Nanometer Structures
Room: C-207 - Session NS+SE+SS+MM-TuM

Nanotribology
Moderator: K.J. Wahl, Naval Research Laboratory

8:20am **NS+SE+SS+MM-TuM1 Ultralow Friction Coatings and Surfaces**, ***J.M. Martin***, Ecole Centrale de Lyon, France **INVITED**

From a technological point of view, very low friction in solid lubrication may be interesting in micromechanisms requiring neither friction noise nor instabilities, together with low power consumption. Theoretical approaches at the atomic scale coupled with experimental approaches using proximal probe techniques have been developed to study atomic scale friction behaviors and energy dissipation modes. The two limiting factors for friction reduction at the macro-scale are S0 (shear strength of the interface film) and a (pressure coefficient).[1] Approaching very low friction requires the reduction of both S0 and a below the MPa range. Thus lowering to zero friction would require the vanishing of both the adhesive and the external pressure. However these conditions are unlikely to be perfectly achieved in practice. Thus zero friction may not be possible. However, friction values in the 10-3 range or even less (near-frictionless sliding) have been experimentally reached in some practical situations. Here we examine ultralow friction by using a macro-scale sphere/plane contact configuration (maximum pressure of 1 GPa). Friction in the 0.001 range is associated with a shear strength of 1 MPa. We report experimental evidence of superlow friction with different coatings: pure molybdenum disulfide MoS2,[2] molybdenum dithiophosphate (Modtp) tribofilms and hydrogenated diamondlike carbon a-CH.[3]

[1] I. Singer, J. Vac. Sci. Technol., A12(5), (1994) 2605.
[2] J.M. Martin, C. Donnet, Th Le Mogne and Th Epicier, Physical Review B 48, No 14, (1993) 10583.
[3] C. Donnet et al, Surface and Coating Technology, 94, (1997) 456.

9:00am **NS+SE+SS+MM-TuM3 Frictional Properties of Small Model Lubricant Molecules Adsorbed on VC(100)**, ***L.C. Fernandez-Torres***, *S.S. Perry,* University of Houston, *B.-I. Kim*, Sandia National Laboratories

The frictional modification of the non polar (100) of vanadium carbide (VC) surface through small molecule adsorption at room temperature has been investigated from a fundamental perspective. These molecules represent the functionalities incorporated into lubricants and used to appropriately tailor the lubricant's properties and enhance its performance. Ultrahigh vacuum atomic force microscopy (AFM) has been employed to determine the changes in frictional response and interfacial adhesion. Scanning tunneling microscopy (STM) has been used to elucidate surface morphology. X-ray photoelectron spectroscopy (XPS) has been utilized to determine the composition of the species formed by the interaction of these adsorbates with the VC surface. This successful methodology has been developed during a recent investigation of ethanol, and in this study has been extended to other low molecular weight alcohols as well as an ester. The results will be rationalized in terms of chemical reactivity, adsorbate layer composition, extent of coverage, and changes in the interfacial shear strength and discussed in terms possible lubrication schemes.

9:20am **NS+SE+SS+MM-TuM4 Adhesion and Deformation in Nanoscale Contacts between W(110) and Au(110) in Ultra High Vacuum**, ***S.A. Smallwood***, *R.J. Lad, W.N. Unertl*, University of Maine

Tribological phenomena change as the contact area decreases from macroscopic to atomic dimensions, but these changes are not well understood. We report studies of the force versus deformation behavior of contacts with diameters up to about 50 nm using well-characterized metal surfaces in ultra-high vacuum. These contact sizes are intermediate between those previously studied. The contacting bodies were a Au(110) single crystal and sharp tips of W wires. The W probes were cleaned by field evaporation and their atomic structure determined using field ion microscopy (FIM). All were terminated by (110) planes and radii varied between 12 nm and 24 nm. The probes were mounted in double cross-hair force sensors. After cleaning by sputtering and annealing cycles, the Au was transferred to a piezoelectric tube scanner and moved into tunneling contact with the probe. Deflection of the force sensor and electrical current were measured as the Au crystal was brought into mechanical contact to a predetermined maximum displacement and then withdrawn. Prior to the first yielding event, the data is well described by elastic contact mechanics theory. The reduced modulus of 61 Â± 26 GPa agrees with the value calculated assuming bulk properties. The work of adhesion has an upper bound of about 0.3 J/m2. The first observable yielding events occur at a mean normal stress of 12 Â± 2 GPa, comparable to the values reported for larger probes, but half that reported for smaller contacts on Au(111). Hardness is about 6 GPa near the surface and decreases by about fifty percent at 8 nm indentation depth. Prior to first yield, contact conductance remains far below one quantum. Deformation is confined to the Au. FIM demonstrates that the W probe is not deformed for penetrations as deep as its radius. Scanning tunneling microscopy shows that the indentation holes are asymmetric and that pile-up extends about one indentation diameter beyond the indent.

9:40am **NS+SE+SS+MM-TuM5 Chemical Force Microscopy of Aluminium Oxide Surfaces**, ***T.T. Foster***, *M.R. Alexander,* UMIST, UK, *E. McAlpine,* Alcan International, UK, *G.J. Leggett*, University of Sheffield, UK

The combination of wettability, chemical force microscopy (CFM) and friction force microscopy (FFM) has been used to analyse changes at the oxide-covered surface of aluminium after magnetron sputter deposition. A model self-assembled monolayer (SAM) system was first developed to enable comparisons to be made with the more complex aluminium system. The monolayers were produced by self-assembly on Au (111) and Ag (111) substrates. The gold-coated AFM tips were modified with SAMs of alkanethiols terminated in a methyl or carboxylic acid group. Friction coefficients were measured for SAMs varying in chain length and terminal group chemistry. Using carboxylic acid modified tips; measurements were performed on the surface of aluminium. Adhesion forces were found to decrease with storage time in a desiccated environment, attributed to the adsorption of contaminant molecules from the atmosphere. In contrast the friction coefficient showed no significant change with storage time, presumably because the sliding tip, under loading, is able to displace contaminant molecules. Contact angle goniometry was used to study changes in surface wettability on the aluminium surface. The water contact angle increased linearly with the log of storage time, supporting the hypothesis that adsorption of hydrophobic contaminants modifies the aluminium surface. Contact mode characterisation of the aluminium oxide surface provided clear images of the oxide surface. A nitric acid-based cleaning procedure was developed that was capable of removing adventitious contamination and returning the aluminium oxide surface to condition that appears similar to the freshly deposited surface. This study clearly demonstrates the capability of CFM for characterising complex aluminium surfaces and studying changes in surface chemistry.

10:00am **NS+SE+SS+MM-TuM6 Nanotribology and Related Structural Changes During Wear of Diamond-like Carbon Films**, ***J. Goldsmith***, *E.A. Sutter, J. Moore, B Mishra,* Colorado School of Mines, *M. Crowder*, Maxtor Corporation

Diamond-like carbon (DLC) thin films are used for wear and corrosion protection of magnetic disks, micro-electro-mechanical systems (MEMS), and tool bits. Magnetic information storage density increases when the read-write head gets closer to the disk. The magnetic layers degrade very quickly without a good protective interface. The use of DLC thin films becomes increasingly popular as they can provide a protective surface due to their excellent tribological properties as low friction and high hardness. In both magnetic disks and MEMS applications, the DLC films are in the thickness range of 2 - 5 nm and in most cases are amorphous in structure. Characterizing the tribological and structural properties and identifying the wear mechanisms of DLC films on the nanoscale is a challenge. Here we present results on the nanotribology of the DLC films performed using both an atomic force microscope and a nanoindenter. We investigate the wear behavior of the DLC films and the role of transfer film. We find that the formation of transfer film plays an important role in providing low-friction. The nanotribological investigations are correlated with the structural changes that occur in the DLC film as well as in the transfer film detected using Raman spectroscopy and cross-sectional transmission electron microscopy.

10:20am **NS+SE+SS+MM-TuM7 Tribology and Surface Forces in MEMS**, ***J.S. Zabinski***, Air Force Research Laboratory, *S.T. Patton, K.C. Eapen,* UDRI, *S.A. Smallwood*, Systran, Inc. **INVITED**

Microelectromechanical systems (MEMS) offer the potential to provide new capabilities and products for commercial and military applications. Simple devices are already common in the marketplace, but friction, stiction, and wear prevent reliable operation of more sophisticated types of MEMS devices that have contacting surfaces in relative motion. These tribological problems are fundamentally difficult to solve and are magnified because MEMS are expected to operate in very harsh environments, such as at elevated temperature and in space. The performance and reliability of MEMS are strongly dependent on the environment in which they operate.

For example, moisture can cause device failure by stiction or it can provide excellent lubrication, depending on the device and the relative concentration of water vapor (i.e., relative humidity). Operation in vacuum is particularly severe and the wear mechanisms are different than in dry or moist environments. Methods to control system tribology include lubricant coatings, monolayers, and new materials. The tribological mechanisms operating in moist air through vacuum will be discussed along with strategies to control friction, stiction, and wear that have significantly improved MEMS reliability. In addition, the effects of storage on device performance will be presented.

11:00am **NS+SE+SS+MM-TuM9 Tribological Measurement on MEMS Platforms**[1], ***M.T. Dugger***, *S.V. Prasad*, Sandia National Laboratories **INVITED**

Microelectromechanical systems (MEMS) fabricated using surface micromachining (SMM) and other lithographic techniques such as LIGA have resulted in actuators, counter-meshing gears and other moving mechanisms having complex tribological interfaces that are rough on the nanometer scale and have unusual surface morphologies. Meaningful friction and wear measurements of microsystems must be made at loads and speeds relevant to MEMS operation. Since friction and wear are properties of systems, measurements must also involve interactions of surfaces having the morphology and chemistry present in real devices. Experimental techniques for acquiring friction data during sub-micron displacement and under nanoNewton forces are critical for the fundamental understanding of energy dissipation and wear mechanisms in MEMS. However, experimental investigation of surface interactions in MEMS under relevant contact conditions requires techniques beyond those that are currently available. MEMS friction measurement platforms which bring real MEMS surfaces into contact are needed to define the design space, to investigate aging and failure mechanisms, and to validate models of friction and wear derived from fundamental studies. We have therefore developed both SMM and LIGA devices containing isolated tribological contacts from which quantitative friction forces can be extracted. These structures are used to investigate interface performance, degradation and failure mechanisms. Methods of quantifying static and dynamic friction in SMM and LIGA micromachined contacts will be presented. Examples will be shown of how these structures are being used to investigate degradation of monolayer lubricants and hard coatings for SMM devices, as well as the tribological behavior of metallic contacts in LIGA.

[1]Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under contract DE-AC04-94AL85000.

Manufacturing Science and Technology
Room: C-109 - Session MS+MM-TuA

Manufacturing Issues in MEMS and Related Microsystems
Moderator: E.G. Seebauer, University of Illinois

2:00pm **MS+MM-TuA1 Silicon Micromachines for Science and Technology**, ***D. Bishop***, Bell Laboratories, Lucent Technologies **INVITED**

The era of silicon micromechanics is upon us. In areas as diverse as telecommunications, automotive, aerospace, chemistry, entertainment and basic science the ability to build microscopic machines from silicon is having a revolutionary impact. In my talk I will discuss what micromachines are, how they are built and show examples of how they will have a revolutionary impact in many areas of science as well as technology.

