Processing at the Nanoscale/NANO 6
Room 302 - Session NS+NANO6+MM-TuM

Nanomechanics
Moderator: W.N. Unertl, University of Maine

8:20am **NS+NANO6+MM-TuM1 Nanomechanical Properties of Molecular Organic Thin Films***, J. Caro,* Institut de Ciencia de Materials de Barcelona (CSIC), Spain*; P. Gorostiza, F. Sanz,* Universitat de Barcelona, Spain*; **J. Fraxedas**,* Institut de Ciencia de Materials de Barcelona (CSIC), Spain

Using Atomic Force Microscopy we have studied the nanomechanical response to nanoindentations of surfaces of highly-oriented molecular organic (MO) thin films (thickness < 1000 nm). Fundamental parameters as the Young' s modulus E, unknown for most MO materials, can be estimated from the elastic deformation using Hertzian mechanics. In the case of the quasi-one-dimensional MO conductor tetrathiafulvalene tetracyanoquinodimethane (TTF-TCNQ) we obtain E ~ 22 GPa, in excellent agreement with previous reported values obtained on single crystals using neutron scattering (E ~ 20 GPa).@footnote 1@ Above ~ 200 nN the surface deforms plastically as evidenced by discrete discontinuities in the indentation curves (~ 1 nm) associated to molecular layers being expelled by the penetrating tip. The estimated critical shear stress @tau@ is ~ 2 GPa. Nanoindentation permits the determination of nanomechanical parameters of MO metastable polymorphs. This is illustrated with the MO radical p-nitrophenyl nitronyl nitroxide (p-NPNN). The @alpha@-phase of p-NPNN, stabilized as thin film,@footnote 2@ exhibits values of E and @tau@ two times smaller than the corresponding values of the thermodynamically most stable @beta@-phase. Measurements were performed with the same tip under the same experimental conditions, thus eliminating the uncertainty associated to the cantilever constant and tip radius. @FootnoteText@@footnote 1@J. P. Pouget et al. Phys. Rev. B 19 (1979) 1792. @footnote 2@J. Fraxedas et al. Europhys. Lett. 48 (1999) 461.

8:40am **NS+NANO6+MM-TuM2 Quantitative Imaging of Dynamic Mechanical Properties by Hybrid Nanoindentation***, **S.A.S. Asif**,* University of Florida*; K.J. Wahl, R.J. Colton,* Naval Research Laboratory

In this paper, we present a novel quantitative stiffness imaging technique and demonstrate its use to directly map the mechanical properties of materials with nm-scale lateral resolution. This is a powerful new approach that can eliminate tedious point-by-point analyses of indentation arrays to obtain quantitative mechanical properties of surfaces. For the experiments, we use a 'hybrid' nanoindenter, coupling depth-sensing nanoindentation with AFM scanning capabilities. AC force modulation electronics have been added, enhancing instrument sensitivity and enabling measurements of time dependent materials properties (e.g. loss modulus and damping coefficient) not readily obtained with DC techniques. Tip-sample interaction stiffness images are acquired by superimposing a small AC force (10's of nN) onto the DC imaging force (1-2 µN), and recording the AC displacement amplitude and phase as the surface is scanned. Combining a dynamic model of the indenter (having known mass, damping coefficient, spring stiffness, resonance frequency and modulation frequency) with the AC response of the tip-surface interaction allows evaluation of complex stiffness maps. We will demonstrate the use of this approach to obtain quantitative loss and storage stiffness images for elastic and viscoelastic surfaces, as well as discuss a method to directly determine loss and storage moduli from the images.

9:00am **NS+NANO6+MM-TuM3 Force-Modulated Nanoindentation of Fluorinated Polymer Thin Films Grown by PECVD***, S.A.S. Asif,* University of Florida*; E.J. Winder, K.K. Gleason,* Massachusetts Institute of Technology*; **K.J. Wahl**,* Naval Research Laboratory

Thin polymer films have been of considerable interest recently in applications for electronics packaging, solid lubrication, MEMS devices, antifouling and adhesives. However, evaluating the mechanical properties of polymer thin films is difficult due to the low elastic moduli and viscoelastic behavior typically observed with polymers. In this paper, we present an approach for measuring the mechanical and dissipative properties of thin, compliant polymer films using AC force-modulated nanoindentation.@footnote 1@ The dynamic response of the indenter is monitored during tip-sample approach, enabling sensitive detection of the surface. Adhesive interactions, contact stiffness and damping are monitored during force-displacement measurements, and hardness and modulus evaluated. In this study, we apply the above approach to investigate the correlation between polymer thin film deposition conditions and the resulting mechanical properties. The thin polymer films were deposited on Si wafers using pulsed plasma-enhanced chemical vapor deposition (PECVD). Two different source gases were used, HFPO (hexafluoropropylene oxide) and HFC-134 (1,1,2,2, tetrafluoroethane); growth conditions were varied by altering the plasma duty cycle during deposition (plasma on-time/plasma off-time). Film thickness was measured by ellipsometry and profilometry, and chemistry examined by XPS and FTIR. Film thickness varied between 100 and 400 nm. Hardness of the films varied between 0.04 to 0.2 GPa, and complex modulus between 2 and 20 GPa, with considerable damping losses observed. Comparisons between the film deposition conditions and resulting chemistry and mechanical properties will be presented and discussed. @FootnoteText@ @footnote 1@ S.A.S. Asif, K.J. Wahl, and R.J. Colton, Rev. Sci. Instrum. 70 (1999) 2408.

