoni, S. De Silvestri, G. Cerullo, CNR-INFM ULTRAS (Italy); P. Villoresi, Univ. degli Studi di Padova (Italy)

Femtosecond pulses close to few cycles duration are a very important tools in the study of molecular processes in time domain. Coherent control of atomic dynamics is an emerging subject which will exploits this technology. We present novel schemes for the generation of tailored pulses of ultra broadband spectrum in the Near Infrared. Such spectral regions are very difficult to manage with Liquid Crystals, acusto optic modulators and AOPDF because they are extremely broad.

We present a novel design of membrane electrostatic deformable mirror actuated on both sides of the membrane allowing for very large membrane stroke. With this mirror we demonstrated both compression to transform limit an pulse shaping of an ultrabroadband NOPA with a spectrum spanning from 1μm-1.7μm.

The mirror is composed by a rectangular (45mm x 15mm) silver coated nitrocellulose membrane. The membrane is placed between two arrays of 30 linear electrodes.

In order to start our work of pulse shaping we initially compress the pulse down to 8.54fs very close to its transform limit of 8.2fs. Then we applied the spectral phase calculated to generate the some interesting pulse time profile. We generated double and triple pulses with controllable separation up to 150fs with a 20fs pulse length.

7595-16, Session 3

Implementation of an adaptive optics wide field microscope using a Shack-Hartmann wavefront sensor and a MEMS deformable mirror

O. A. Azucena, Jr., J. A. Kubby, Univ. of California, Santa Cruz (United States)

Adaptive optics (AO) improves the quality of astronomical imaging systems by using real time measurement of the turbulent medium in the optical path using a guide star (natural or artificial) as a point source reference beacon. AO has also been applied to vision science to improve the current view of the human eye. This paper will address our current research focused on the improvement of fluorescent microscopy for biological imaging utilizing current AO technology. An Adaptive Optic Wide Field Microscope (AOWFM) was constructed and tested. The AOWFMA's Shack-Hartmann wavefront sensor (SHWS) was used to measure the aberration introduced by two different biological samples, a Drosophila Melanogaster embryo and a mouse breast sample were each implanted with a one micron fluorescent bead that serves as a point source reference beacon. We employed a MicroElectroMechanical System (MEMS) Deformable Mirror (DM) from Boston Micromachines (Multi-DM) with 140 actuators and 3.5 microns of stroke. Results from the reconstructor and the control algorithm used to apply the wavefront to the DM will be discussed. Characterization results of the MEMS DM will also be discussed.

7595-17, Session 3

New results of unimorph laser mirrors with screen printed actuator

C. Bruchmann, Fraunhofer Institute for Applied Optics and Precision Engineering (Germany) and Friedrich Schiller Univ. of Jena (Germany); R. Eberhardt, E. Beckert, Fraunhofer Institute for Applied Optics and Precision Engineering (Germany); A. Tünnermann, Fraunhofer Institute for Applied Optics and Precision Engineering (Germany) and Friedrich Schiller Univ. of Jena (Germany)

This paper reports on new results of the development of a unimorph laser beam shaping mirror based on Low Temperature Cofired Ceramics (LTCC). The deformable mirror is actuated by a side screen printed piezoceramic thick film based on lead zirconate titanate (PZT). The reflective surface is electroplated copper that is diamond machined after.

We built two types of mirrors with two different membrane diameters. The diameter of the small mirror is 20 mm and the larger one is 35 mm diameter. The small mirror exhibit one actuator. The large mirror exhibits up to 19 actuators. The stroke amounts from 10 µm for the small mirror to 40 µm for the large mirrors. We will present results on deflection (influence matrix) and bandwidth for different mirror designs. Especially the influence of the electroplated copper height is shown.

7595-18, Session 4

Bimorph mirrors and other correctors: What is the best?

A. V. Kudryashov, V. V. Samarkin, A. L. Rukosuev, Moscow State Open Univ. (Russian Federation)

In this paper we would like to compare various types of deformable mirrors and expect to answer the famous question - which kind of corrector is the best? And for what kind of application.