2:40pm **MS+MM-TuA3 Silicon Nano-biotechnology**, ***G. Timp***, University of Illinois, Urbana **INVITED**

Silicon nanotechnology can now manufacture logic that incorporates more than 43 million Metal-Oxide-Semiconductor Field Effect Transistors (MOSFETs) into a monolithic integrated circuit (IC). Some of these MOSFETs have a gate or control electrode that is only 130nm long with a gate oxide that insulates the control electrode from the current-carrying channel that is as thin as 1.7nm. Moreover, we have recently shown that further miniaturization is practical. We have produced nanometer-scale MOSFETs or nano-transistors with a gate electrode as shorter than 40nm and a gate oxide thinner 1nm. Inexorably, within the next ten years (according to the ITRS roadmap) the electronics industry is expected to integrate over a billion nanotransistors into a ~3-10cm2 area chip, packing about 5-10 nano-transistors/mm2. Integration on this scale, along with the facility for nanofabrication, will enabled new types of ICs. For example, we will show that it is now possible to fabricate ICs so small that they could inserted inside a living cell. Since the cell is the key to biology, such a chip combined with sensors could provide unprecedented access to it. We will also show how silicon nanofabrication technology can be used to produce sensors out of nanometer-scale pores (~2nm in diameter) in an ultra-thin glass membrane (~2nm thick), which function like ion channels in the membrane of a living cell. Such devices may ultimately be used in proteomics or for rapid sequencing of minute amounts of DNA to discover the genetic origin of a disease.

3:20pm **MS+MM-TuA5 Manufacturing Issues in MEMS and Related Microsystems**, ***B.P. Gogoi***, Motorola **INVITED**

MEMS(MicroElectroMechanical Systems) use IC(Integrated Circuit) manufacturing technology for the fabrication of sensors and actuators that utilize a wide variety of transduction principles to interact with the physical world. The three dimensional aspects of the sensor require some additional process technology that is not available in conventional IC technology. Also, since many of these sensors and actuators require the presence of intentional gaps in which mechanical motion is initiated, MEMS technology also require methods to form these intentional gaps. Using this enabling technology, a number of high volume sensors have been developed for the mainstream market in the automotive, consumer, industrial and medical segments. However, as the trend in IC manufacturing has progressed towards more shallower and planar technology, the trend in MEMS technology has moved towards high aspect ratio structures. The issues related to manufacturing of sensors and actuators using MEMS technology will be discussed. Some of the specific requirements of the process technology to enable well-controlled high volume manufacturing of sensors will be presented. In addition, examples of failure mechanisms that result from the interaction of design and the fabrication process will be discussed. The choices in the integration of these sensors and actuators with the system circuitry will also be presented.

4:00pm **MS+MM-TuA7 MEMS Technology Challenges for Volume Manufacturing**, ***V. Rao***, Intel Corporation **INVITED**

MEMS(Micro Electro Mechanical Systems) is a silicon technology for fabricating miniature mechanical devices made mostly of beams, membranes and channels. These mechanical devices are integrated with electronics to form Microsystems which find use in Communications and computing, Inertial sensing, environmental sensing and Biomedicine. MEMS devices are particularly attractive in the personal communications space because they can provide significant benefits such as energy efficiency and small footprint. However as these are high volume markets the technology must provide the required reliability and cost characteristics for these applications. In RF systems today many passive devices are discrete and off chip. MEMS technology provides a way to integrate the high value passive elements (such as switches, filters and high Q inductors) thereby reducing footprint and enhancing performance. Another example in the communication space is in the use of micromirrors for all optical switching. This is very compelling as light signals can be switched directly in the optical domain by moving mirrors avoiding the expensive Optical to Electrical to Optical conversion as is currently done. This paper will discuss some of the key manufacturing hurdles that must be overcome to realize the reliability and cost benefits that MEMS technology must meet. We will start by discussing key process modules that differentiate MEMS technology from traditional CMOS. We will then describe the stare of the art for these modules today and discuss the technological hurdles that must be addressed for future volume manufacturing.

4:40pm **MS+MM-TuA9 Manufacturing Issues of Automotive Sensors produced at Bosch**, ***M. Offenberg***, Robert Bosch GmbH, Germany **INVITED**

An ever increasing number of electronic systems in vehicles helps to increase the safety and comfort of the driver as well as to increase fuel efficiency and to reduce toxic emissions. Sensors are enabling components for the functionality of these electronic systems. Over the last decade microfabrication technologies have contributed to reduce the cost of these sensors - and thus overall system cost - while at the same time increasing their functionality and reliability. This paper describes selected micro sensors that have been successfully introduced to the market such as pressure sensors, mass flow sensors, acceleration and angular rate sensors. Manufacturing aspects and processes with and without monolithic integration are illustrated for a surface micro-machining process. The embedding of MEMS manufacturing in an existing 6-inch ASIC production environment to achieve an optimized low-cost process is described. Key process steps such as deposition of mechanical-grade thick poly-silicon layers, trench etching, sacrificial oxide etch and hermetic sealing are illustrated. Some of the key processes require dedicated equipment that was developed in collaboration with equipment manufacturer. High rate silicon deep silicon etcher in cluster tools ensure low cost of ownership. Process monitors for mechanical stress and stress gradient will be presented and manufacturing issues such as cross contamination and particle protections are discussed using inertial sensors as an example.

Microelectromechanical Systems (MEMS)
Room: C-210 - Session MM+NS-WeM

Nanotechnology and Nanofabrication in NEMS
Moderator: H.G. Craighead, Cornell University

8:20am **MM+NS-WeM1 Probing Nanomechanical Systems with Electron Tunneling Devices**, ***A.N. Cleland***, University of California, Santa Barbara **INVITED**

We have been integrating active electronic devices with nanomechanical systems, in order to probe both the mechanical and thermodynamical behavior of the integrated system. I will discuss experiments in which we have developed fabrication approaches allowing the integration of superconductor-normal metal tunnel junctions with suspended mechanical structures to develop an ultrasensitive bolometer and calorimeter, with which we have been able to confirm the observation of the quantum of thermal conductance, the integration of single-electron transistors with mechanical resonators, displacement sensing using an integrated quantum point contact, and the development of a double quantum dot integrated with an L-band mechanical resonator. I will briefly discuss the potential application of these types of integrated probes for quantum-limited measurements.

9:00am **MM+NS-WeM3 Fabrication and Characterization of a Carbon Nanotube Torsional Oscillator**, ***P.W. Williams***, *A.M. Patel, S.J. Papadakis, M.R. Falvo, S. Washburn, R. Superfine*, University of North Carolina

Carbon nanotubes have extraordinary mechanical properties and have been demonstrated to show atomic scale effects in the frictional[1] and electronic properties[2] of their contacts. We are exploring the applications of these properties in nanoelectromechanical Systems (NEMS). Torsional oscillators represent a device geometry for the measurement of fundamental properties of nanotubes as well as high frequency oscillators and sensors.[3] Using individual multi-wall carbon nanotubes as torsional springs, we have fabricated NEMS paddle oscillators. We will report on the fabrication of these structures as well as measurements of their torsional compliance using atomic-force-microscope force-distance curves. The measured shear modulus will be compared with existing theoretical expectations, and unexpected hysteresis effects will be discussed. Along with compliance measurements, progress toward characterization of resonant behavior including measurements of quality factor and resonant frequencies will be presented. This work is supported by the National Science Foundation and the Office of Naval Research.

[1]M. R. Falvo, J. Steele, R. M. Taylor, et al., Physical Review B 62, R10665 (2000).
[2]S. Paulson, A. Helser, M. B. Nardelli, et al., Science 290, 1742 (2000).
[3]S. Evoy, D. W. Carr, L. Sekaric, et al., Journal of Applied Physics 86, 6072 (1999).

9:20am **MM+NS-WeM4 Femtogram Detection using Nanoelectromechanical Oscillators**, ***B. Ilic***, *D. Czaplewski, H.G. Craighead*, Cornell University, *P. Neuzil*, Institute of Microelectronics, Singapore

Micro and nanoelectromechanical systems (MEMS and NEMS) represent an emerging sensor technology that provides a closely coupled link between the physical, chemical and biological worlds. Nanomechanical systems can be used as mass based sensors with sensitivity several orders of magnitude better than conventional quartz crystal oscillators. Here we present a resonant frequency-based NEMS mass sensor, comprised of surface micromachined low-stress polycrystalline silicon cantilever beams for the detection of self assembled monolayers. In our experiment, we demonstrate a method for detecting the mass of Aminopropyltriethoxysilane (APTS), Hexamethyldisilazane (HMDS) and Octadecyltrichlorosilane (OTS) self assembled monolayers (SAM) using a resonant frequency-based detection sensor. The highly sensitive balance considered here is a resonating cantilever beam fabricated using electron beam lithography. For this experiment, devices with dimensions of varying length (l) from 3µm to 15µm, width (w) of 500nm to 2µm and thickness (t) of 150nm and 320nm, were used. Devices were coated with various monolayers and resonant frequency was measured before and after the addition of SAM. Signal transduction was accomplished in vacuum by employing an optical interferrometric system to measure the frequency shift due to the additional mass loading. The measured frequency shift was correlated to the mass of the SAM and was found to be in good agreement with the analytical results. For the smallest device geometry, we observed a resonant frequency shift due to the presence of 4 femtograms of HMDS. By further tailoring cantilever dimensions, the sensitivity of our devices can be greatly improved, thus extending their application to DNA, viruses and other analytes with mass on the order of attograms.

9:40am **MM+NS-WeM5 IR Imaging Using Uncooled Nanostructured Microcantilever Thermal Detectors[1]**, ***P.G. Datskos***, Oak Ridge National Laboratory and University of Tennessee, *S. Rajic, L.R. Senesac, J. Corbeil, N.V. Lavrik*, Oak Ridge National Laboratory

Bimaterial microcantilevers have been shown to detect infrared (IR) radiation and can operate as uncooled thermal detectors. The transduction mechanism is the bending of the bimaterial microcantilever due to thermally-induced stress. Therefore, it is important to minimize cantilever deflections caused by factors other than IR radiation (e.g. intrinsic mechanical stresses and ambient temperature fluctuations) while increasing photon absorption in the desired spectral region. In this paper we report on IR imaging using optimized microcantilever designs that are immune to ambient temperature changes and other sources of interfering mechanical stresses. In addition, we achieved increased absorption of IR photons using resonant nanostructured detector surfaces. We modeled and experimentally measured responses of such devices to IR radiation as well as to ambient temperature changes. We will present and discuss our latest results.

[1] We like to acknowledge support from the Defense Advanced Research Projects Agency, the National Science Foundation and DOE. This work was partially supported by the Laboratory Director's Research and Development Program of Oak Ridge National Laboratory. Oak Ridge National Laboratory is operated for the U.S. Department of Energy by UT-Battelle under contract DE-AC05-96OR22464.

10:00am **MM+NS-WeM6 Frequency and Phase Entrainment in MEMS Oscillators**, *M. Zalalutdinov*, ***K.L. Aubin***, *A.T. Zehnder, B. Ilic, D. Czaplewski, L. Sekaric, J.M. Parpria, H.G. Craighead*, Cornell University

Synchronization of light-induced self-sustained vibration of MEMS resonators by external parametric perturbation was demonstrated. Self-oscillation of disc-type MEMS resonators induced by CW laser light has been described earlier.[1] In the work presented here, partial modulation of the laser power was used to provide additional parametric excitation through the laser beam induced stress as a physical mechanism to control the parameter - the effective spring constant of the resonator. Modulation depth as low as 5% of CW laser power at frequencies near n times (n=1,2,3...) the natural resonant frequency of the oscillator was shown to cause the frequency and phase of the mechanical motion to become entrained to the modulation frequency (over n). The range of frequencies over which entrainment was possible was shown to vary with modulation amplitude. Once entrainment of the mechanical vibrations is achieved, one can tune the mechanical frequency of vibration by about 10% by changing the modulation frequency. During that tuning, the phase difference between the modulation signal and the mechanical motion was shown to vary as much as 130°. In a synchronized state, stability of the vibrations appears to be limited only by that of the modulation source, allowing us to demonstrate better than 10^{-9} stability for the frequency of the mechanical motion. Integration of entrained MEMS and NEMS oscillators into a phase-locked loop (PLL) circuit in order to build a high stability reference oscillator is currently under study.