9:20am **NS+NANO6+MM-TuM4 Dynamic Contacts to Adhesive Viscoelastic Materials***, **M. Giri**, W.N. Unertl,* University of Maine

Dynamic mechanical contacts with nanometer to micrometer dimensions are important in scanned probe microscopy, ultra-low load indentation, microelectromechanical systems, compact discs, etc. These contacts are poorly understood if they involve adhesive viscoelastic materials such as polymers. We have studied contacts to styrene-butadiene latex films with Tg in the range 253-301 K. Contact times were in the range 0.01-1000 s and loads were up to 1 mN. Nanoindentation was used, rather than scanned force microscopy, because of its well-defined geometry and capability to control the applied load while simultaneously measuring the displacement. Diamond probes with Berkovich and spherical end shapes were used. Load vs. displacement data showed substantial adhesion hysteresis between the loading and unloading portions. The hysteresis is at least partially due to creep as indicated by the continued increase in penetration after the start of unloading. Works of adhesion were estimated by extrapolating the measured pull-off forces to long times as suggested by Johnson.@footnote 1@ Theoretical models that include adhesion but neglect long-range creep effects could not fit the data over an entire loading-unloading cycle. Creep tests were carried out under constant load. The model of Hui, Baney, and Kramer (HBK),@footnote 2@ which predicts the response of an adhesive viscoelastic contact under increasing load, was used to extract a Mode I stress intensity functional. When this functional is normalized by the indentation strain rate, it has a simple universal time-dependence. This result supports the suggestion of HBK that the stress intensity functional may be a simpler alternative to surface energy for characterization of adhesion of viscoelastic materials. @FootnoteText@ @footnote 1@K.L. Johnson in Microstructure and Tribology of Polymers,Eds. V.V. Tsukruk and K.J. Wahl (ACS Books, 2000). @footnote 2@C.Y. Hui, J.M. Baney, E.J. Kramer, Langmuir 14 (1998) 6570.

9:40am **NS+NANO6+MM-TuM5 Precision Nanoscale Machining with STM-QCM***, **J. Krim**, B. Borovsky,* North Carolina State University

We have constructed an apparatus which allows us to investigate the nanoscale machining of metal surfaces resulting from the contact of a sharp tip with a high speed vibrating surface (maximum speeds over 1 m/s).@footnote 1@ The tip (tungsten or platinum alloy) is that of a Scanning Tunneling Microscope (STM), and the surface is that of a metal film deposited onto a Quartz Crystal Microbalance (QCM). The STM-QCM combination enables machining-and-imaging experiments in which the topography of the substrate is compared before, during, and after tip-surface rubbing contact at well-defined locations. The rubbing contact is either direct tip-surface contact or tunneling contact through an oxide layer. While the STM tip alone is able to machine softer materials (such as copper), the high speed vibrations of the QCM greatly enhance machining of more durable materials and oxide films. Specially prepared surfaces permit the creation of sharper, more detailed structures with 10 to 100 nm dimensions, as is demonstrated using copper and silver surfaces exposed to oxygen gas. Our talk focuses on the robustness of resulting structures compared to the ease with which they were machined. Research supported by the NSF and the AFOSR. @FootnoteText@ @footnote 1@ B. Borovsky, B. Mason, and J. Krim, submitted to J. Appl. Phys.

10:00am **NS+NANO6+MM-TuM6 Size-Dependent Mechanical Properties of MoO@sub 3@ Nanoplates***, **J. Wang**, K.C. Rose, J.W. Hutchinson, C.M. Lieber,* Harvard University

The mechanical properties of materials on the nanometer scale are of great interest both for furthering our fundamental understanding as well as for use in a wide range of micro- and nano-mechanical systems. Previous experimental studies have focused on one-dimensional systems, including carbide nanorods and carbon nanotubes. For example, atomic force microscopy (AFM) has been used to show that silicon carbide nanorods have similar Young's moduli to defect free macroscopic crystals and that carbon nanotubes are much stiffer than carbon whiskers and fibers. Here, we used AFM to determine the bending stiffness of individual, structurally-isolated molybdenum oxide (MoO@sub 3@) nanocrystal nanoplates (5-16 nm thick). These nanoplates were pinned to molybdenum disulfide (MoS@sub 2@) surfaces on one side and were suspended freely over MoS@sub 2@ steps on the other side. Bending forces were measured versus displacement on the unpinned side of these MoO@sub 3@ nanoplates. Finite element analysis revealed that the effective Young's moduli of these MoO@sub 3@ nanocrystals are significantly smaller than that of bulk MoO@sub 3@ single crystals and that the moduli decrease with decreasing nanocrystal thickness. This novel behavior was further substantiated in subsequent experiments where it was shown that MoO@sub 3@ nanocrystals (1.4 - 5 nm thick) had enormous flexibility when slid over multilayer MoS@sub 2@ steps. These results have important implications for the sliding of nanoscale structures on rough surfaces and even for the fabrication and manipulation of smaller mechanical systems evolving in nanotechnology.

10:20am **NS+NANO6+MM-TuM7 High Frequency Nanomechanical Systems***, **D.W. Carr,*** Lucent*; L. Sekaric, A. Olkhovets, S. Evoy, J.M. Parpia, H.G. Craighead,* Cornell University **INVITED**

Nanofabricated mechanical systems are highly useful tools for research in physics, optics, and dynamics. We have developed fabrication processes that allow us to make suspended nanostructures in silicon and silicon nitride. We can actuate motion in these structures using electrostatic forces, and this motion is detected optically using interferometric effects. This measurement technique is sensitive to sub-nanometer motion. We have measured doubly-clamped silicon beams with fundamental resonant frequencies as high as 380 MHz. Such structures are being considered for use as chemical and biological sensors, force gauges and frequency filters. One of the obstacles for practical applications are intrinsic losses which lower the mechanical quality factor (Q-factor) of these devices. We see a strong dependence in the Q-factor on the width of these beams. As the width decreases below 100 nm, the Q factor drops sharply, indicating that the dominant energy loss mechanisms are surface related. We are also focusing on surface treatment and the effects of device geometry on dissipation. We have conducted a study of the effects of amorphous metal layers that are used in driving and detection schemes for NEMS and found that the metal layers have a detrimental impact on the devices' mechanical quality factor. We are also studying the effects of various levels of doping in single-crystal silicon on dissipation and driving schemes, a study significant for industrial use in integration with electronic devices. We have also studied the effect of parametric amplification in very small torsional resonators. An applied bias voltage effectively changes the spring constant of the system. Oscillating this bias at a specific frequency results in an amplification of the resonant motion. Swept-frequency measurements show interesting properties of the resonant spectrum, and these results agree well with the theory. Such systems may have interesting application in resonant sensors and surface probes.