7595-19, Session 4

Results, images and strategy control of the mirao 52e, large stroke electromagnetic deformable mirror, for non linear microscopy

J. Ballesta, Imagine Optic Inc. (United States)

Optical microscopy is an inescapable technique in the life sciences, in particular for studying the intracellular organisation of biochemical events. However, there is an increasing need in a variety of fields (neurophysiology, developmental biology, biopsy, ...) to image cells in their native environment, i.e. intact tissue. The task is difficult because tissues are heterogeneous media that strongly affect light propagation, causing large amounts of scattering and wavefront aberration at large depths. These effects reduce the signal and contrast in usual optical techniques (such as confocal microscopy), and prevent them to provide images deep within intact tissue.

In this article we will present first qualitative and quantitative results obtained with the mirao 52 e, large stroke electromagnetic deformable mirror developped and supported by Imagine optic, and detailed different strategy of control developped to increase drastically image resolution of several type of non linear fluorescence microscopy.

7595-20, Session 4

Adaptive optics control system for segmented MEMS deformable mirrors

C. J. Kempf, Iris AO, Inc. (United States)

Segmented MEMS DMs, unlike continuous face-sheet designs, have advantages in terms of optical quality and coating versatility, ease of calibration, and design scaling. Control of such mirrors has not received the same level of attention as for continuous face-sheet devices. Perceptions that Shack-Hartmann based closed-loop control of such devices is difficult have been proven to be unfounded. With a properly selected lenslet array and control strategy, the on-line computations can be structured in a particularly simple form suitable for low-cost digital signal processors. Iris AO has developed a full closed-loop control system which relies upon a wavefront sensor matched to the DM geometry and utilizes well-known modal techniques to represent the wavefront. Segment-by-segment calibration is used to assure reliable open loop operation and allows mirror commands to be specified as positions rather than voltages. This combination of matched sensing, modal wavefront representation and reliable open loop operation enables reliable closed-loop operation inherently free of problems related to co-phasing segments or undetectable waffle patterns. This controller has been implemented on a PC and has been applied to test-beds and research instruments utilizing Iris AO's 111 actuator (37 segment) deformable mirrors. The algorithm has also been benchmarked on an inexpensive, stand-alone, DSP-based system and it easily runs at the relatively low frame rates (30Hz) required in vision-science and biological imaging. Development and refinement of the stand-alone system as well as extensions to higher frame rates is currently underway.

7595-21, Session 4

Development of through wafer interconnect assembly process for MEMS DMs

A. Diouf, T. G. Bifano, Boston Univ. (United States); J. B. Stewart, S. A. Cornelissen, Boston Micromachines Corp. (United States)

The development of MEMS deformable mirrors (DMs) with through-wafer electrical interconnects is needed for future adaptive optics applications requiring 4000 or more actuators per device. Current MEMS DMs typically contain 140-1000 actuators and their scalability is primarily limited by the area occupied by the wirebonds. The development and integration of an assembly process that uses through-wafer

interconnects eliminate the actuator scalability barrier while maintaining minimal optical footprint. The fabrication method presented here uses through-wafer interconnects to vertically connect devices to underlying electronics. It combines flip chip bonding, existing through-wafer via technology, and proven MEMS DMs fabrication processes to provide an electrical signal path from the back of the device to the front of the silicon wafer, where the DM is fabricated. This approach eliminates the area previously used for the peripheral bond pads and wire routing. The connections are established in a single fabrication step (parallel bonding) unlike wire-bonding where every single bond is individually attached with an automatic robotic bonding apparatus (serial bonding).

Two flip chip bonding methodology for MEMS DMs will be presented. The first one involves a generic thermocompression bonding process using gold studs. The second one involves using isotropic or anisotropic adhesives and gold studs. Due to the cost and manufacturing restrictions of metals used in bonding, a flip chip solution that uses a silicon interposer board was selected for assembly process demonstration. Using an interposer provides the ability to transfer the fine pitch of through wafer via connections to something larger and easier to connect with.