[1]M. Zalalutdinov, A. Zehnder, A. Olkhovets, S. Turner, L. Sekaric, B. Ilic, D. Czaplewski, J. M. Parpia and H. G. Craighead, "Auto-Parametric Optical Drive For Micromechanical Oscillators" Appl. Phys. Lett., Vol. 79, pp 695 (2001).

10:20am **MM+NS-WeM7 Fabrication of Submicron-Scale Metallic Comb-Drive Actuators**, ***S.W. Park***, *N.A. Kumar, J.B. Lee*, The University of Texas at Dallas

Comb-drive actuators have been widely used for more than a decade in many applications including resonators, accelerometers, and tunable capacitors with the advance of micromachining technologies. While single crystal or poly Si have been preferred materials for comb-drive actuators, metallic high aspect ratio comb-drive actuators were also of interest due to its electrical property such as lower resistivity in some applications. In this paper, we report the development of fabrication of a sub-micron scale (sub-micron gap and width) all metallic comb-drive actuator with small overall foot-print. All metallic comb-drive actuators with sub-micron gap/width and small foot-print have many advantages over traditional silicon-based micron scale comb-drive actuators. Such advantages include large increase of capacitance per unit area (good for sensing applications) and higher quality factor due to low equivalent series resistance of the metallic comb-finger structures (good for tunable capacitor application). The comb-drive actuator was designed as a tunable capacitor and intensive modeling of such tunable capacitor was carried out. Fabrication of such comb-drive actuators was started with a multiple spin-coatings of polymethyl methacrylate (PMMA) or SU-8 on an oxidized silicon substrate. PMMA was investigated for low aspect ratio and SU-8 was investigated as a potential electron beam photoresist for high aspect ratio comb-drive actuator fabrication. Numerous experimental runs were performed to find optimum exposure doses, developing conditions, etc. Different metals such as Cu, Cr, Ti/Cu, and Cr/Cu were investigated as candidate materials for comb-drive actuators. Optimum fabrication process based on PMMA was developed for 1:1 aspect ratio all metallic 500-nm width/gap comb-drive actuator. Preliminary results on negative tone SU-8 resist based comb-drive actuator with a goal of achieving high aspect ratio (up to 5:1 aspect ratio) structure will also be reported.

10:40am **MM+NS-WeM8 Controlling Energy Losses in Nanoscale Structures with Surface Chemistry**, ***J.A. Henry***, *Y. Wang*, *M.A. Hines*, Cornell University

Why are we unable to predict the dynamic properties of nanoscale devices from the well -known behavior of bulk materials? For example, the quality (or Q) of nanoscale resonators is often orders of magnitude lower than similar macroscopic devices. Here, we show that simple changes in the surface chemistry of MHz silicon resonators can lead to large changes in Q, indicating that surface loss mechanisms become very important at this length scale. For example, the oxidation of H-terminated silicon resonators causes the Q to plummet by as much as 50% while inducing only a minuscule change in frequency of approximately 0.05%. The scaling of both the energy losses and the frequency shifts with oscillator size and thickness are consistent with a surface-driven process. Infrared absorption measurements confirm that chemical changes are limited to a few monolayers of the surface. Possible mechanisms for these losses will be discussed.

Microelectromechanical Systems (MEMS)
Room: Exhibit Hall B2 - Session MM-WeP

Poster Session

MM-WeP1 Metallization Schemes for RF MEMS Switches, ***K. Leedy***, *R. Cortez, W. Cowan, J. Ebel, J. McFall, R. Strawser, A. Walker*, Air Force Research Laboratory

A series of surface micromachined MEMS switches with composite metal bridges were fabricated by standard photolithographic techniques. The study was conducted in order to assess the influence of film stress and composition on the released shape of cantilever and fixed-fixed beam structures. A 1 µm thick evaporated Au film was the basis for all bridge materials with additional 20 nm layers of evaporated or sputter deposited Ti, Pt, or Au on the top or bottom surface of the thick Au. The planarity and stress gradient of cantilever beam structures and the planarity of fixed-fixed beam structures were measured with optical interferometry. Au-only bridge structures displayed the best planarity of those examined while structures including Ti layers displayed the least planarity. Tensile cantilever stress gradients were calculated using both cantilever tip deflection and radius of curvature techniques. The thin film biaxial moduli used in stress gradient calculations were measured with a wafer curvature technique and were slightly higher than the bulk Au value. Results of this study show that thin metal layers (2% of total beam thickness) have substantial influence on released beam curvatures but that beam planarity can be achieved with a suitable combination of materials.

MM-WeP2 Inorganic Electret Using SiO_2 Thin Films Prepared by r.f. Magnetron Sputtering, *T. Minami*, ***T. Yamatani***, *T. Utsubo, T. Miyata,* Kanazawa Institute of Technology, Japan, *Y. Ohbayashi*, Hosiden Corporation, Japan

The ability to fabricate inorganic thin-flim electrets on low temperature substrates is necessary for applications such as electret actuators and sensors in MEMS. In this paper, we describe the fabrication of silicon dioxide (SiO_2) thin-film electrets that exhibit a highly stable surface potential in tests at high temperatures as well as high relative humidities in air. The SiO_2 films were prepared on various conductive substrates at a temperature of 250 to 400^{o}C by rf magnetron sputtering using a fused quartz target. It was found that operational stability in highly humid atmospheres can be considerably improved by postannealing in a highly humid atmosphere at a high temperature. In addition, the obtained surface potential stability also proved to be dependent on the deposition conditions. The surface potential of SiO2 films postannealed in a highly humid atmosphere at 350 to 450^{o}C for 10 to 180 min was found to be highly stable even when tested at a relative humidity of 90% and a temperature of 60^{o}C. In addition to the postannealing conditions, the deposition conditions were optimized: substrate temperature, about 350^{o}C; sputter gas pressure,0.3 Pa; and O_2 partial pressure, 20%. As a result, the surface potential of SiO_2 electret films prepared under optimized deposition and postannealing conditions exhibited no decay when tested over a long term at a temperature of 60^{o}C and a relative humidity of 90%. SiO_2 thin-film electrets with a thickness of 2 to 5 µm maintained a surface potential above 300 V when tested at temperatures above 250^{o}C in air or at 60^{o}C with a relative humidity of 90%. It was concluded that highly stable thin-film electrets can be realized by SiO_2 thin films prepared on various conductive substrates at a temperature of about 350^{o}C and postannealed at 400^{o}C in a highly humid atmosphere.

MM-WeP3 MEMS Electrostatically Actuated Vertical Mirror Switch for Optical Transceiver, ***M.W. Lee***, *K.C. Lee, S.B. Jo, B.H. O, S.G. Lee, S.G. Park, E.H. Lee,* Inha University, Rep. of Korea, *H.S. Lee, H.G. Ryu*, Neoptek, Rep. of Korea

We have developed a simple structured MEMS vertical mirror switch for optical transceivers. As the optical characteristics and mechanical stability of MEMS switches is sufficient for excellent performance in communication networks, it is necessary to lower the fabrication cost by simplifying or eliminating processes of manual assembly or alignment. Here, novel structures for mirror assembly and stopper are proposed and fabricated to satisfy simplicity and accuracy of a vertically-assembled mirror, made with only three layers by deposition, polysilicon, silicon-oxide, silicon-nitride layers on a silicon substrate. Poly-silicon layer is to build a cantilever and a mirror. The silicon-oxide layer is a sacrificial layer and the silicon nitride layer is for electrical isolation. Fabrication processes of semiconductor micromachine offers accurate position due to it's nature. PR-pads are also used for the technique of photoresist(PR) applied self-assembly (the works of R.R.A. Syms[1]). The characteristics of fabricated devices will be discussed in detail. Low actuation voltage and other performances are considered to be enough for the application in optical communication systems.

[1] Richard R.A. Syms, Surface Tension Powered Self-Assembly of 3D Micro-Optomechanical Structures, Journal of Microelectromechanical Systems, Vol. 8, No. 4, Dec. 1999.

MM-WeP4 Development of Microfluidic Devices for Gas Centrifuge Separation, ***S. Li***, *R. Ghodssi*, University of Maryland

A mass spectrometer on a chip (MSOC) is suited for environmental monitoring with the advantages of fast response, low power consumption and portability. Gas centrifuge separation (GCS) is capable of concentrating the minor constituents in a gas mixture and increasing the sensitivity of MSOC. An integrated MEMS fabrication method is presented for developing GCS devices as the front-end for MSOC. A hybrid device that incorporates silicon, plastic and glass is realized by utilizing a combination of deep reactive ion etching (DRIE) and low temperature wafer bonding techniques. Inlet and outlet ports (500 µm in diameter and depth) are created in the silicon substrate by DRIE. Using standard photolithography, micro converging-diverging nozzles with throats as small as 3.2 µm wide and 5 µm deep are formed in EPON SU-8 supported on the silicon substrate. The second SU-8 layer, coated on a pyrex wafer, is bonded with the first SU-8 layer to form sealed micro nozzles. Macroscale capillary needles (400 µm in diameter) and quick-setting glue are used to interface the microfluidic device to the macroscopic world (i.e., the pressure measurement setup). Measures are taken to prevent the glue from seeping through the gaps and blocking the microfluidic channels. Calibration results demonstrate the feasibility of the test setup for measuring pressure distributions of gas flow in the micro nozzles. Preliminary measurement results and a detailed fabrication process will be presented.

MM-WeP5 Characterization of the Residual Stress in Titanium/Platinum and Tantalum/Platinum Thin Film Electrodes used in the Processing of PZT MEMS Devices, ***R.G. Polcawich***, *J.P. Clarkson, J. Pulskamp, A. Wickenden, M. Wood, K. Kirchner, M. Ervin, E. Zakar, M. Dubey*, U.S. Army Research Laboratory

Residual stress in freely suspended MEMS devices is critical for optimal performance. The high temperature anneals required to crystallize lead zirconate titanate (PZT) thin films create stress gradients within the piezoelectric stack yielding non-planar released structures. From our previous studies, tantalum/platinum (200 Å / 1700 Å) metallization used as bottom electrodes for PZT MEMS has contributed the largest residual stress (~850 Mpa) to the multilayer stack. This research focused on using the sputter deposition parameters as a means of producing low stress (~<450 Mpa) Ta/Pt and Ti/Pt metal layers. Ti, Ta, and O diffusion were investigated with Auger electron spectroscopy by using O^{18} as a tracer during the anneal process. Additionally, x-ray diffraction and scanning electron microscopy were used to identify the presence of second phase compounds within the Pt metal layer. From this combined analyses, oxygen diffusion and the subsequent formation of TiO_2 and Ta_2O_5 compunds within the Pt matrix was the primary cause of reducing the residual stress in metal stacks with Ta and Ti thin films greater than 200Å.