11:00am **NS+NANO6+MM-TuM9 Quantum Well Micromechanical Photon Detectors***, **P.G. Datskos,** S. Rajic, L.R. Senesac,* Oak Ridge National Laboratory*; I. Datskou,* Environmental Engineering Group, Inc.

We have developed a method of fabricating quantum well microstructure arrays for a variety of sensing applications. Microstructures with quantum wells allow real-time manipulation of energy states using external stress. For example this can result in an effective and rapid change in electron energy levels in photon detection devices. Such changes make possible tuning the levels to respond to desired wavelengths. We applied such GaAs/GaAlAs micromechanical quantum well arrays to detection of photons and especially uncooled infrared detection. We will present and discuss our results.

11:20am **NS+NANO6+MM-TuM10 Nanomechanical Systems***, **M.L. Roukes**[1],* California Institute of Technology **INVITED**

Microelectronics technology is now pushing deep into the submicron regime, yet, for the most part, work on micromachines still remains back at the few micron scale, or larger. The time is ripe to embark upon a concerted exploration of mechanical systems at the nanoscale. In this talk will highlight the promise and intrigue of this domain. Nanoelectromechanical systems, or NEMS, are MEMS scaled to submicron dimensions. In this size regime, it is possible to attain extremely high fundamental frequencies while simultaneously preserving very high mechanical responsivity (small force constants). This powerful combination of attributes translates directly into high force sensitivity, operability at ultralow power, and the ability to induce usable nonlinearity with very modest control forces. In this overview, I shall provide an introduction to NEMS and will outline several of their exciting initial applications. Our recent efforts at Caltech have culminated in nanomechanical devices with potential for new applications in electronics and metrology. These include development of the first VHF (very high frequency) mechanical resonators;@footnote 1@ the development of mechanical electrometers yielding sensitivity below a single electron charge;@footnote 2@ explorations of thermal transport and energy equilibration in nanoscale devices,@footnote 3@ which have recently culminated in the measurement of the quantum of thermal conductance;@footnote 4@ and development of mechanically-detected magnetic resonance imaging.@footnote 5@ However, a rather stiff entry fee exists at the threshold to this new domain, new engineering is crucial to realizing the full potential of NEMS. Our work also serves to indicate some of the most crucial issues that must be addressed before the full potential of nanomechanical systems can be realized. An important example is that certain mainstays in the methodology of MEMS will, simply, not scale usefully into the regime of NEMS. Most problematic among these issues are the size of the devices compared to their embedding circuitry, their extreme surface-to-volume ratios, and their unconventional "characteristic range of operation". These give rise to some of the principal challenges in developing NEMS. Prominent among these are the need for: ultrasensitive, very high bandwidth displacement transducers; an unprecedented control of surface quality and adsorbates; novel modes of efficient actuation at the nanoscale; and precise, yet robust and reproducible approaches to surface and bulk nanomachining. Ultimately nanomechanical devices will permit access to a regime where mechanics is determined by atomistic properties; where quantum, rather than thermal, fluctuations predominate; where force and displacement detection can meet, or even exceed, the standard quantum limit; and where thermalization involves "granular" heat flow via individual phonons.@footnote 6@ I will conclude by making some projections about this domain that initially seems exotic, but is, in reality, imminent. @FootnoteText@ @footnote 1@ A.N. Cleland and M.L. Roukes, "Fabrication of High Frequency Nanometer Scale Mechanical Resonators from Bulk Si Substrates", Appl. Phys. Lett., 69, 2653 (1996). @footnote 2@ A.N. Cleland and M.L. Roukes, "A Nanometre-Scale Mechanical Electrometer", Nature 392, 160 (1998). @footnote 3@ T.S. Tighe, J.M. Worlock, and M.L. Roukes, "Direct Thermal Conductance Measurements on Suspended Monocrystalline Nanosturctures", Appl. Phys. Lett. 71, 2678 (1997). @footnote 4@ K. Schwab, E.A. Henriksen, J.M. Worlock, and M.L. Roukes, "Measurement of the Quantum of Thermal Conductance", Nature 404, 974 (2000). @footnote 5@ P.C. Hammel, Z. Zhang, G.J. Moore, and M.L. Roukes, "Subsurface Imaging with the Magnetic Resonance Force Microscope", J. Low Temp. Phys. 101, 59 (1995). / P.C. Hammel, Z. Zhang, M.Midzor, M.L. Roukes, P.E. Wigen and J.R. Childress, "The Magnetic Resonance Force Microscope", in "Frontiers in Magnetism of Reduced Dimensional Systems", B.G. Bar'yakhtar et al., eds., (Kluwer Academic, 1998). @footnote 5@ M.L. Roukes, "Yoctocalorimetry: Phonon Counting in Nanostructures", Physica B: Condensed Matter 263-264, 1 (1999).

[1] **Featured Speaker - Science and Technology in the 21st Century**

MEMS
Room 309 - Session MM-WeM
Microfabricated Sensors

Moderator: C. Zorman, Case Western Reserve University

8:20am **MM-WeM1 Microfabricated Platform for Semiconducting Metal Oxide Thin Film Gas Sensors***, **D.J. Frankel,** C. Silvestre, G. Bernhardt, S.C. Moulzolf, N. LeCursi, R.J. Lad,* University of Maine

A sensor platform for chemiresistive and impedance based thin film gas sensors has been developed which can be fabricated using conventional microfabrication techniques. The platform utilizes a highly polished sapphire substrate with platinum electrodes, heater element, and resistance temperature detector (RTD). The use of highly polished and well characterized sapphire substrates allows controlled growth of thin metal oxide sensing films, yielding reproducible and well-defined microstructures. Techniques have been optimized that allow for more than 400 sensing devices to be fabricated on 3" diameter sapphire substrates using liftoff technology. Delamination of metallization on the sensor platform can be problematic, particularly following high temperature annealing. Strong adhesion between the platinum electrodes and sapphire substrate is achieved with a thin Zr adhesion layer. Adhesion is such that parallel gap welding of 4 mil Pt wire can be successfully obtained with bond strengths exceeding 100 grams force. Strong bonding is achieved after fabrication and following extended anneals up to 500C. These anneals are required to stabilize the resistance of the RTD and heater elements. The platform materials exhibit stable operation after accelerated temperature cycling between room temperature and the typical sensor operation temperature of 200-400C. We have also used microfabrication techniques to fabricate sensor platforms with a variety of electrode configurations, including under and on top of the metal oxide sensing film, that explore the effect of sensor resistance measurement configuration on sensor operation while keeping substrate effects constant.