7595-22, Session 4

Study on dual movement of microdeformable mirror

J. Yao, F. Hu, H. Ren, L. Huang, Institute of Optics and Electronics (China)

With the rapid developments of design theories and micromachining techniques, MEMS (Micro - electro - mechanical - system) has found diverse applications in many novel and unique uses, which generally are difficult or not possible to be addressed by the miniaturization of conventional systems, such as WDMs (Wavelength division multiplexing) [1], DMD (Digital mirror device), and RF (Radio frequency) MEMS, etc. For the unique advantages of large number actuators, high bandwidth, large deflection and short response time, the electrostatic-driven micro deformable mirrors have been actively implemented in optical communications and AO (Adaptive Optics) systems. However, the working mechanism applied to most of their actuators is an attractive force generated by an electrostatic field, this leads to further considerations on the pull-in effect and depositions of thicker sacrificial layers. Alternative mechanism based on repulsive forces through specific layout of electrodes and its relevant discussions have been reported in details [2], however, it can not avert the major drawback of solo moving direction of the micro mirror. In this paper, we propose a novel design of dual-movement micro mirrors, which is able to move towards and move away from bottom electrodes of the actuator from the balanced level plane, i.e. the position where there is no electric loads applied, it therefore achieves larger deflections without inputting higher voltages. Design of segmented mirrors has been studied, and its optical effects cause by separating gaps and etching holes have also been investigated.

[1] X.M. Zhang, F. Chollet, F.S. Chau, C. Quan, A.Q. Liu, “Polysilicon micromachined 3D mirror integrated frequency tuner for WDM applications”, Proc. SPIE 4178, 278-287, 2000.

[2] Jun Yao; Fangrong Hu; Dongmei Cai; Wenhan Jiang, “Design and analysis of repulsive electrostatic driven MEMS actuators”, Proc. 7209, 2008.

7595-23, Session 4

Pseudo-analog electrostatic piston micromirror

T. E. Dallas, H. Gu, G. Sivakumar, Texas Tech Univ. (United States)

We report on the design, simulation, fabrication and testing of a pseudo-analog micromirror. An electrostatically actuated piston micromirror was fabricated using the SUMMiT V process with a goal of achieving nearly analog displacement using digital voltage control. The mirror is controlled by multiple electrodes with varying areas that correspond to a binary system. As an example, a mirror is actuated using four electrodes with unit areas of 1, 2, 4 and 8. The same voltage level is applied to one or more of the electrodes to control the vertical displacement. This arrangement will allow up to 16 different displacements, with more levels possible with a larger number of electrodes. The system is amenable to digital control and can be scaled to large arrays. Parametric numerical models built in ANSYS simulations were used to predict performance and further refine the design parameter values derived from the theoretical models. An interferometric microscope has been used to measure the vertical displacement of the mirrors. Experimental results have shown that mirror displacement is directly proportional to the total electrode area used to actuate the mirror. Reasonable repeatability in displacement has been seen for a mirror actuated by the same total electrode area and voltage.

7595-24, Session 4

Hi-speed compact and large stroke deformable mirror: status, applications and perspectives

F. Rooms, S. Camet, J. Curis, ALPAO (France)

Membrane deformable mirrors based on magnetic actuators have been known for years. State-of-the-art deformable mirrors usually have large strokes but low bandwidth. Furthermore, this bandwidth decreases with the diameter. In this paper, we present the status of a new actuator principle based on magnetic forces allowing high bandwidth (up to a few kHz), very large large stroke (>30µm) with a record pitch of 1.5mm.

The benefits of this technology will be presented for three applications: astronomy, vision science and microscopy. The parameters of the technolgoy have been tuned for astronomy (more than 2.0µm of the inter-actuator stroke and increased bandwidth) in order to fit the atmosphere turbulence characteristics.. In vision science, efforts have been made to correct both simultaneously the low and high order aberrations (more than 45µm of wavefront correction on astigmatism and focus). Finally, we will demonstrate how we have developed a deformable mirror able to correct aspherical aberrations (microscopy). The last part of the article is devoted to give some perspectives about this technology.

Conference 7596: Emerging Digital Micromirror Device Based Systems and Applications II

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Emerging Digital Micromirror Device Based Systems and Applications II

7596-01, Session 1

Surgical and clinical needs for DLP® hyperspectral imaging

E. Livingston, The Univ. of Texas Southwestern Medical Ctr. at Dallas (United States)

Hyperspectral imaging provides real time biochemical imaging by augmenting conventional imaging modalities using light ranging from visible to NIR wavelengths. Because chemicals have unique spectra, they can be identified by matching the observed spectra to that expected for the chemical of interest. This technology has been enabled by several important technological advances. The first breakthrough was the applications of novel chemometric approaches analyzing measured spectra at each pixel detector. The speed of Texas Instruments DLP® technology illuminating human organs greatly increased the systems performance resulting in chemically encoded images at near video rates. This technology has many potential applications in medically relevant fields for example Surgery, Gastroenterology, Urology, Neurology, Ophthalmology, Plastic, Anesthesiology and Pathology will be discussed.