MM-WeP6 Mitigation of Residual Film Stress Deformation in Multi-Layer MEMS Devices, ***J. Pulskamp***, *B. Piekarski, R.G. Polcawich, A. Wickenden, M. Dubey*, U.S. Army Research Laboratory

An approach to compensate for the residual thin film stress deformation of multi-layer MEMS devices is presented based upon analytical modeling and in-process thin film characterization. Thermal and intrinsic deposition stresses can lead to the warping of released MEMS structures. This detrimental phenomenon in many cases can prevent proper device operation. Ellispsometric and laser wafer bow measurements yield thickness and film stress values that are used to update the deflection model during device fabrication; allowing for the compensation of the fabrication process variability. The derivations of linear and nonlinear residual film stress induced deflection models are presented. These models are based upon Bernoulli-Euler beam theory and are thus restricted to the associated geometric constraints. The models are initially validated by comparison with surface micro-machined sol-gel PZT (Lead-Zirconate-Titanate) cantilever structures; with initial experimental results agreeing well with both models.

MM-WeP7 Epitaxial Growth and Characterization of the Ferromagnetic Shape Memory Alloy Co_2NiGa on (001) GaAs, ***T.C. Shih***, *J.W. Dong, J.Q. Xie, X.Y. Dong, S. McKernan, R.D. James, C.J. Palmstrom*, University of Minnesota

Recently Wuttig and his coworkers[1] reported a new ferromagnetic shape memory alloy Co_2NiGa, using bulk samples. This present study focuses on the growth of (001) Co_2NiGa thin films on (001) GaAs substrate by molecular beam epitaxy. In-situ reflection high energy electron diffraction, ex-situ X-ray diffraction, and cross-sectional transmission electron microscopy indicate the single crystal growth of Co_2NiGa on (001) GaAs. X-ray diffraction data from bulk samples[2] indicate that the Heusler alloys $Co_2Ni_{1+x}Ga_{1-x}$ ($0<x<0.3$) order in the B2-phase (CsCl structure) with doubled its lattice parameter close to 5.75 Å, which corresponds to a 1.8 % mismatch to GaAs. The X-ray diffraction data from the Co_2NiGa thin films indicate an out-of-plane lattice parameter of 6.10 Å, which suggests that the Co_2NiGa thin film may grow in a strained epitaxially stabilized tetragonal structure. Vibrating sample magnetometry and superconducting quantum interference device magnetometry measurements have been performed for the Co_2NiGa film with magnetic fields applied in-plane. The room temperature magnetic moment versus applied field curve shows a hysteresis loop with a coercivity of 170 Oe and a saturation magnetization ~250 emu/cm^3. The Curie temperature is above room temperatures which is comparable to the bulk measurement (Tc=326K).[2] In this talk, the crystal structure as a function of growth conditions as well as the mechanical properties of released films will be presented.

[1] M. Wuttig, J. Li, and C. Craciunescu, Scripta Mater., 44, 2393 (2001).

[2] J. G. Booth, R. Cywinski, and J. G. Prince, Journal of Magnetism and Magnetic Materials, 7, 127 (1978).

MM-WeP8 Micromirror Coatings with Low-stress, High Reflectivity, ***Y.N. Picard***, University of Michigan--Ann Arbor, *D.P. Adams, O.B. Spahn*, Sandia National Laboratories, *S.M. Yalisove*, University of Michigan--Ann Arbor, *D.J. Dagel*, Sandia National Laboratories

While thin film coatings can greatly improve the reflectivity of micromirrors used in optical MEMS devices, such coatings can yield a moderate compressive or tensile stress, leading to a significant change in the micromirror curvature. This work seeks to develop highly reflective optical coatings exhibiting near-zero average film stress and minimal through-thickness stress. In this study, multilayer thin films consisting of Cr, Ti, Au, Si and Si_3N_4 are deposited on blank Si (100) substrates using DC planar magnetron sputtering. Au is greater than 90% reflective over a range of infrared wavelengths, and either Cr or Ti can be employed as an adhesion promoter between Au and Si. The residual stress of multilayer films is determined through curvature based measurements using laser-scanning and applying Stoneys equation. The influence of sputter gas pressure and deposition rate on residual film stress is assessed for a variety of multilayer systems. Also assessed is stress aging at room temperature over a period of one year. Using optical interferometry, we have already demonstrated that low stress Au/Ti films deposited on micromirrors 125-500 µm in size induce less than λ/40 change in bow. This work seeks to extend these initial results by combining low stress Au/Ti films with Si_3N_4/Si Bragg reflectors to achieve a near-zero stress multilayer exhibiting both a ~99% reflectivity for a target wavelength of radiation while inducing minimal curvature changes when deposited on pre-released polysilicon micromirrors. Since thin film microstructural defects and interfacial roughness can contribute to optical absorption, examination of both is conducted using cross-sectional transmission electron microscopy. Surface roughness is also measured using atomic force microscopy. Spectral reflectivity of thin film coatings is measured using an optical spectrum analyzer.

MM-WeP9 Deep Reactive Ion Etching of Silicon Using an Aluminum Etching Mask, ***W. Wang***, *P. Reinhall*, University of Washington

A novel double-sided micromachining process for the silicon based device fabrication has been developed that allows the use of capacitively coupled RIE equipment for high aspect ratio etching. The resulting etch rates in Si of 2.2 µm/min is comparable to 1 to 3 µm/min from the standard ICP deep reactive ion etching process. Although a lower anisotropy (~0.5) and lower selectivity to thermal oxide (Si: SiO_2 = 10:1) and to photoresist (Si: +PR = 9:1) resulted, the proposed process is much simpler and requires only the use of an aluminum mask. Based on the experimental results, a 1000 Å thick Al film sufficiently protects the unexposed substrate while allowing the etching of a 350µm deep hole with an area of 3x3mm^2 when etching with SF_6 /CHF_3/O_2 plasma. A 2000µm long and 100µm wide (with layers of Al/SiO_2/Si and thicknesses of 0.1µm/2.2µm/40µm respectively) cantilever is also achieved. The technique was developed mainly for bulk micromachining of silicon or composite silicon cantilever structures.

Plasma Science
Room: C-105 - Session PS+MM-WeA

Feature Profile Evolution /Plasma Processing for MEMS
Moderator: A. Kornblit, Bell Labs, Lucent Technologies

2:00pm **PS+MM-WeA1 Plasma Molding Over Trenches and Resulting Ion/Fast-neutral Distribution Functions**, ***D. Economou***, *D. Kim**, University of Houston

Plasma molding over surface topography finds applications in MEMS microfabrication, neutral beam sources, plasma extraction through grids, and plasma contact with internal reactor parts (e.g., wafer chuck edge). The flux, energy and angular distributions of ions incident on the substrate are of primary importance in these applications. These quantities depend critically on the shape of the meniscus (plasma-sheath boundary) formed over the surface topography. When the sheath thickness is comparable to or smaller than the feature size, the sheath tends to "mold" over the surface topography. A two-dimensional fluid/Monte Carlo simulation model was developed to study plasma "molding" over surface topography. The radio frequency (RF) sheath potential evolution, and ion density and flux profiles over the surface were predicted with a self consistent fluid simulation. The trajectories of ions and energetic neutrals (resulting by ion neutralization on surfaces or charge exchange collisions in the gas phase) were then followed with a Monte Carlo simulation. Ion flow and energy and angular distributions of ions and energetic neutrals bombarding the walls of a trench will be reported. Emphasis will be placed on high aspect ratio features of interest to MEMS and neutral beam sources. Simulation results will be compared with experimental data, taken at Sandia National Labs, on ion flux and ion energy and angular distributions at the bottom of trenches. Work supported by the National Science Foundation and Sandia National Laboratories.

2:20pm **PS+MM-WeA2 Physically Based Modelling of High-Density-Plasma-CVD on the Feature Scale**, ***G. Schulze-Icking***, *A. Kersch*, Infineon Technologies AG, Germany, *A. Knorr*, Infineon Technologies, *A. Hausmann*, *J. Radecker*, Infineon Technologies Dresden GmbH & Co. OHG

Due to its low thermal budget and its highly directional deposition HDP-CVD of SiO_2 has become an important process in IC fabrication. In order to study (and ultimately improve) the HDP-CVD process we have developed a physically based model for feature scale simulations. This model has been implemented into our custom Topography Simulator "Topsi" and extensive studies of the HDP-CVD process have been performed. In this presentation we give a survey of our simulation results and compare them to experiments. The model we propose retains the characteristics of a complex reactor scale model published by Meeks et al.[1] and extends it to the feature scale. A key aspect of both models is a "structural passivation" of the surface due to the chemisorption of gas phase precursors. In contrast to conventional CVD (at much higher temperatures) in HDP-CVD this passivation is removed by cations striking the surface. Accordingly ions not only sputter surface material but also are responsible for its directional deposition. The final topography therefore is the result of simultaneous neutral deposition/passivation, ion induced activation, and sputtering. It is well known[2] that the sputtering yield crucially depends on the ion energy and the angle of incidence. This probably also applies to ion induced surface activation, but very little is known about its energy and angular dependence. We therefore have performed deposition experiments and compared the final topography to simulations performed using our new model. With the derived set of parameters we are now able to predict the surface evolution as a function of process conditions. This is a major improvement over a more empirical model proposed by Conti et al.[3]

[1] E.Meeks et al.; J.Vac.Sci.Techn. A, 16, pp 544 (1998)
[2] C.Abrams et al.; J.Vac.Sci.Techn. A, 16, pp 3006 (1998)
[3] R.Conti et al.; DUMIC Conference (1999).

2:40pm **PS+MM-WeA3 Micro- and Nano-Fabrication Technology for High Aspect Ratio Micro-Electromechanical Systems (MEMS)**, ***S.W. Pang***, The University of Michigan **INVITED**

For many applications in micro-electromechanical systems (MEMS), having high aspect ratio sensors or actuators can improve performance, increase sensitivity, and lower power consumption. Micro- and nano-fabrication technology can be used to generate these high aspect ratio MEMS. Etch rate, profile, selectivity, and uniformity could vary as aspect ratio becomes higher since plasma etching characteristics depend on aspect ratio of microstructures. These variations could affect MEMS performance. In this talk, key issues to provide precise control in MEMS fabrication by plasma processing will be discussed. High aspect ratio MEMS including micromirrors for optical switching arrays, submicrometer resonators for accelerometers, sharp tips for emitters or scanning probes, and microheaters for micro-gas chromatography systems will be reviewed.

3:20pm **PS+MM-WeA5 Critical Tasks in the High Aspect Ratio Silicon Dry Etching for MEMS**, ***I.W. Rangelow***, University of Kassel, Germany **INVITED**

Microscopically uniform anisotropic etching of semiconductor layers is a critical step in ME(O)MS and ULSI circuit fabrication. The non-ideal etched feature limits density, yield and reliability of these devices. Artefacts such as RIE-lag, notching, sidewall bowing, micro-trenching, and mask facetting are typically accompaniment effects occurring during the etching high aspect ratio features in silicon. Because etch rates and the shape of etched features depend on circuit layouts-design, considerable effort have to be spent in the near feature to understood all common single and simultaneous phenomena during the high aspect ratio dry etching. The development of effective manufacturing processes requires a fundamental understanding of the factors, which determine etched feature shape. Gas reactivity, pressure (affecting ion bowing in the sheath due to scattering with neutrals), ion, electrons and reactant transport to the surface, and product transport away from the surface, have been identified as the key factors that control the microscopic etching uniformity in high aspect ratio etching. The choice of these can cause numerous secondary aspect ratio-dependent effects. The modelling of the most significant effects as RIE-lag, notching, bowing, facetting, micro-trenching, profile shape dependence etc. will be discussed.