8:40am **MM-WeM2 The Use of Micromachined Arrays to Develop Processing/Performance Databases for Metal/Oxide Sensing Materials***, **J.E. Tiffany**, R.E. Cavicchi, S. Semancik,* National Institute of Standards and Technology

We describe the efficient study of multiple metal/oxide microsamples on micromachined platforms called microhotplate arrays. These platforms include addressable temperature control of 36 individual elements which is employed in fabricating and evaluating varied sensing films being examined for solid state conductometric gas microsensors. Each 100 micron array element consists of a suspended structure with a buried heater and surface electrodes. We present results of screening experiments (metal coverage and type, annealing and sensing temperature, gas type) designed to generate a response database of sensitivity and selectivity. Tin oxide was deposited on all array elements via a Ni seeded, self-lithographic MOCVD process. Low coverage (25-100 Å) catalytic metal s (Ni, Pd, Pt, Cu, Ag, Co, Rh, Ir, Ru) were then deposited on select elements using masked evaporation or sputtering. We describe the response of these array elements to a wide variety of gases (2-butanone, acetone, toluene, benzene, methanol, ethanol, hydrogen, and carbon monoxide). Response data was collected for bare and catalyst modified sensors. The bare tin oxide films showed a normally distributed (10%) conductance response when exposed to the test gases at fixed temperature, demonstrating the statistical stability of the screening approach. Relative sensitivities for the different metal catalysts are reported as a function of sensing temperature for each test gas. We observed, for example, that the addition of Ni catalyst decreased hydrogen response, whereas 2-butanone response was increased. Benzene response was also observed to cross over from negative to positive at a specific temperature due to competing surface reactions both with and without Ni catalyst. Such cases of increased sensitivity, selectivity and crossover response can be extracted from the materials screening response data and be used in customizing microsensors for specific tasks.

9:00am **MM-WeM3 Chemical Detection Based on Adsorption-Induced and Photo-Induced Stresses in MEMS Devices***, P.G. Datskos, S. Rajic, L.R. Senesac,* Oak Ridge National Laboratory*; **I. Datskou,*** Environmental Engineering Group, Inc.*; M.S. Sepaniak, C.A. Tipple, B.C. Fagan,* University of Tennessee

Recently there has been an increasing demand to perform real-time in-situ chemical detection of hazardous materials, contraband chemicals, and explosive chemicals. Currently, real-time chemical detection requires rather large analytical instrumentation that are expensive and complicated to use. The advent of inexpensive mass produced MEMS (micro-electro-mechanical systems) devices opened-up new possibilities for chemical detection. For example, microstructures were found to respond to chemical stimuli by undergoing changes in their bending and resonance frequency even when a small number of molecules adsorb on their surface. In our present studies, we extended this concept by studying changes in both the adsorption-induced stress and photo-induced stress as target chemicals adsorb on the surface of microstructures. For example, microstructures that have adsorbed molecules will undergo photo-induced bending that depends on the number of absorbed molecules on the surface. However, microstructures that have undergone photo-induced bending will adsorb molecules on their surfaces in a distinctly different way. Depending on the photon wavelength and microstructure material, the microstructure can be made to bend by expanding or contracting the irradiated surface. This is important in cases where the photo-induced stresses can be used to counter any adsorption-induced stresses and increase the dynamic range. Coating the surface of the microstructure with a different material can provide chemical specificity for the target chemicals. However, by selecting appropriate photon wavelengths we can change the chemical selectivity due to the introduction of new surface states in the MEMS device. We will present and discuss our results on the use of adsorption-induced and photo-induced bending of microstructures for chemical detection.

9:20am **MM-WeM4 Optical Emission Study of a Microfabricated Inductively Coupled Plasma***, **O. Minayeva**, J.A. Hopwood,* Northeastern University

Recently, the fabrication@footnote 1,2@ and characterization@footnote 3,4@ of a micromachined 5-mm inductively coupled plasma (ICP) generator was reported. One of the applications for a microplasma source is the detection of gaseous impurities in air using a micromachined Fabry-Perot interferometer to monitor the optical emissions of the plasma. In this work the complete system that includes a microplasma generator, vacuum chamber, optical path, and lab-scale spectrometer was built and tested on several gas discharges. The goal was to maximize the electronic excitation reaction followed by the light emission from a toxic gas sample (e.g., SO@sub 2@) diluted in air (or argon). It was found that an electron temperature of ~3 eV favors the excitation reaction for SO@sub 2@. The chamber was designed to provide this value of electron temperature over an operating pressure of 0.5-1 torr. Optical paths were incorporated in the chamber in order to collimate the plasma's light emission to within 3-4@super o@ prior to filtering and detection by the interferometer. Multiple optical paths also allow one to determine the spatial structure of the plasma. The optical emission spectra were taken at different points within the micro ICP, and the results on light intensity distribution across the discharge will be presented. @FootnoteText@ @footnote 1@ J. Hopwood, "Monolitic miniaturized inductively coupled plasma source;" U.S. Patent No. 5,942,855 (August 24, 1999). @footnote 2@ Y. Yin, J. Messier, and J. Hopwood, "Miniaturized inductively coupled plasma sources," IEEE Transactions on Plasma Science, 27(5), 1516-1524, (1999). @footnote 3@ J. Hopwood, O. Minayeva, Y. Yin, "Fabrication and characterization of a micromachined 5-mm inductively coupled plasma generator," submitted to J. Vac. Sci. Technol. @footnote 4@ J. Hopwood, "A microfabricated inductively-coupled plasma generator," submitted to J. Microelectromechanical Systems.