7596-02, Session 1

DLP® technology's pivotal role in O2view's versatile medical projection / illumination device

R. G. M. van Melick, O2view BV (Netherlands)

The design of a versatile pattern light projection device was an essential step in the development of O2view's Artemis Broad Spectrum Vision System for surgical oncology. During medical imaging procedures, specific patterns of projected NIR-light contribute to better visibility of hidden structures and consequently to best possible depth vision.

Several performance criteria had to be met: The mixing various wavelengths from different light sources via a 3-channel prism, the projector's zoom function to follow the Artemis camera zoom settings, the angle of projection to adapt to the full working distance range, and the integration of O2view´s custom camera controls with the DLP-chip.

The development project with all its considerations will be presented, as well as the final result. For many other medical (laser/LED) applications the presented innovative projection / illumination device might be of significant benefit.

7596-03, Session 1

The robustness of DLP® hyperspectral imaging for clinical and surgical utility

K. J. Zuzak, The Univ. of Texas at Arlington (United States); M. Litorja, National Institute of Standards and Technology (United States); R. Ufret-Vincenty, J. A. Cadeddu, E. Livingston, The Univ. of Texas Southwestern Medical Ctr. at Dallas (United States)

Utilizing seed funding from Texas Instruments a DLP® Hyperspectral Imaging system was developed by integrating a focal-plane array, FPA, detector with a DLP based spectrally tunable illumination source. DLP technology provides the capability of varying center wavelength, bandpass, and illumination intensity at each center wavelength capable of producing light illumination consisting of a precisely predetermined spectrum. Software is used to synchronize the FPA with the DLP hardware for collecting spectroscopic images, as well as, running novel illuminations schemes and chemometric deconvolution methods for producing gray scale or color encoded images visualizing molecular constituents at video rate. The system was translated to the UTSW Medical Center where it is being used to monitor several clinically and surgically relevant applications helping physicians visualize disease. Optical spectra and spectroscopic image data of a variety of live human organs and diseased tissue was collected from patients during surgical procedures and clinical visits being cataloged for a database will be presented.

7596-04, Session 1

Application of novel hyperspectral imaging technologies in combat casualty care

L. C. Cancio, U.S. Army Institute of Surgical Research (United States)

Combat Critical Care Engineering (C3E) is a new Army medical research program directed at improving care on the battlefield by responding to a Critical Care Technology Gap. This gap exists because it is difficult to provide the same state-of-the-art care on the battlefield as can be provided in a U.S. trauma center Emergency Department (ED) or Intensive Care Unit (ICU). Technology includes hardware and software systems which incorporate sensors, processors, and effectors. Specifically, the program seeks (1) New Vital Signs, i.e. improved patient monitors that predict the need for lifesaving interventions more accurately; (2) Automated Critical Care systems that provide automation of difficult critical care tasks; and Better Effectors for support of organ function. In this technology model, novel imaging methods may play several important roles: (1) Hyperspectral imaging (HSI) of the skin may provide spatial data on hemoglobin saturation of oxygen, as a "window" into adequacy of perfusion during shock. Given adequate time resolution, such imaging may further be able to track fluctuations in the data as a measure of autonomic nervous system function. (2) HSI may provide information about tissue viability and/or wound infection not available from other modalities. (3) HSI in the near-infrared range may provide information on the tissue water content--greatly affected, e.g., by the fluid resuscitation process. (4) Devices based on HSI or similar technology could be incorporated into closed-loop, feedback-controlled resuscitation systems. Further refinements in the speed and size of HSI systems are sought to make these capabilities available on the battlefield.

7596-05, Session 2

Spatial mapping of oxygen levels in the brain using a digital micromirror device

A. K. Dunn, A. Ponticorvo, The Univ. of Texas at Austin (United States)

Mapping of absolute oxygen levels in the brain is critical during stroke and other disorders. One of the standard methods for measuring oxygen tension is through oxygen dependent quenching of phosphorescence. Typically these measurements are limited to a single spatial location due to the need to measure phosphorescence lifetimes. We have developed an instrument to obtain spatial maps oxygen tension in the brain by combining a DMD with phosphorescence lifetime measurements. Blood flow is measured simultaneously with laser speckle contrast imaging. In this talk we will describe this instrument and demonstrate its use in studying stroke progression in animal models.