4:00pm **PS+MM-WeA7 Deep Silicon Etch Profile Control for Micro-Sensor Applications**, ***R.J. Shul***, *M.G. Blain, S.G. Rich, S.A. Zmuda, C.G. Willison, R.P. Manginell*, Sandia National Laboratories

The ability to etch deep, high-aspect ratio, anisotropic, Si features has opened up new areas of application for microelectromechanical systems (MEMS) devices, as well as revolutionized the conception and implementation of "mixed technology" integration. For example, a fully integrated microsystem could include sensors, actuators, electronics, fluidics, and optics in a variety of material systems on a single chip or in a single package. Fabrication of such structures often requires profile control, multi-level etched features, and the ability to form freestanding membrane structures. For example, Si deep reactive ion etch (DRIE) has been used to fabricate a gas chromatographic (GC) separator as part of a micro-chemical analysis system (µChemLab™) used for the detection of trace concentrations of gas phase analytes. Maintaining uniform, controlled flow dynamics to optimize device performance requires well-controlled etch profiles and smooth etch morphologies. We will report on the use of the DRIE platform to fabricate anisotropic GC columns 100 µm wide, 400 µm deep with 25 µm walls. To improve the separation sensitivity of the GC columns, a new GC design that incorporates 50 µm diameter posts on 80 µm pitch located within 500 µm deep GC columns has recently been fabricated. A new DRIE process was developed to etch these features using parameter ramping, varying reactive gas flow, pressure, and ion energy. The profiles were very anisotropic with smooth features. The use of parameter ramping as well as multi-level masking processes to meet the challenges of advanced micro-sensor designs will be discussed. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under contract DE-ACO4-94AL85000.
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4:20pm **PS+MM-WeA8 Profile Control as a Function of Process Parameters in Deep Anisotropic Etching of Silicon**, ***M.L. Steen***, *T.J. Dalton*, IBM T.J. Watson Research Center

Deep etching of silicon is integral to the fabrication of microcomponents for microelectromechanical systems (MEMs). New commercially-available etching tools from several manufacturers are capable of deep silicon etching beyond 300 µmm. These systems offer the time multiplexed deep etching (TMDE) technique developed and licensed by Robert Bosch Gmbh, which uses alternating etching and deposition cycles for anisotropic etching of deep silicon structures. During the deposition step, sidewalls are passivated by a polymer deposited from a C_4F_8 discharge. During the subsequent etching cycle flowing only SF_6, both the polymer and silicon are preferentially etched from the base of the trench by ion bombardment. Accurate control of the depth and anisotropy of etched structures is

* PSTD Coburn-Winters Student Award Finalist

achieved by a fine balance between deposition and subsequent removal of the passivating layer. Processes are well controlled and many types of MEMS devices, such as pressure sensors and accelerometers, are produced using this technology. We are interested in expanding the number and scope of applications using deep silicon etching. Many of these applications have additional demands on surface morphology including minimization of the scalloping observed on vertical sidewalls during TMDE and the roughness of surfaces exposed to the discharge. Moreover, mask undercut and bowing of the etch profiles must be reduced to tailor the slope of etch profiles. Our goal is to understand the evolution of these traits as a function of operating conditions. Toward this goal, a number of process variables were explored using a commercial inductively-coupled plasma etcher. We report a significant increase in the silicon etching rate, minimization of mask undercut, and substantial reduction in bowing. These improvements demonstrate enhanced process performance and flexibility to meet a broad range of needs in deep silicon etching.

4:40pm **PS+MM-WeA9 Mechanisms Involved in the Silicon Cryogenic Etching Process**, ***M. Boufnichel***, GREMI / ST Microelectronics, France, *P. Lefaucheux, R. Dussart,* GREMI, France, *P. Ranson*, GREMI-Universite d'Orleans-CNRS, France

In this study, we investigated the etching and passivation mechanisms involved in the deep cryogenic etching of silicon trenches. More precisely, we studied the dependence of sticking coefficient of oxygen and fluorine as regards to wafer temperature. We showed that fluorine radicals sticking coefficient does not strongly depend on wafer temperature at the contrary to oxygen radicals. XPS measurements allowed us to obtain further informations concerning the nature and behaviour of the passivation layer deposited on trench sides during the cryogenic silicon etching with a SF6/O2 mixture. XPS measurements pointed at the fact that the passivation layer formed during the cryogenic etching of silicon is not mainly composed of SiO2 species. Furthermore, a new method has been employed to determine the effective angular dispersion of ions (EIAD) involved in the etching of silicon and its impact on trench etching evolution. A comparison of the performances of RF and LF bias generators has also been performed so as to highlight the impact of bias-frequency on profile characteristics. A complete study of the etching mechanisms would not have been possible without parallel measurements of physical plasma parameters using Langmuir probe and actinometry with Optical Emission Spectroscopy (OES). The parallel between the etching experiments and diagnostics measurements shows for example that local bowing seems to depend on ion local surface bombardment and passivating mechanisms. Finally, we are able to etch deep anisotropic trenches (100 microns deep and 2 microns in aperture) at a high etch rate, high selectivity (SiO2 mask) and high anisotropy. We performed to reduce or eliminate defects such as local bowing, undercut and notching for different application: etching of HARTs (High Aspect Ratio Trenches), LARTs (Low Aspect Ratio Trenches), vias, SOI (Silicon On Insulator) layers.

5:00pm **PS+MM-WeA10 3-Dimensional Feature Profile Evolution Using Level Set Methods**, ***H. Hwang***, *T.R. Govindan, M. Meyyappan*, NASA Ames Research Center

Modeling feature profile evolution due to etching of semiconductor materials is typically done in two dimensions. However, these 2-D simulations make assumptions about geometries, such as semi-infinite trenches, that are unrealistic. Since a semi-infinite trench will "collect" higher amounts of fluxes than a finite one, the calculated ion and neutral fluxes to the surfaces in 2-D will not account for the shadowing of the opening due to the finite size. These larger fluxes will then lead to a larger overall etch rate, compared with calculations done in 3-D. Furthermore, any asymmetries (due to ion angular distribution functions, for example) can only be captured in 2-D. Inherently 3-D situations, such as striation patterns of the trenches, cannot be studied without the third spatial dimension. We will present results using an etching 3-D simulation which uses level set methods to advance the moving front. This code is an extension of SPELS, the Simulation of Profile Evolution using Level Sets, to calculate etch rates of silicon in chlorine discharges. We will show animations of the evolving trench for different geometries as well as for different process conditions. We will make comparisons of cross sections of the 3-D profiles to calculations from 2-D simulations and demonstrate the effects of a finite trench versus a semi-infinite trench on etch rates.

Microelectromechanical Systems (MEMS)
Room: C-210 - Session MM+TF-ThM

Development and Characterization of MEMS Materials
Moderator: R. Ghodssi, University of Maryland

8:20am **MM+TF-ThM1 Tetrahedral Amorphous-carbon (ta-C) for MEMS Applications**, ***T.A. Friedmann***, *J.P. Sullivan, R.V. Ellis, T.M. Alam, M.P. de Boer, T.E. Buchheit*, Sandia National Laboratories **INVITED**

This presentation will focus on ta-C film properties (primarily stress relaxation) and MEMs and sensor devices fabricated from low stress ta-C material (not coatings of Si devices) with an emphasis on mechanical and adhesion property measurements enabled by device fabrication. Pulsed laser deposition (PLD) was used to grow the ta-C films. They can be fully stress relieved by simple thermal annealing without significantly altering the film mechanical properties. Two mechanisms for stress relief in these materials have been postulated, each involving strain-relieving transformations between sp^2 and sp^3 carbon. Recently, we have made fully ^{13}C enriched films by ablating from a ^{13}C (99%) target. NMR magic-angle spinning measur ements of these enriched f ilms have been made to quantify the changes in structure with annealing in an effort to validate the proposed models. Results of these measurements will be presented along with Raman, TEM, and cross-section EELS experiments. The low stresses that are achievable in ta-C enable interesting MEMS and sensor applications. We have demonstrated several one-level MEMS structures from this material (e.g. cantilever beams, microxylophone resonators, fatigue test, tensile test, and membran e based sensors) and used these structures for materials property measurements. Results of selected experiments will be presented. *This work was supported by the U.S. DOE under contract DE-AC04-94AL85000 through the Laboratory Directed Research and Development Program, Sandia National Laboratories.

9:00am **MM+TF-ThM3 Challenges of Compressible Microfluidics and MEMS Device Development**, ***C.B. Freidhoff***, Northrop Grumman ES, *E. Hong*, The Pennsylvania State University, *R.L. Smith*, University of Maryland-Baltimore County, *T.T. Braggins, S.V. Krishnaswamy*, Northrop Grumman ES, *S. Trolier-McKinstry*, The Pennsylvania State University **INVITED**

MEMS vacuum pump for a miniature mass spectrograph challenges current modeling techniques compared to other microfluidic devices that utilize incompressible fluids. The ability to estimate boundary layers accurately is needed to save resources in determining the optimum dimensions for geometries in the micrometer scale. This device development also adds in the need for dynamic analysis over a broad pressure range. Results for actuator and pump performance measurements as well as results on the expected reliability of the thin films used in the pump's mechanical operation will be presented. The paper will discuss the challenges and empirical results we have achieved to date.

9:40am **MM+TF-ThM5 Micro-Mechanical Characterization of Indium Phosphide (InP) for Active Optical MEMS Applications**, ***M.W. Pruessner***, University of Maryland, *T. King*, NASA Goddard Space Flight Center, *D. Kelly, R. Ghodssi*, University of Maryland

Monolithic integration of InP-based optoelectronics with MEMS actuators will enable wavelength division multiplexed (WDM) lossless switches, tunable lasers, and optical filters at the 1550 nm communications wavelength. Before InP-based MEMS can be realized, however, the mechanical properties of thin-film InP need to be determined. Three methods are presented. In nanoindentation, the applied load vs. displacement of thin films or bulk substrates is measured, and Youngs modulus (E) and film hardness (H) can be extracted. In the bending test, load-displacement data of microbeams is used to extract E. Finally, M-Test takes advantage of the pull-in instability of electrostatically actuated microbeams. Measurement of the pull-in voltage enables E and residual stress to be extracted. A surface micromachining fabrication process for InP-based MEMS actuators was developed. The devices consist of 1.7 µm thick InP beams oriented in the [011] direction with 1.7 µm $In_{0.53}Ga_{0.47}As$ sacrificial layer on a (100) InP substrate. Fabrication utilizes methane-hydrogen-argon RIE of InP followed by sacrificial etching of the InGaAs layer and supercritical CO_2 drying. After release the longer cantilevers curved out of plane indicating a stress gradient. Furthermore, the longer fixed-fixed beams buckled indicating compressive stress. Both are likely the result of arsenic (As) contamination of the InP beam layer during MBE sample growth. An optimization of growth parameters should alleviate this effect. Bulk nanoindentation experiments resulted in E=103 GPa and H=6.3 GPa. Bending tests on short fixed-fixed beams resulted in E=80 GPa. InP beam-type electrostatic actuators were also demonstrated. However, M-Test could not be performed reliably on the existing samples due to out-of-plane curvature of the longer beams. Short beams were flat but required excessive actuation voltage. Device design and experimental results are presented.