9:40am **MM-WeM5 A Micromachined Scanning Fabry-Perot Interferometer***, **F.C. LI,*** Northeastern University, U.S.A*; N.E. McGruer,* Northeastern University*; P.M. Zavracky, K.L. Denis,* Northeastern University, U.S.A

This work describes a novel process to fabricate a micromachined scanning Fabry-Perot interferometer (FPI) employing electrostatic actuators. The Northeastern University MEtal Micromachining (NUMEM) is used to build the electrostatic actuators, which consist of four free standing gold cantilever beams. Two highly reflective mirrors are fabricated separately. @footnote 1@ The final assembly step bonds the upper mirror to the beams and completes the device. The two plane parallel mirrors are initially separated by a gap of approximately 600nm. By applying appropriate control voltages between the beams and electrodes on the substrate, the device can be tuned to wavelengths in the visible spectrum from 450 to 750 nm. Four sense capacitors are placed underneath the upper mirror to detect the spacing between the two mirrors. The spacing information is supplied to a closed-loop control circuit which scans the upper mirror vertically and maintains parallelism. Devices fabricated with aluminum mirrors (reflectivity approximately of 85%) showed resolving powers of 26, 24 and 18.2 at the wavelengths of 525nm, 615nm and 660nm, respectively. Proposed applications of the micromachined FPI include in situ measurements of plasma composition, colorimetric, and chemical analysis. @FootnoteText@ @footnote 1@ P.M. Zavracky, K.L. Denis, H.K. Xie, T. Wester and P. Kelly, "A Micromachined Scanning Fabry-Perot Interferometer", Proceedings of SPIE-The International Society for Optical Engineering, v 3514 p 179-187, Sep 21-22, 1998.

10:00am **MM-WeM6 Passivation of MEMS Structures that are Integrated with Support Electronics*, J.R. Martin,*** Analog Devices Inc. **INVITED**

MEMS devices are susceptible to surface conditions because they are seldom passivated. For example, electrical and optical performances are affected when unpassivated surfaces adsorb or chemically react with ambient gases. Stiction can occur if shock impacts cause these high-energy surfaces to touch. Unfortunately, it is difficult to passivate MEMS wafers due to microstructure flatness requirements, metal temperature limitations and surface charging during low temperature plasma processes. Some SAM coatings are reasonable candidates. However, organics do not normally survive the cerpac process used to package ADXL accelerometers (several furnace passes in air at 430-450C). This presentation will describe a new MEMS passivation process based on a custom synthesized diphenyl siloxane. Organics with the best thermo-oxidative resistance contain phenyl rings so vapor deposited diphenyl siloxane films were evaluated on polysilicon accelerometers. Silicones (molecules with a silicon oxide backbone) were used to transport and bond phenyl rings to the sensor surface. As a result, the native oxide is modified by formation of a low-energy (organic-rich) surface that survives the packaging process. This approach also minimizes contamination concerns because any degradation products are essentially identical to the native oxide that already exists on polysilicon surfaces. A variety of deposition conditions and two types of equipment were evaluated for both electrical and stiction characteristics. Varying the type of diphenyl siloxane caused large differences in anti-stiction performance. Control of the final process is impressive. For example, 100 wafer coating runs have a thickness uniformity of +/- one angstrom. There is no practical way to measure coatings on MEMS surfaces with this level of precision. Therefore, specially prepared monitor wafers are placed in each furnace boat. Early results show that run to run uniformity is also in the +/- one angstrom range.

MEMS
Room Exhibit Hall C & D - Session MM-WeP
Poster Session

MM-WeP1 Characterizing the Thermal Behavior of Thin Films Using Micromachined Cantilevers*, **H.-C. Tsai**, W. Fang,* National Tsing Hua University, Taiwan

The thermal stress is a very important factor of fracture for microstructure. In this paper, we exploit the micromachined cantilever to investigate the thermal behavior of the thin films. The thermal behaviors of thin films were characterized under two thermal loads including the thermal cycle load and the isothermal load. Thus, the variation of the thermal stress of thin film with the thermal loading time is studied. Moreover, the variation of the thermal strain rate of thin film with the film thickness is also discussed. In summary, the strain rate of thin film is proportion to the film thickness after the isothermal load test. On the contrary, the strain rate of thin film is in inverse proportion to the film thickness after the thermal cycle load test. In this study, the silicon dioxide cantilevers were fabricated through the bulk micromachining. The film to be characterized was then deposited on top of the cantilever to form a bi-layer beam. Since the thermal expansion coefficient (CTE) of the film and that of the silicon dioxide are different, the film will subject to stress during the thermal load test. The strain of the deposited film is determined by the deflection of the bi-layer beam. For the isothermal load test, the bilayer beam was heated by a heating stage. As to the thermal cycling load test, the sample was placed into a chamber that can set the variation of the temperature with time. In application, the thermal behavior of the sputtered Al film is studied. The Al film is under compression during heating since its CTE is larger than that of the silicon dioxide. As a result of isothermal load, the total compressive strain of the Al film was increased drastically in the beginning. However, the compressive strain of the Al film was gradually decreased after a certain heating time. It was obtained that the decreasing rate of the strain was proportional to the film thickness. For the thermal cycle load test, the variation of the strain of Al film with the number of thermal cycle was measured. We obtained that the compressive strain of Al film was drastically increased for the first 200 cycles, and then gradually decreased. According to this study, the thermal behaviors of thin films under the static and the dynamic loads are discussed. In addition, the film thickness will be an important factor for the thermal behaviors of thin film.