7596-06, Session 2

Use of a spectrally-tunable source to explore improvement in chromatic contrast for illumination of tissues

M. Litorja, B. Ecker, National Institute of Standards and Technology (United States)

Human vision by a clinical practitioner is often the first disease detection tool. Illumination for such procedures as endoscopy use broadband white light, with luminance level being the only control available. The use of staining dyes for contrast improvement have shown limited adoption due to the additional steps needed and small number of approved dyes for in vivo use. Here we explore the control of the illuminant spectral distribution to improve chromatic contrast without the use of dyes. The computational steps used in converting spectral data to RGB and use of the CIELAB chromatic and luminance contrast metric as criteria in determining the appropriate lighting spectral distribution will be discussed.

7596-07, Session 2

Confocal fluorescence detection of cell-based assays using a digital micromirror device

J. Choi, Yonsei Univ. (Korea, Republic of); J. H. Sung, M. L. Shuler, Cornell Univ. (United States); D. Kim, Yonsei Univ. (Korea, Republic of)

We report the development of a confocal fluorescence detection system based on fluorescence microscopy using a digital micromirror device (DMD). A DMD can offer transverse surface scanning with programmable light modulation at an ultrahigh speed in comparison with using multiple motorized stages for sample scanning, while providing simultaneously source and/or detection pinhole arrays to enhance depth resolution for confocal detection. In this paper, we present a DMD based fluorescence detection system for studying dynamics of multiple cells in vitro that are cultured in a microfluidic cell culture device. Initially, we test the optical system using fluorescence microbeads of various sizes. The fluorescence microbeads have 1 and 10 micron diameter with fluorescence properties that may be compared with fluorescently labeled cells. Subsequently, we employ cells cultured in 2-D and 3-D conformations to investigate the cell viability in response to externally injected anti-cancer drugs. For this proof-of-concept study, we used the DMD-based confocal detection system to acquire cell viability of 2-D and 3-D cultures of HCT-116, a colon cancer cell line which is generally used to test the effect of 5-fluorouracil, an anti-cancer drug that is widely employed for the treatment of colon cancer.

7596-08, Session 2

Quantifying heat transfer in DMD-based optoelectronic tweezers using infrared thermography

P. J. Pauzauskie, Lawrence Livermore National Lab. (United States); H. Hsu, A. Jamshidi, J. K. Valley, S. N. Pei, M. C. Wu, Univ. of California, Berkeley (United States)

The demonstration of single-beam laser tweezers in the 1970's sparked a flood of interest in non-contact, optical manipulation of micron-scale structures. One constraint of single-beam laser tweezers is that the large optical intensities necessary to trap particles also can cause a significant amount of photo-thermal damage.

Optoelectronic tweezers (OET) have emerged in recent years as a powerful form of optically-induced dielectrophoresis for addressing single cells and trapping individual nanostructures with DMD-based virtual-electrodes. In this technique an alternating electric field is used to induce a dipole within structures of interest while very low-intensity optical images are used to produce local electric field gradients that create dynamic trapping potentials.

Addressing living cells and chemically reactive nanostructures with OET's optical virtual-electrodes requires an in-depth understanding of heating profiles within OET devices, particularly for heat-sensitive cell lines such as Yersenia pestis (bubonic plague). In this paper we present quantitative measurements of the thermal characteristics of two distinct OET-photoconductors: single-crystalline-silicon phototransistors (PhOET) as well as hydrogenated-amorphous-silicon (a-Si:H). Midwave infrared (3 - 5 micron) thermographic imaging is used to determine relative heating in PhOET and a-Si:H devices both with and without DMD-based optical actuation.

Temperature increases of approximately 2°C from electrolyte-heating are observable in the absence of DMD-illumination when glass is used as a support for PhOET devices. An additional temperature increase of no more than 0.2°C is observed when DMD-illumination is used. Furthermore, significantly reduced heating can be achieved when devices are fabricated in direct contact with a metallic heat-sink.