10:00am **MM+TF-ThM6 Stiction/Friction Studies of MEMS Materials Using a Novel Microtriboapparatus**, *H. Liu*, ***B. Bhushan***, The Ohio State University

Microelectromechanical systems (MEMS) are the next logical step in "silicon revolution". Many studies have shown that stiction/friction impacts the efficiency, power output, and steady-state speed of microdevices. It is essential to study the stiction/friction of the compoents and materials that are commonly used in MEMS/NEMS devices. A microtriboapparatus is needed which can be used to perform stiction/friction studies using microcomponents relevant for applications. Such an apparatus has been developed and used in this study. In this apparatus, two components/specimens are mounted on two piezos, which can deliver the motion in X and Z directions, respectively. A total of four fiber optical sensors are used to measure the sample displacement in X and Z directions, adhesive force, friction force, and normal load. The microtribological properties of silicon, diamond like carbon films are investigated by this apparatus. Experiments have been also performed to study the effect of velocity, relative humidity and temperatures on these materials.

10:20am **MM+TF-ThM7 Free-standing Single-crystal Ni_2MnGa Thin Films: A New Functional Material for MEMS**, *J.W. Dong, J.Q. Xie, J. Lu, Q. Pan, J. Cui, S. McKernan, R.D. James*, ***C.J. Palmstrom***, University of Minnesota

Ferromagnetic shape memory (FSM) alloys are a new type of materials that experience thermodynamically reversible martensitic phase transformations and demonstrate ferromagnetic property. This ferromagnetic property provides unique handle on the configuration of the martensitic phases. Practically, moderate external magnetic/stress field can be applied to the FSM alloys in the twinned martensitic phase to adjust the volume fraction of the variants by the motion of twin boundaries, which will yield macroscopic shape change. In bulk single crystals of Ni_2MnGa, a typical FSM alloy, strain as large as 9.5% has been demonstrated.[1] This makes Ni_2MnGa a promising candidate for magnetic field driven actuator material. For micro-electro-mechanical-system (MEMS) actuators, several conceptual designs based on single crystal Ni_2MnGa films have been proposed.[2] The first single crystal growth of Ni_2MnGa thin film has been reported in ref. 3. The 300 Å-thick film grows pseudomorphically on a GaAs (001) substrate (a = b = 5.65 Å, c = 6.12 Å) and has a Curie temperature ~320 K. Furthermore, 900 Å-thick single-crystal Ni_2MnGa films have been processed into free-standing bridges and cantilevers.[4] The free-standing cantilevers show two-way shape memory effect under repeated thermo-cyclings. In this presentation, focus will be put on the shape memory effect and the magnetic field induced strain in the free-standing Ni_2MnGa films to elucidate the concept of using it as a new functional material in MEMS design.

[1] A. Sozinov, et al., Appl. Phys. Lett., 80, 1746 (2002).
[2] K. Bhattacharya, et al., Mat. Sci. Eng. A, 275, 685 (1999).
[3] J. W. Dong, et al., Appl. Phys. Lett., 75, 1443 (1999).
[4] Q. Pan, et al., to be published in J. Appl. Phys.

10:40am **MM+TF-ThM8 A New Approach to Electrical Characterization of Spin-on Dielectrics for Power MEMS Applications**, ***A. Modafe***, *R. Ghodssi*, University of Maryland

We have developed a new method and special-purpose test structures for electrical characterization of spin-on low-k dielectrics for Power Micro-Electro-Mechanical Systems (MEMS) that operate under high voltages. The spin-on low-k dielectrics in this study are ACCUGLASS T-12B, a methylsiloxane-based spin-on glass (SOG) from Honeywell and CYCLOTENE 3022-35, a polymer based on B-staged bisbenzocyclobutene (BCB) monomer from Dow Chemical. Due to their simple, low-temperature processes, these materials are suitable for the inter-level dielectric layer in a Power MEMS device, in this case a bottom-drive variable-capacitance micro-motor supported on micro-ball bearings. The existence of relatively high voltages makes the electrical components of the device, especially the inter-level dielectric more vulnerable to failure. Furthermore, the likelihood of failure increases with time due to absorption of moisture and dust. The proposed method performs capacitance and current vs. voltage measurements (C-V and I-V) on the inter-digit comb-type and spiral-type capacitor test structures to characterize the electrical properties of the dielectric film under test, i.e. dielectric constant, dielectric strength, leakage current, and their dependency on absorbed moisture and operation time. The measurement of the dielectric constant is based on a geometry-extractor method that compares the capacitance of the test structure before and after dielectric deposition. The dielectric constant is calculated by extracting a geometry factor representing the shape of the test structure from the C-V test. The dielectric constant measurement error is minimized using the extracted geometry factor, instead of measuring the geometrical features in separate experiments. The measurement of the dielectric strength and the leakage current is based on a ramped voltage-stress (RVS) method using the I-V test on the developed test structures. Preliminary results for electrical characterization are presented.

11:00am **MM+TF-ThM9 Physics of Metal Micro-contact Events in Micro-Electro-Mechanical (MEM) Relays**, ***J.W. Tringe***, *T.A. Uhlman*, Air Force Research Laboratory, *A.C. Oliver, J.E. Houston*, Sandia National Laboratories

Much research has been previously performed on the physics of electrical contacts, but this has mostly focused on larger contact areas, force and current levels than are relevant for typical MEM switches. Recent work using interface force microscopy (IFM) has experimentally approximated single-asperity gold-gold electrical contact events under conditions appropriate to MEM relay materials. The contact force and resistance were measured simultaneously under constant-current conditions as a function of relative probe-surface separation using parabolic gold probes a few microns in diameter on an electroplated gold surface, typical of the contact surface found in MEM relays. Results will be presented which demonstrate that a very small number of asperities define the electrical behavior of gold-gold MEM switches. Further, the existence of a non-metallic contamination layer on the gold surfaces, up to many tens of angstroms thick, will be shown to critically determine the force and current levels necessary for low contact resistance (on the order of a few ohms or lower). Contact resistance decreases precipitously upon break-down or thinning of the contamination layer, then more slowly and linearly as the probe-surface contact area increases. The contamination layer deforms plastically upon initial contact, then maintains physical and electrical contact with the tip to distances over 5 nm from the point of initial contact. Due to the topography of the electroplated gold surface and the mechanical, electrical and chemical nature of the contamination layer, contact events in gold-gold microsystem relays involve relative contact areas on the order of 0.1%.

Sandia is a multi-program laboratory operated by Sandia Corporation, a Lockheed Martin company, for the DOE under Contract DE-AC04-94AL85000.

11:20am **MM+TF-ThM10 Growth and Characterization of Doped 3C-SiC Films for Micro- and Nanoelectromechanical Systems**, *A.J. Fleischman*, ***C.A. Zorman***, *M. Mehregany*, Case Western Reserve University

An outstanding combination of mechanical, electrical, and chemical properties coupled with recent advances in micromachining make SiC a leading material for microelectromechanical systems requiring performance characteristics that cannot be achieved using Si. For these applications, 3C-SiC is particularly attractive since it is the only SiC polytype that can be grown as single and polycrystalline thin films on Si substrates, giving it a versatility unmatched by the other leading polytypes, specifically 4H- and 6H-SiC. Recently, 3C-SiC has found favor as a material for nanoelectromechanical systems (NEMS), due to the fact that it has a higher acoustic velocity than Si. For nanomechanical resonators, 3C-SiC is currently used solely for its mechanical and chemical properties, while electrically active components are constructed of other materials. Advanced 3C-SiC NEMS will likely capitalize on the electrical properties of 3C-SiC, requiring the use of doped material grown in a well-characterized and highly controllable fashion at the submicron level. In this study, 0.5 micron thick, doped 3C-SiC films were epitaxially grown on (100) Si wafers by APCVD, using silane and propane as precursor gases, hydrogen as a carrier gas, and phosphine and diborane as doping gases. To investigate the effects of dopant incorporation on microstructure, the films were grown as thin multilayers, with a doped layer sandwiched between two undoped layers. SIMS and XRD were used to characterize the multilayer samples. In general, phosphorus doping had no adverse affect on the microstructure of the single crystal films. In contrast, boron doping did influence the microstructure, with high diborane concentrations resulting in the formation of polycrystalline SiC layers. Details concerning the experimental procedure, the effects of outgassing reactor components on the composition of the films, and the implications for submicron 3C-SiC devices will be covered in this presentation.

11:40am **MM+TF-ThM11 Incorporating Chemically Functional Materials on MEMS Structures**, ***S. Semancik***, *R.E. Cavicchi, N.O. Savage, C.J. Taylor, D.C. Meier, C.B. Montgomery*, National Institute of Standards and Technology

Low power microsensors and microanalytical systems based on MEMS platforms are expected to profoundly impact the areas of chemical and biological sensing. Fabrication of such chemical microdevices, however, requires that chemically functional materials be integrated with a variety of MEMS structures, challenging researchers to develop processing methods that are reliable, as well as compatible with microelectronic materials and micromachining. In this presentation we describe a range of film deposition procedures for localized deposition of oxides, metals, polymers and other materials on surface-micromachined components. The procedures, which have been developed within our chemical microsensor program, are typically performed on target areas of ~ 100 µm x 100 µm. They include: self-lithographic, thermally-activated CVD on microhotplate structures; addressable electrodeposition; spinning on and selectively removing sol-gels and colloidal suspensions as well as thermally-evolved resists; the use of microheaters to process high area porous films (from silsesquioxanes); utilization of tiny (lithographically-defined) shadow masks with evaporation; and micro-pipetting. Locally-deposited materials are characterized by SEM, AFM, EDS and other spectroscopic methods, and by electrical probing when it is relevant. We provide examples of processing for nanostructured SnO_2 and TiO_2, high-area SiO_2, ultrathin Pt, Au, Ni and Pd, organosilanes and modified polymers. These materials have been employed on MEMS platforms, individually and in certain combinations, for sensing, preconcentration, separation and patterning. The role of multielement microarrays in efficiently optimizing deposition methods for some films will also be discussed.

Microelectromechanical Systems (MEMS)
Room: C-210 - Session MM-ThA

Fabrication, Integration, and Packaging Techniques for MEMS
Moderator: C.A. Zorman, Case Western Reserve University

2:00pm **MM-ThA1 Addressing MEMS Reliability Through Innovative Fabrication, Integration, and Packaging Techniques**, ***V.M. Bright***, University of Colorado, Boulder **INVITED**

MEMS research at the University of Colorado in Boulder (UCB) has been focused on MEMS reliability through innovative design, materials, and fabrication. The UCB has applied techniques from other fields in a novel way to solve reliability issues in MEMS. This approach has improved the reliability of more traditional silicon-based MEMS. It also has resulted in a number of innovative new MEMS designs and applications. As the silicon-based MEMS manufacturing techniques mature and products transition from the R&D phase to production, the reliability aspects of MEMS design, fabrication, and packaging become more of a reality. It is known that MEMS reliability problems are related to nano-scale interface phenomena. One approach to solve MEMS reliability challenges is through novel materials and/or fabrication methods. Another approach is to improve MEMS reliability through proper design, which takes into account interface phenomena such as adhesion or charging. The barriers to MEMS reliability include: thin film structure susceptibility to adhesion due to large contact surface area and/or dielectric charging; limited life-time of microstructure due to friction and wear at micro-scale; multilayered structure change in curvature during thermomechanical loading or fabrication/packaging processes that require temperature cycling; multilayered structure stress relaxation over time, which may result in changing device functionality. In order to build reliable devices, advanced design knowledge must emphasize interactions among thermal, mechanical, chemical, and atomic effects bridging the necessary nano- and micro-scales. The fabrication must focus on nano-scale materials synthesis, characterization, material processing and packaging technologies that are critical to assure device reliability. The technologies that this talk is focused on include: atomic layer deposition of coatings, self-assembly of MEMS using surface tension forces, flip-chip MEMS assembly and packaging.