MM-WeP2 Electrical and Spectroscopic Characterization of Palladium Implanted Elevated Temperature Silicon Carbide Chemical Sensors*, **C.I. Muntele**,* Alabama A&M University*; P. McCarty,* University of Alabama, Huntsville*; I. Muntele, D. Ila,* Alabama A&M University*; J.J. Weimer, M.A. George,* University of Alabama, Huntsville*; D.J. Larkin,* NASA Glenn Research Center*; D.B. Poker, D.K. Hensley,* Oak Ridge National Laboratory

Silicon carbide is a promising material for creating microelectromechanical devices and integrated chemical sensors capable of working at room temperature as well as at high temperatures, and in harsh environments. This team has developed a unique miniaturized SiC chemical sensor that operates from room temperature to above the temperatures (300-500oC) of previously reported semiconductor based chemical sensors. To produce these sensors, we have implanted Pd ions at energies between 100 keV to a few MeV into the Si face of 6H-SiC at both room temperature and at 5000C. The peak concentration of implanted Pd was kept between .01% to 10% of the host. The electrical properties of fabricated sensors were measured at room temperature up to 500oC. We will discuss both the preparation and characterization of these sensors. In order to understand the sensing mechanism of specifically implanted samples, the change in the chemical structure of SiC at the surface and near the implant layers were analyzed using ESCA, micro Ramman, UV absorption spectroscopy and Raman techniques both before and immediately after exposure to hydrogen and Methane. The location of the implanted species was simulated using TRIM code as well as using RBS techniques. We will report the correlation of this simulation to the experimental results obtained from measurements of electrical properties, optical properties and surface analysis Research sponsored by the NASA Grant No. NG3-2302, and partially by the Center for Irradiation of Materials of Alabama A&M University and the Division of Materials Sciences, U.S. Dept. of Energy, under contract DE-AC05-96OR22464 with Lockheed Martin Energy Research Corp.

MM-WeP3 Polymer Based Microsensors Using Piezoresistive Microcantilever Technology*, **T.L. Porter**, M.P. Eastman, D. Pace, M. Bradley,* Northern Arizona University

We have tested a new type of microsensor based on piezoresistive microcantilever technology. In these devices, tiny beads of polymeric or functionalized polymeric material deposited on a substrate are in direct contact with the microcantilevers. Upon exposure to analytes, the polymers may expand or contract, and this volume change is measured directly by the piezoresistive cantilever. The measured response is a simple change in the resistance of the cantilever. There are many advantages of this type of sensor over microsensors based on chemiresistor or vibrating cantilever methods. Many individual sensing units may be incorporated into a "single chip" array using existing semiconductor fabrication techniques. Control and sensing electronics are very simple and inexpensive, making portable sensing arrays practical. There is no need to coat, functionalize, or attach species to the cantilever. Using biologically active layers in place of the polymeric materials, bio-sensor arrays may also be produced. In this paper, the piezoresistive cantilever technology is tested using plymers such as PEVA in the prsence of analytes such as toluene, hexane, water vapor, ethanol and acetone.

MEMS
Room 309 - Session MM-WeA
MEMS Processing

Moderator: W.D. Cowan, Air Force Research Laboratory

2:00pm **MM-WeA1 Surface Micromachining - Process Modeling***, **C.C. Wong**, P. Ho,* Sandia National Laboratories*; R.W. Walker,* Los Alamos National Laboratory*; R.P. Pawlowski,* Sandia National Laboratories

Advances in microsystem technology are allowing increasingly complex micro-structures to be built. The ability to visualize structures during the design phase is becoming correspondingly more important. Surface micromachining involves multiple deposition (CVD) and etching (plasma or wet) steps, and each step can introduce non-idealities to the geometry of the structure. Virtual prototyping can speed the design process and reduce the time lost when flaws are discovered during fabrication. Predicting the true dimensions of the final product requires that the effects of the manufacturing processes be modeled accurately. At Sandia, we are developing detailed "physics-based" models to generate the correct shape of micro-features. A modular approach examines the various processes used in device fabrication, and separates the disparate length scales in the fabrication processes. The initial studies investigate the low pressure CVD of polysilicon from silane, which deposits the structural Si material. First, models of the process reactor, MPSalsa (3D) and OvenD (two coupled 1D models), analyze the reacting flows in the multi-wafer furnace. Using a published silane mechanism, the predicted deposition rates for the standard conditions agree with experiment (within 15%). Results from the reactor-scale models are then used as boundary conditions for feature-scale models of the time-dependent evolution of the polysilicon. Simulations using TopoSim3D reproduce the observed conformal deposition. Wet-etch processes to remove sacrificial oxide layers are also being studied. Preliminary analyses using the 3-D GOMA code give reasonable agreement between experiment and the predicted position of the advancing etch front.

2:20pm **MM-WeA2 Application of Magnetic Neutral Loop Discharge Plasma in Deep Silica Etching***, **W. Chen**,* ULVAC JAPAN, Ltd., Japan*; K. Sugita,* ULVAC JAPAN, Ltd.*; T. Hayashi,* ULVAC JAPAN, Ltd., Japan*; T. Uchida,* ULVAC JAPAN, Ltd.

Generally, plasma density is well known to be concerned with etch rate, and electron temperature is a key parameter for the decomposition of reactive gases which is also relative to the operating pressure. So, margin of plasma production in process can be defined as the highest density, lowest applicable electron temperature and pressure, which indicate the variability of gas chemistry for processes. Process pressure is an especially important parameter for the Micro-Electro-Mechanical-Systems (MEMS). Metal mask and/or doped glass are usually used. These metal masks, such as Cr, Ni and WSi, and doped materials do not reactive to the dominant reactive species of CF@sub x@, which are consumed by physical sputtering mainly. Certainly, the sputtered clusters are easily re-deposited to sample substrate by collision of the sputtered metal cluster with neutral gases in high-pressure process, which may result in a rough surface and large taper angle. Magnetic neutral loop discharge (NLD) plasma@Footnote 1-3@ is a wide marginal one with a high density (>10@sup 11@ cm@sup -3@) and low electron temperature of about 2.5eV in a very low pressure of about 0.2Pa. Using NLD system, vertical trench structures for optical wave-guide were successfully fabricated on fused quartz glass and silica film with very smooth surface in the depth of 6-30mm. Meanwhile, the etch rate were kept greater than 500nm/min with good uniformity (deviation of @sigma@