7596-09, Session 3

High-precision laser beam shaping using binary-amplitude DLP® spatial light modulators

M. F. Becker, J. Liang, R. N. Kohn, D. J. Heinzen, The Univ. of Texas at Austin (United States)

Laser beams with precisely controlled intensity profiles with less than 1% root-mean-squared (RMS) error from a target profile are essential for many areas of optics and optical physics. We create such beams from real-world lasers: dirty, quasi-Gaussian beams obtained directly from a laser and beam-expanding telescope without spatial filtering. Our application is the formation of optical standing-wave lattices for Bose-Einstein Condensates (BECs) in quantum simulators. This requires controlled amplitude and flat phase for the beam, and that the beam be free of modulation from either time domain pixel dithering in a DMD or from residual temporal modulation in a liquid crystal SLM due to its refresh cycle. Our target profiles are flattop beams and beams with 1-D linear intensity variation, both with square cross-section and smooth taper at the edges.

We describe the development of the pattern design algorithms and demonstrate the performance of such a high precision beam shaper to make flattop beams (8th order super-Lorentzian, for example) and other spatial profiles with similarly low spatial frequency content. The DMD was imaged through a telescope containing a pinhole low-pass filter. An error diffusion algorithm was used to design the initial DMD pixel pattern based on the measured input beam profile. This pattern was iteratively refined based on output image measurements by changing DMD pixels to lift valleys and suppress peaks. We demonstrate forming a variety of beam profiles with less than 0.23% RMS error with respect to the target profile and with nearly flat phase.

7596-10, Session 3

DMD-based multi-target laser tracking for motion capturing

F. Souvestre, HLP Technologies (France) and CEA LIST (France); M. Hafez, CEA LIST (France); S. Regnier, ISIR-Institut des Systèmes Intelligents et Robotique (France)

The two novel conceptual approaches presented in this paper consist of splitting the tracking action into two sub-systems. The decoupling of local scanning and global scanning functions is an alternative solution to the use of fast-steering, power-consuming galvanometric scanners.

Applications targeted are multi-objects tracking and 3D perception in safe condition. This paper presents two consecutives approaches based on the same concept.

The first approach consists of a static local scanning based on several laser sources, globally oriented by a tilt/pan motorised tracking unit. Scattered light is sensed by a single non-imaging photodetector. The serial switching strategy of the laser sources allows localising the identified target. The DC motors continuously adjust the tilt/pan angles so that the center of the photodetector is aligned with the target center.

Even if this first approach offers a hemispheric field of view with a simple optical setup, it suffers from the lack of flexibility as the laser pattern is fixed. Moreover, it is a high inertia solution dedicated to a single target tracking task.

The second approach consists of synchronously projecting a fully resizable laser pattern provided by the DMD pattern. The collimated laser pattern is projected and scanned with a global angular resolution using a “Risley prim” configuration. This approach allows a wide field of view, a multi-target tracking, and a sub-pitch angular DMD scanning. Finally, the flexibility given by the DMD allows a very fine positioning and could correct optical aberration spawned by the prisms.

7596-11, Session 3

Enabling technology for next-generation data storage of high-fidelity recordings in volumetric crystal media

G. A. Gladney, M. Hutt, G. Cadet, Access Optical Networks, Inc. (United States)

The global non-volatile memory market was over $66B in 2008 with the market for disk and memory chip products forecast to be over $166B in 2011 according to Silicon Strategies. Merrill Lynch estimated the addressable enterprise data storage market at $18B in 2006 with a forecast to grow at 5% a year to $24B in 2010. The United States represented half of the 2008 data storage market with growing demands driven by growth of Blade Servers, Storage Virtualization, and Video content. Current data storage technologies have limited abilities to scale performance (e.g. density and read/write access times). Next-Generation data storage must be able to scale performance while concurrently reducing the power requirements, form factor, and costs.

Access Optical Networks, Inc. (AON) is a leader in applied research and development to commercialize a new data storage product based on writing high-fidelity optical binary images into a volumetric crystal media. Holographic data storage has recently become realizable due to the availability of enabling technologies such as microelectromechanical systems (MEMS) device(s) including high reflectivity, binary spatial light modulators (SLMs) as well as dual-axis mirrors for beam steering or angular multiplexing to address the data stored in the volumetric crystal media. Other important commercial device availability includes small form factor lasers that provide sufficient optical power while maintaining low noise and long coherence length.