2:40pm **MM-ThA3 Development of Individually Addressable Micro-Mirror-Array for Space Applications**, ***S.B. Dutta***, NASA, Goddard Space Flight Center **INVITED**

MEMS is a strategic technology thrust area for NASA's missions of the 21st century. It will enable development of sensors and actuators for communication, navigation, propulsion and optical subsystems with low mass and power that operate in space environment. Currently, NASA is supporting MEMS technology development for the Next Generation Space Telescope (NGST), successor of the Hubble Space Telescope (HST) to be launched in 2009. NGST would have a Near InfraRed Multi Object Spectrometer (NIRMOS) that would use programmable slits to select multiple stars and galaxies for simultaneous observation. A team at NASA, Goddard Space Flight Center (GSFC), has developed aluminum, bi-state Micro-Mirror-Array (MMA) operating at 30K that could be used as programmable slits, to support science objectives of NGST. MEMS technology permits fabrication of MMA with self-contained actuation mechanism and direct interfaces to digital electronics. 32x32 MMA has been designed and fabricated using standard CMOS and surface micro-machining processes. The unit cell of MMA contains a square mirror on 100µm pitch and tilts by ± 10 °. The MMA are built on top of CMOS driven address and driver circuit for individual addressing and a CMOS compatible MEMS process has been implemented for compact design. The tilting of the mirrors is achieved by electrostatic attraction between two parallel plate aluminum electrodes. A pair of thin aluminum torsion straps is used so that the voltage required for tilting is less than 20V. The array has been tested successfully to operate at room temperature and at 30K for over 10^6 cycles. Operation of mirror elements has been simulated extensively. Experimental data are in good agreement with model predictions. For optimal operation of MMA, different alloy materials were studied for mirror fabrication. Electro-mechanical modeling, material property studies, fabrication, packaging and optical characterization of the MMA will be presented.

3:20pm **MM-ThA5 Transformer Coupled Plasma Etching of Polycrystalline 3C-SiC Films for MEMS Applications**, ***D. Gao***, *M.B.J. Wijesundara*, *C. Carraro*, *R.T. Howe*, *R. Maboudian*, University of California at Berkeley

Polycrystalline 3C-SiC films were etched by oxygen-mixed sulfur hexafluoride transformer coupled plasmas (TCP) in a commercial LAM TCP 9400 etcher for MEMS applications. The SiC films were grown by single-source CVD at 850°C using 1,3-disilabutane as the precursor.[1] Low-temperature CVD SiO_2 and plasma-enhanced CVD SiO_2 were employed as etching masks, which avoided micromasking phenomena and chamber contamination commonly involved when using metals as masks in most SiC etching processes. The SiC etch rates changed slightly with O_2 percentage, reaching maximum of 3800 Å/min at 16% O_2. Etching rate ratio of SiC/SiO_2 increased with O_2 percentage, reaching 2.6 at 50% O_2. By integrating the etching process into micromachining techniques, SiC-based micromechanical structures were fabricated. The etching profile and the chemical components of etched SiC surfaces were examined by cross sectional SEM and X-ray photospectroscopy respectively.

[1] C.R. Stoldt, et al., Proceeding of Transducers 01, the 11th International Conference on Solid-State Sensor and Actuators, Munich, Germany, June 10-14, 2001, pp. 984-987.

3:40pm **MM-ThA6 MEMS-based Gray-scale Technology**, ***C.M. Waits***, *A. Modafe*, *R. Ghodssi*, University of Maryland

Micro-electro-mechanical systems (MEMS) fabrication technologies originated directly from integrated circuit (IC) fabrication, consisting of primarily planar techniques. Consequently, structures fabricated for MEMS devices have been traditionally designed with nominally vertical sidewalls (dry anisotropic etching), undercut sidewalls (wet isotropic etching), or sidewalls with limited angles due to the crystallographic orientation of the substrate (wet anisotropic etching). There exists a breadth of potential applications for a fabrication technique that can achieve 3-D structures (arbitrarily sloped sidewalls) in silicon suited for small and large high aspect ratio MEMS structures. A micromachining technique using gray-scale lithography along with dry anisotropic etching enables the development of 3-D structures in silicon. The gray-scale lithography allows the fabrication of a differential-height photoresist-masking layer. The key components in gray-scale lithography include (a) design of the optical mask and (b) use of a projection lithography system. A sub-resolution optical mask and a photolithography stepper system together locally modulate the intensity of ultraviolet light through diffraction. The modulated light exposes a photoresist film to specified depths where a gradient height profile remains once developed. This method results in the fabrication of differential-height photoresist masking layers with up to 22 different height levels. The masking layers are then used in Reactive Ion Etching (RIE) to successfully transfer the structures in silicon, resulting in various shaped 9-micron tall silicon structures with sloped sidewalls ranging from 5 to 90 degrees with respect to the silicon surface. The results of preliminary characterization for both gray-scale lithography and RIE etching in silicon are presented.

4:00pm **MM-ThA7 Thick and Thermally Isolated Si Microheaters for Preconcentrators**, ***W.-C. Tian***, *S.W. Pang*, The University of Michigan

Thick, thermally isolated microheaters in Si are fabricated using high aspect ratio etching technology. These thick microheaters with large surface area provide large adsorbent capacity needed for high sensitivity preconcentrators in a micro gas chromatography system (µGC). Microheaters in this work are different from previous work which consisted of mostly thin poly-Si or metal microheaters (<2 µm) on top of the dielectric membranes. Instead, thick microheaters (>500 µm) surrounded by air gaps are generated to provide large surface area and good thermal isolation, which are important for high sensitivity, low power preconcentrator in a µmGC system. A 520 µm thick Si microheater with good thermal isolation has been made and its backside is anodically bonded to a pyrex glass substrate. To provide good thermal isolation, a 500 µm wide air gap around the microheater, thin poly-Si interconnects on top of dielectric membrane, and air gap isolation from the bottom glass substrate are used. Microheaters with 500 µm air gap can be heated up 50% faster to a temperature of 270 °C compared to those with 100 µm air gap, while the power consumption is 25% less and there is a larger temperature difference between the microheater and the bonding area. Operating the microheater in vacuum results in lower power consumption. At 250 °C, 38% less power is needed at 1.2 Torr compared to atmosphere pressure. Power consumption is further reduced by minimizing the contact area with the heater support substrate. Up to 33% power reduction has been demonstrated by placing heaters on thin membrane or etching trenches in supporting substrate. This is the first demonstration of using thick Si microheaters with air gap isolation for μmGC system. These thick, thermally isolated Si microheaters can provide good power efficiency, large adsorbent capacity, and high mechanical strength as preconcentrators.

4:20pm **MM-ThA8 Silicon Nitride Micromesh Bolometric Detectors for Planck**, ***M. Yun***, *T. Koch, J. Bock, W. Holmes*, Jet Propulsion Laboratory, *A. Lange,* California Institute of Technology

We report on the design, fabrication and testing of the bolometric detectors for the High Frequency Instrument (HFI) on the Planck Surveyor, ESA mission designed to image the Cosmic Microwave Background that is scheduled for launch in 2007. The bolometric detectors consist of NTD Ge thermistors indium bump-bonded to a fine mesh of silicon nitride. The mesh is metalized to efficiently absorb mm-wave radiation. Unmetalized support becomes excellent thermal isolation from the heat sink. The absorber geometries are of 2 types: one sensitive to both linear polarizations and optimized for background-limited sensitivity at 100, 143, 217, 353, 545 and 857 GHz, the other sensitive to a single linear polarization and optimized for background-limited sensitivity at 143, 217, 353 GHz. The detectors have NEP ~ 10^{-17} W/$(\mathrm{Hz})^{0.5}$ and time constants of several msec.

4:40pm **MM-ThA9 Piezoelectric MEMS for RF Filter Applications**, ***A. Wickenden***, *B. Piekarski, L. Currano, J. Pulskamp, R.G. Polcawich, E. Zakar, R. Piekarz, D. Washington, J. Conrad, M. Dubey*, U.S. Army Research Laboratory

Resonator arrays for RF filter devices operating in the GHz frequency range are of interest for lightweight, low power, high precision frequency selection applications. A high quality factor (Q) is required to reduce phase noise and ensure stability against frequency-shifting phenomena. MEMS-based resonator devices offer potential advantages in size, weight, and power consumption over surface wave acoustic wave (SAW) or bulk acoustic resonators currently used for frequency filtering applications. Piezoelectric electromechanical resonator devices should demonstrate advantages over equivalent electrostatic devices for high frequency applications, since they are less sensitive to degraded coupling strength as the device dimensions are reduced.[1] Resonant frequency response is determined by both device geometry and materials properties. PZT is attractive for piezoelectric filters due to its high piezoelectric coupling coefficient, although the operating frequency of PZT resonators is limited to the MHz range by the large acoustic time constant of the material. Piezoelectric materials such as aluminum nitride (AlN), zinc oxide (ZnO), and related alloys are of interest because their fast acoustic response times translate to theoretical maximum frequencies of >100 GHz.[2] Models are being developed to predict the response of piezoelectric MEMS resonators. These models are currently being validated using PZT resonator devices with beam lengths ranging from 400µm to 20µm, with natural frequencies in the MHz regime. Deviation from standard mechanical models has been observed in the measured response of these devices having lengths less than 50µm. The fabrication, testing, and modeling of piezoelectric PZT resonator devices will be discussed, and the extension of the predictive models to alternate materials systems and submicron geometries for GHz applications will be outlined.

This work is supported in part by DARPA

[1]D.L. DeVoe, Sensors and Actuators A 88, 263-272 (2001)

[2]A. Ballato, "Micro-electro-acoustic Devices for Wireless Communication," IEEE Sarnoff Symposium on Advances in Wired and Wireless Communications (March 1999)

5:00pm **MM-ThA10 Micro-Thermal Conductivity Detector for Chemical Sensing**, ***D. Cruz***, UCLA and Sandia National Laboratories, *J.P. Chang*, University of California, Los Angeles, *F. Gelbard, R.P. Manginell, S.K. Showalter, L.J. Sanchez, S.S. Sokolowski, M.G. Blain*, Sandia National Laboratories

Microsensors are essential for detecting biological and chemical warfare agents in state-of-the art micro chemical analytical systems. We have designed and fabricated a micro thermal conductivity detector to analyze the effluent from a gas chromatography column (GC). The TCD can be integrated with a micro-GC column to form a complete "lab-on-a-chip" separation-detection scheme. The TCD consists of a two-flow cell Wheatstone bridge circuit where the resistor elements are suspended by a thin SiN_x membrane in pyramidal and trapezoidal shaped flow cells. A four-flow cell detector can also be constructed for doubling of sensitivity. Rapid computational prototyping by simulating the heat transfer in the TCD with a Boundary Element Method enables a cost-effective way of optimizing the TCD geometries yielding the greatest sensitivity. Two flow patterns, six operating temperatures, five heater sizes, and five channel widths were theoretically investigated, and the optimal geometry along with eight additional promising geometries was fabricated. The change in heat flow versus the change in gas thermal conductivity (dQ/dk) of He was first determined to verify the simulation results. Nitrogen and a carbon-fluoro-carbon were added as effluents to the He gas stream. The voltage response in the Wheatstone bridge changed by approximately 40% and 70% respectively. A four-cell detector was used, where He was flowed at 5 sccm through 2 reference resistors and a mixture of the carrier gas (He) and effluent was flowed through the other two resistors. The measured voltages yielded heat flux values that consistent with the theoretical values. In addition; results verified that convection became a dominant effect over conduction when the carrier gas was flowed at a rate greater than 10 sccm.

[1]Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under contract DE-AC04-94AL85000.