2:40pm **MM-WeA3 Application of Deep Silicon Etching and Wafer Bonding in the MicroManufacturing of Turbochargers and Micro Gas Turbine Engines***, **A.A. Ayon**, J. Protz, R. Khanna, X. Zhang, A. Epstein,* Massachusetts Institute of Technology **INVITED**

This paper describes the first successful micromanufacturing of MEMS turbochargers and micro gas turbine engines (MGTE), complete with an integrated compressor, turbine, and combustor. The realization of both devices involves the deep etching and fusion bonding of six single-crystal silicon wafers. The deep etching steps define turbomachinery and gas bearings, associated with the rotor, as well as fluidic interconnects and instrumentation access ports. A turbocharger includes a freely rotating rotor comprised of a turbine and a compressor mounted on the same shaft. It increases the power output of the engine to which it is attached by effectively acting as a pump to force more fuel into the engine. With this scheme, the turbine extracts power from the hot exhaust gas stream to drive the compressor that, in turn, raises the fluid density, and, hence, the mass flow rate to the engine. Turbochargers have applications to conventional and rocket engines, fuel cells, and microfluidic systems. A MGTE integrates a combustor with the turbocharger, making the device a complete, self-powered engine, for propulsion and electrical power generation applications. For the fabrication of the MGTE, the turbocharger geometry was modified to include a cooling jacket that linked the compressor and turbine and that also surrounded a combustion chamber. This introduced additional challenges for the microfabrication of three of the six required wafers, due to the extensive removal of the underlying silicon substrate and the concomitant fragility of the wafers involved. Fully operational, the demonstration MGTE is expected to have a rotor spinning at the rate of 1.2 million rpm, burn 16 g/hour of H2 fuel and produce 11 g of thrust. The present work is applicable to projects with intricate geometries requiring stacks of bonded wafers. We describe and discuss the etching and bonding challenges, as well as observations and results obtained in the microfabrication of these heat engines.

3:20pm **MM-WeA5 MEMS Fabrication Technology Applied to Large Area X-ray Image-sensor Arrays***, **J.H. Daniel**, B. Krusor, R. Apte, R.A. Street,* Xerox Palo Alto Research Center*; A. Goredema, P. Kazmaier,* Xerox Research Center Canada

Micromachining has potential applications for large area image sensors and displays, but conventional MEMS technology, based on crystalline silicon wafers cannot be used. Instead, large area devices use deposited films on glass substrates. This presents many challenges for MEMS, both as regards materials for micro-machined structures and the integration with large area electronic devices. We are exploring the novel thick photoresist SU-8, as well as plating techniques for the fabrication of large area MEMS. As an example of its application, we have applied this MEMS technology to improve the performance of an amorphous silicon based image sensor array. SU-8 is explored as the structural material for the X-ray conversion screen and as a thick interlayer dielectric for the thin film readout electronics of the imager. Medical X-ray imagers have a thick (200-500 micron) layer of phosphor, which converts the X-rays into visible light, placed directly on top of the photodiodes. Spatial resolution is limited because of light scattering in the phosphor. In order to obtain the full resolution of the pixel array the phosphor layer needs to be micro-patterned into cells which collimate the generated light. This cell structure was patterned with a 300-400 micron thick layer of SU-8. The SU-8 cell walls need to be made reflective in order to prevent light from scattering into a neighboring cell which is achieved by sputtering a thin metal layer. Subsequently the cells are filled with a phosphor. A second application is the use of SU-8 as a thick interlayer dielectric to reduce noise due to capacitive coupling in the thin film electronic circuit of the imager. Nickel electroplating is used to metallize the deep contact vias. The compatibility of SU-8 with thin film deposition methods, such as amorphous silicon PECVD, will be discussed. Processing challenges which are particularly important for large area fabrication, will be addressed.

3:40pm **MM-WeA6 Switching of Interfacial Energies in Polymeric Coatings***, **B.C. Bunker**, J.G. Kushmerick, W.L. Smith, M.S. Kent,* Sandia National Laboratories*; G.P. Lopez,* University of New Mexico*; X.-Y. Zhu,* University of Minnesota*; D.L. Huber, T.D. Dunbar,* Sandia National Laboratories

Polymeric coatings are under investigation for controlled switching of interfacial energies in microanalytical systems. Switching of water contact angles using films of poly n-isopropylacrylamide (PNIPAM) is of interest for driving liquids in microchannels, while switching of polymer configurations within polyethylene oxide (PEO) films could control properties such as protein adsorption. Films of PNIPAM and PEO have been tethered to gold and silicon substrates. Thermal and electrical stimuli have then been applied to the films to try to induce inverse temperature transitions. Film behavior has been monitored using a combination of contact angle measurements and force-distance profiles obtained using an interfacial force microscope. Results show that below the phase transition, PEO films are hydrated, and are attractive to scanning probe tips. Above the transition, the water is removed and the attractive potential drops by an order of magnitude. Moving above and below the transition temperature in PNIPAM films can induce changes in the water contact angle of from 10° up to 60° depending on how the polymer is tethered to the surface. The number of switching cycles is also dependent on the nature of the polymer-substrate interface. Limited switching is sometimes associated with decomposition or desorption of the active polymer. Such decomposition is illustrated for the specific example of a short-chain PEO film (EG3) attached to gold via a thiol coupling agent.