Holographic data storage in a volumetric crystal media is a technology poised to scale performance by more than an order of magnitude beyond the most competitive electronic non-volatile storage solutions available today. In this paper we introduce the basic elements of a holographic data storage system and show how the Texas Instruments DLP chip, when used as a binary SLM can paginate a continuous-wave laser beam producing a high-fidelity, multi-level grayscale-encoded image within a volumetric crystal media.

7596-12, Session 3

A single-pixel optical sectioning programmable-array microscope

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We report the fabrication of a single pixel optical sectioning programmable array microscope (SP-PAM). Programmable array microscopy (PAM) systems use “multi-pinhole” masks in confocal planes to define illumination patterns and block the out-of-focus light. Compared to traditional confocal microscopy (CM), PAM has higher efficiency in utilizing the signal light and faster image acquisition speed. However, these advantages are gained at the cost of using more complicated optics and detectors. PAM uses a complex optical relay system and a CCD camera to collect the optical information after the detector mask, while traditional CM only uses a single pixel detector. Compressive sensing (CS) measurement patterns can be used as pinhole masks in PAM systems. As such, the light collected after the detector mask can be summed up and used to reconstruct the imaging scene via solving an l1-minimization problem. Only a simple focusing lens and a single pixel detector are needed to measure the intensity of the summed light. Therefore the optical complexity associated with conventional PAM systems can be greatly reduced. In this work, we introduce the design and characterization of a single pixel optical sectioning PAM setup. A digital micromirror device (DMD) is used as the hardware platform for realizing the pinhole masks. Different CS measurement patterns are implemented with the hardware architecture, including traditional image space random patterns, conventional Hadamard patterns and scrambled block Hadamard ensemble (SBHE) patterns. Their performances are compared and analyzed with respect to experiment results.

7596-13, Session 3

Evaluation of the DMD chip in a space environment for the ESA EUCLID mission

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EUCLID mission from the European Space Agency (ESA) will study the dark universe by characterizing a very high number of galaxies in shape and in spectrum. The high precision spectra measurements could be obtained via multi-object spectroscopy (MOS) using Digital Micro-Mirror Arrays. These arrays will act as objects selection reconfigurable masks.

ESA has engaged with Visitech and LAM a space evaluation of a DMD chip from Texas Instruments. In order to get more than 2 millions independent mirrors, the selected component is a DMD chip in a 2048 x 1080 “pixels” format, with a pitch of 13.68µm. Usual operational parameters are room temperature, atmospheric pressure and mirrors tilting several hundreds times in a second, while for EUCLID, the device might work in vacuum, at low temperature, and each MOS exposure lasts 1500s with mirrors frozen in one state (either ON or OFF) during that duration.

A specific thermal/ vacuum test chamber has been developed for test conditions down to -40°C at 10-5 mbar vacuum. Imaging capability for resolving each micro-mirror has also been developed for determining any failure for a single mirror. A dedicated electronics and software permit to freeze any pattern on the device for duration as long as 1500s.

Tests in vacuum at low temperature, radiations, vibrations, thermal cycling, and preliminary life tests are under way. First results do not reveal any real show-stopper concerning the ability of the DMD chip to fulfil most of EUCLID requirements. MOS-like tests on a specific optical bench are also scheduled.

7596-18, Session 3

Time-resolved confocal microscopy using a digital micromirror device

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Confocal and confocal laser scanning microscopy (CLSM) is based

on imaging the focal spot of excitation light from a sample under investigation. Within the focal plane whatever reflective or fluorescent object delivers its maximum intensity yield. A pinhole (ca. 10 µm diameter) positioned at the conjugate focal point in front of the detector rejects all light not originating from the excitation spot. This effectively enhances the signal-to-noise ratio thus giving high contrast images at negligible blurring effects. The focal spot is scanned in x,y,z-direction and intensity readouts are digitally converted into a 3D-image of the sample.

To overcome scan speed limitations both in x,y- and z-direction digital micromirror devices (DMD) can be employed. Each mirror (ca. 14x14 m2) simultaneously serves as deflecting device and virtual pinhole thereby making not only the pinhole but also a scanning device superfluous. Arbitrary patterns can be generated custom designed to fit the demands of the sample under investigation. An intensified CCD-camera synchronized to the DMD takes the images of each single optical slice. Due to the high DMD-frequency (8000 frames/s), each complete measurement plane is recorded within a single frame of the intensified CCD-camera. The z-scan is realized by a piezo-driven microscope objective.