Applied Surface Science
Room: C-106 - Session AS+MM+BI-FrM

BioMEMS and Medical Devices
Moderator: K. Healy, University of California, Berkeley

8:20am **AS+MM+BI-FrM1 Characterization of Implant Surfaces**, ***M. Grunze***, University of Heidelberg, Germany **INVITED**

In this talk I will describe my personal recollection of the development of polymer coating (Polyzene FÂ®) for cardiovascular stents from concept to market. The idea was to develop a "stealth" surface coating for metallic stents which reduces inflammation, thrombosis and restenosis of the blood vessels. My talk discusses the design strategies of the polymer, development of the coating process and the necessary Surface Science characterization, protein, cell and bacteria adhesion experiments, the technical certification process, in vivo experiments in animal models, and the problems and successes in starting a new company to market the product. At this time the story is open-ended, since the results of ongoing long term clinical studies were not available at the time this abstract was written.

9:00am **AS+MM+BI-FrM3 Probing the Orientation of Surface-Immobilized IgG by ToF-SIMS**, ***H. Wang***, *D.G. Castner, B.D. Ratner, S. Jiang*, University of Washington

The orientation of a surface-immobilized IgG is crucial for its ability to detect antigen in biosensors. To probe the orientation of a surface-immobilized IgG, two factors are important. One is a powerful surface analysis technique while the other is a well-controlled surface for specific protein orientation. Static time-of-flight secondary ion mass spectrometry (ToF-SIMS) is well suited for this purpose since the sampling depth of ToF-SIMS (1-1.5 nm) is less than the typical dimension of most proteins (4-10 nm). At the same time, IgG orientation can be controlled by appropriately adjusting microenvironments (e.g., surface charges and solution properties). In this work, we apply ToF-SIMS combined with principle components analysis (PCA) to study the orientation of anti-hCG (human chorionic gonadotropin) on two controlled surfaces using its Fab and Fc fragments as references. The controlled surfaces are achieved using self-assembled monolayers (SAMs) with different terminal groups. Results show that the combined ToF-SIMS and PCA technique is able to probe the difference in orientations for ani-hCG adsorbed on different surfaces. In addition, ToF-SIMS results are compared with those from the protein structure. Consistency of these results indicates the reliability of this method.

9:20am **AS+MM+BI-FrM4 TOF-SIMS Analysis to Monitor Coating Processes in Organic and Biological Surfaces**, ***R. Chatterjee***, *B. Lakshmi, M.J. Pellerite*, 3M

Time of Flight Secondary Ion Mass Spectrometry (TOF-SIMS) has proved to be very useful in molecular surface characterization of organic coatings, polymeric systems and biological surfaces. This paper will focus on the application of TOF-SIMS in identifying reaction processes involved in formation of bio-reactive surfaces and organic coatings. In SIMS, absolute quantitative analysis becomes difficult because the ion yield is highly dependent on the morphology and the physical and chemical nature of the surface. Different examples will be used to illustrate how with the use of suitable control experiments, relative quantitative analysis can provide direction in the development of surface modification and surface coating processes. Relative quantitation of TOF-SIMS data was applied to monitor the reaction of aminoacids to different bioreactive surfaces. TOF-SIMS was used to identify presence of different proteins in a multistep sandwich assay. In thin organic coatings, the degree of cure of the silane end group was correlated to the coating durability. Relative quantitation was applied to determine the degree of cure, specify process conditions needed for suitable curing, identify a suitable catalyst to reduce curing times and determine whether lack of cure is the cause of failure. The rate of cure of mono-, bis- and trifunctional silanes, and their effect on the coating durability was investigated.

9:40am **AS+MM+BI-FrM5 Characterization of Protein Interactions with MEMS Devices under Non-Static Conditions**, ***K. Lenghaus***, *J. Dale, D. Henry, J. Hickman,* Clemson University, *J. Jenkins, S. Sundaram*, CFD Research Corporation

The emerging field of micro electromechanical systems (MEMS), when directed to biological applications (environmental monitoring, biosensors etc.), requires an understanding of protein/surface interactions under conditions of flow at low concentrations. Previous protein studies have focussed on adsorption under static conditions and at high concentrations, which can not necessarily be extrapolated to those conditions found in Bio-MEMS under non-static or flow conditions. In an analogous system, the adsorption of proteins to surfaces in in vivo biological systems differs from other adsorption phenomena in that its consequences can be aggressively non-linear, with a biological system's response to minute deviations and changes greatly out of proportion to the magnitude of the change. Thus a relatively small fraction of aggressive sites can induce a response quite out of proportion to their numbers. To study both phenomena we have developed assays to allow enzymes to be quantified at ng/mL levels, and combined with a syringe pump we have created a simple, yet sensitive and robust test bed for protein adsorption under flow conditions. Using this approach, a PEEK capillary was found to have a small number of highly aggressive sites for protein adsorption, corresponding to 5% total surface coverage. These would serve as nucleation sites for further interactions in MEMS devices, and be difficult to detect by other methods. It was further shown that the adsorbed enzymes were in an active state, and this was used to confirm that the rate of desorption from the surface was of the order of 10-4.s-1, corresponding well with values derived from fitting the adsorption isotherm to a computational fluid dynamics model. Thus, studying enzyme adsorption can be used to give several useful insights into the adsorption/desorption behaviour of surfaces at low bulk concentrations of protein as well as generate insights for an in vivo system's protein nucleation behaviour.

10:00am **AS+MM+BI-FrM6 Selective Thermal Patterning of Self-Assembled DNA Monolayers on MEMS-based Microheater Devices**, ***T.H. Huang***, National Institute of Standards and Technology, *N. Ku*, Montgomery Blair High School, *R.E. Cavicchi, M.J. Tarlov*, National Institute of Standards and Technology

We report the selective patterning of self-assembled thiolated DNA probes on gold-coated microheater devices using temperature. The goal of our investigation is to utilize the rapid heating and cooling capabilities of MEMS-based microheaters to prepare biosensing surfaces and to monitor reactions such as DNA hybridization, melting and polymerase chain reaction (PCR). In this study, the self-assembly of thiolated-DNA probes on gold microheater array (four element array) is used as the model system. Modified DNA probes (5' end with disulfide and 3' end with fluorescein) are selectively immobilized onto the gold surface in several steps. First, a passivating layer consists of 1-mercapto-6-hexanol (MCH) is self-assembled onto the gold microheaters. The temperature for one the four heaters is elevated to ca. 200 ^{o}C to drive off the MCH. Then the thiolated DNA probes are deposited onto the freshly exposed bare gold surface. Using this method, one can use temperature to selectively deposit different DNA probes on specific heaters. The presence of the DNA probes on the surface is detected using fluorescence microscopy. In order to use the DNA-microheater surface to monitor DNA melting reactions or PCR (which require cycling to high temperatures), it is important for the probe to be thermally stable at the operating temperatures (i.e. 85 ^{o}C). We will also present results on the thermal stability of thiolated DNA monolayers on gold.

10:20am **AS+MM+BI-FrM7 Soft and Fuzzy Polymer Coatings for Microfabricated Neural Prosthetic Devices**, ***D.C. Martin***, The University of Michigan, *X. Cui*, Unilever, *R. Kim, J. Yang, Y. Xiao*, The University of Michigan **INVITED**

Neural prosthetic devices facilitate the functional stimulation of and recording from the peripheral and central nervous systems. It is important that these implantable devices function in vivo for long periods of time. Bioactive and electrically conductive materials are deposited on the surfaces of neural microelectrode arrays through various means to build a stable interface for better biocompatibility and signal transduction. To mediate the mechanical property differences between the brain tissue and silicon device, integrate the device within tissue and minimize the host reaction, bioactive coatings were developed that can be applied over the whole surface of the silicon micro-devices. One approach that has been developed is electrospinning of protein polymers to form a porous film composed of electrospun nano-scale protein fibers with cell-binding sites exposed. Another ongoing approach has been to coat the device with bioactive hydrogel materials which change volume according to their environment, and therefore integrate the device in the tissue with minimal insertion damage. To stabilize the connection between neurons and the electrode sites and facilitate the signal transduction from electrically conductive metal electrode to the ionically conductive tissue, conductive polymers together with bioactive molecules were co-deposited on the electrode site areas by electrochemical deposition. The coatings presented a fuzzy and conductive surface which lowered the impedance of the electrode by 1 to 2 orders of magnitude. The bioactive molecules with cell binding ability in the deposited films on the electrode sites were shown to be able to anchor neurons in both in vitro and in vivo experiments.

11:00am **AS+MM+BI-FrM9 Voltage-Dependent Assembly of the Polysaccharide Chitosan onto an Electrode Surface**, *L.-Q. Wu, A.P. Gadre, H. Yi, M.J. Kastantin, G.W. Rubloff, W.E. Bentley, G.F. Payne,* ***R. Ghodssi***, University of Maryland

We examined the assembly of a basic polysaccharide - chitosan - from solution onto electrode surfaces as a result of voltage bias on the electrode. Chitosan is positively charged and water-soluble under mildly acidic conditions, and is uncharged and insoluble under basic conditions. We observed that chitosan is deposited from acidic solution onto the surface of a negative electrode and that the thickness of the deposited layer is dependent upon the deposition time, the applied voltage, and the chitosan concentration. No deposition occurs on the positive or neutral electrode. Once deposited and neutralized, the chitosan layer can be retained on the electrode surface without the need for an applied voltage. Infrared (FTIR) and electrospray mass spectrometry (ES-MS) confirmed that the deposited material was chitosan. The voltage-controlled deposition of chitosan provides a means for anchoring biopolymer material in specific locations in bioMEMS environments, such as encapsulated microfluidic devices fabricated in our laboratory using MEMS-based polymeric materials (EPON SU-8, Polypyrrole and Polydimethylsiloxane). Furthermore, chitosan's amine functionality should enable standard coupling chemistries to be exploited to anchor additional biomolecules (e.g. DNA and proteins) to the surface of bioMEMS devices.

11:20am **AS+MM+BI-FrM10 Alternative Approaches to Microfluidic Systems Design, Construction and Operation**, ***D.J. Beebe***, University of Wisconsin, Madison **INVITED**

Many approaches to the construction of microfluidic systems have appeared in the last few years including glass and silicon etching and bonding, laser machining, micromolding and others. Here we present an alternative approach to the design, construction and operation of microfluidic systems that we call Âµfluidic tectonics (ÂµFT) that compares to injection molding in cost, but allows for a wide variety of functionality. ÂµFluidic Tectonics utilizes liquid phase photopolymerization, responsive materials and in situ fabrication to achieve elegant yet functional designs. Ultra rapid microchannel fabrication (2 minutes) is demonstrated using off the shelf components (glass microscope slides, polycarbonate top, simple UV lamps and transparency masks). The process eliminates the need for traditional bonding to achieve a closed channel and no master is required (as in elastomeric micromolding). The same basic process has been used to create filtering, flow control, readout (chemical and biological) and mixing components. Thus, the construction platform leads to highly integrated systems by using a single fabrication process and class of materials (photopolymerizable polymers). Closed loop feedback control is demonstrated without the use of electronics. A single structure created in situ from responsive materials performs the sensing and actuation functions. The responsive component senses the local chemical environment and undergoes a volume change in response to changes in the local environment. The volume change is coupled to a valve that regulates the compensating stream providing closed loop regulation. The design flexibility ÂµFT combined with the ease of fabrication and low cost (similar to injection molding) enhances the microfluidic toolbox and broadens the base of potential designers and users by simplifying the construction process and reducing the infrastructure needed to create and use microfluidic systems.

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