This configuration allows us to image objects with a diffraction limited spatial resolution of approx. 300 nm laterally and approx. 1000 nm axially @ 408 nm. High temporal resolution of less than 5 s for 50 layers at ca. 1 µm optical slicing space enables one to visualize and analyse e.g. physiological processes within living cells in a 3D-film.

7596-14, Session 4

The use of DMD technology in rapid manufacturing equipment for mass customization applications

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The Use of DMD based Rapid Manufacturing systems for the production of highly accurate plastic based components for use in mass customization market such as hearing aids, and dental markets. The voxelization process currently afforded with the DLP technology eliminates any layering effect associated with all existing additive Rapid Manufacturing technologies. The smooth accurate surfaces produced in an additive process utilizing DLP technology, through the voxelization approach, allow for the production of custom finished products. The ability to control the depth of cure for each individual voxe, through grayscale value adjustment, on the inner and outer contours of the 3 dimensional part to be manufactured eliminates the layering effect typically associated with laser and jet based rapid manufacturing and rapid prototying systems currently available in the market today.

The implementation of DLP technology in rapid prototyping and rapid manufacturing systems allow for the usage of highly viscous photopolymer based liquid and paste composites for rapid manufacturing that could not be used in any other additive process prior to implementation of DLP technology in RP and RM systems. The presentation will showcase the usage of glass filled photopolymers that are used to manufacture temporary crowns and bridges that are placed in the patients mouth for use up to one year.

7596-15, Session 4

DMD-based 3D micro-manufacturing

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The development of the Digital Micromirror Device (DMD) by Texas Instruments has made a significant breakthrough in 3D micro-manufacturing, and in particular, in the area of additive layer-based manufacturing. One area of particular interest for using DMD technology is microstereolithography; a technology that builds 3D shapes through successive photopolymerization of individual thin 2D layers that are stacked vertically. A DMD-based projection microstereolithography system and a robust micro-manufacturing process have been developed. This system and various micro-fabricated 3D structures with features on the order of 10 microns, including recent advancements in multiple material micro-fabrication, will be presented and described.

7596-16, Session 4

Application of DLP® technology to the spectral-response characterization of detectors

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A key parameter in evaluating the performance of photovoltaic solar cells is characterization of electrical response to various incident source spectra. Conventional techniques utilize monochromators that emit single band-passes across a spectral region of interest. Since many solar cells respond differently at different broadband source light levels, a white bias light source that raises the overall light level to simulate the sun's broadband emission. However, such sources cannot render realistic solar continua. We present some initial results demonstrating how a spectrally-dispersed broadband source modulated with TI's DLP® technology can be used to more faithfully synthesize solar spectra for this application.

7596-17, Session 4

Subpixel scatter in digital micromirror devices

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The Texas Instruments' Digital Micromirror Device (DMD) has become an intricate part of many new scientific and entertainment applications. The DMD has been continuously revised and the technological advancements of the IC manufacturing industry have enabled the robust integration design of both silicon transistors and Microelectromechanical Systems (MEMS) optical components. The Mirrors are used for a variety of functions, the common utilization being a Spatial Light Modulator (SLM). Prior optical characterization has been done for optimizing the Digital Light Processing (DLP) projector applications which utilize a collimated wavefront impinging on the DMD; however, these models are insufficient for applications when the DMD used at the focal plane of an optical system such as in a multi-object spectrometer. Characterizing the sub-pixel scatter from a DMD will be beneficial for designing future micromirrors and optimizing optical systems. The bi-directional scattering function (BSDF) of a DMD is examined in great detail. The experimental setup to characterize the DMD's BSDF involves using a diffraction-limited optic to generate a subpixel spot and a computer-controlled high-precision piezo stage to scan this spot across several pixels. Using a long working distance microscope objective attached to a CCD camera, the scattered light was collected at various view angles. This resulted in subpixel scattering model, which describes the geometrical and optical parameters that cause stray light when utilizing a DMD at the focal plane. This research will be useful for controlling the stray light in new scientific applications.