4:00pm **MM-WeA7 A Novel Anti-Stiction Method Using the Harmonic Excitation on the Microstructure***, **W.P. Lai**, W. Fang,* National Tsing Hua University, Taiwan

The sticking problem due to the reaction mechanism between rinse liquid and microstructures becomes a serious issue in micromachining fabrication processes. A novel anti-stiction method using the harmonic excitation on the microstructure is presented in this research. The proposed method had been studied through the analytical and experimental approaches. Consequently, the yield of the micromachining processes can be significantly improved by this technique. We exploit a simplified model consisting of a single degree of freedom mass-spring-damper system to simulate the drying process of the microstructure. In this model, the equivalent spring effect mainly comes from the Laplace pressure@footnote 1@ of the liquid film and the equivalent damping effect @footnote 2@ is due to the squeeze@footnote 3@ of the liquid film. Based on the analysis, the dynamic response of the microstructure including the resonant frequency and the damping characteristic of the drying system were predicted. Analysis results displayed that the system is initially underdamped, then is critically damped, and finally is overdamped when the drying time increased. Hence the cantilever beam could be separated with the liquid film by the harmonic excitation at the underdamped condition. In application of the proposed anti-stiction technique, we fabricated silicon oxide cantilevers on (111) silicon wafer. The micromachined cantilever was 0.7 µm thick, 16 µm wide, and 120 µm long, and the gap between the beam and the substrate was 4 µm. The sample was excited by a PZT actuator at various frequencies. After excited by a 250 KHz harmonic load for 10~110 seconds, the beam was released from the substrate. However, the beams were sticking to the substrate permanently if they were not driven by the harmonic excitation. The application of this technique is also demonstrated by the experiment. Theoretical predictions of the dynamic behavior of microstructure during drying process agree well with experimental results. In short, the proposed technique effectively enhances yield rate of the microstructure without additional masks and complicated process. Although the application of the proposed approach is limited to the overdamped system, it provides an additional option to prevent stiction problem. @FootnoteText@@footnote 1@Takeshi Abe, W. C. Messner, and M. L. Reed, 'Effects of elevated temperature treatments in microstructure release procedures' Journal of Microelectromechanical System, vol. 4, pp. 66-74, 1995. @footnote 2@ H. Hosaka, K. Itao, and S. Kuroda, 'Damping characteristics of beam-shaped micro-oscillators' Sensors and Actuators A, vol. 49, pp. 87-95, 1995. @footnote 3@ J. J. Blech 'On isothermal squeeze films' ASME Journal of Lubrication Technology, vol. 105, pp. 615-620, 1983.

4:20pm **MM-WeA8 Control of Residual Stress in Thick Sputtered Metal Films***, **J.M. Melzak**, D.A. Greer,* Case Western Reserve University*; S. Rajgopal, K.S. Lebouitz,* XACTIX, Inc.*; M. Mehregany,* Case Western Reserve University

Metals are the structural material of choice for a growing number of MEMS applications (e.g., optical elements, relays) because of their high reflectivity and low resistivity. This paper investigates the relationship between the parameters used to deposit such thick (1µm) films by DC magnetron sputtering and the resulting residual stress values. The materials of interest-aluminum, tungsten, and a ternary alloy of aluminum/silicon/copper-exhibit quite different residual stresses for a given set of deposition parameters, as well as reacting quite differently to changes in deposition parameters. For example, 1µm-thick tungsten films deposited on silicon at a pressure of 5 mTorr exhibit a compressive stress of 253 MPa while aluminum films deposited under the same conditions have a tensile stress of 73 MPa. Increasing the deposition pressure to 15 mTorr results in a highly tensile tungsten film, whereas the effect on aluminum's residual stress is minimal. As-deposited thick films of these materials have been characterized using wafer curvature, surface profilometry, and TEM analysis. Furthermore, a one-mask surface micromachining process that selectively etches the underlying silicon with xenon difluoride (XeF@sub 2@) has been used to fabricate metal cantilever beams, in order to qualitatively examine residual stress gradient.

4:40pm **MM-WeA9 SiC Surface Micromachining Process Development and Device Characterization***, **J.D. Scofield**, B.N. Ganguly,* Air Force Research Laboratory*; A.J. Steckl,* University of Cincinnati

TA silicon carbide surface micromaching process has been developed for the fabrication of robust MEMS structures. A direct etch and release procedure has been demonstrated using both Silicon dioxide and poly-silicon sacrificial layers. Cubic silicon carbide films were grown and characterized on silicon nitride, silicon dioxide, and poly-Si to determine the most suitable sacrificial layer for device fabrication. Excellent film quality was obtained on all substrates investigated as determined by x-ray diffraction, IR absorption, and mechanical testing. Diagnostic and resonant structures were subsequently fabricated on the poly-Si based sacrificial layer coated substrates and characterized. On chip strain gauge characterization and Raman spectroscopy were both used to empirically determine the residual stresses present in the device structures. Resonance measurements were completed in order to ascertain Young's modulus of the mechanical films. Release of completed MEMS structures is accomplished using both wet and dry (XeF2) etch processes with excellent success realized in both cases. The results of these experiments, and target applications for the fabricated devices will be summarized in the proposed presentation.

5:00pm **MM-WeA10 Micro- and Nanotube Fabrication using Deposited Porous Silicon***, **W.J. Nam**, S. Bae, A.K. Kalkan, S.J. Fonash,* The Pennsylvania State University

There is a great deal of interest in micro- and nano- scale tube and channel structures. Conventional polycrystalline silicon (poly Si) material has been commonly used in such structures as a sacrificial layer. However, the etch rate of conventional poly Si sacrificial layers decreases rapidly in the case of the small etch access windows needed in etching small dimension structures due to reactant and reaction product transport limitations. Porous Si produced by electrochemical etching can eliminate these problems to some degree due to the multiplicity of transport paths to the access window but its formation requires wet processing. We solve this problem by introducing a new material, porous Si deposited using a high density plasma. Our deposited porous Si, produced using low temperature electron cyclotron resonance (ECR) deposition, can be made polycrystalline or amorphous and has a porosity that is controllable (up to ~90% porosity) without the need for any post-deposition etching. Used as a sacrificial layer, the material exhibits a high etch rate (1.5µm/min) since its connected-void morphology provides excellent transport pathways for the reactants and reaction products even when etched through a small access/exit window. The fast etch rate of this deposited porous Si prevents thinning or damaging of the other structural materials. We report specifically on structures using 500 Å of silicon dioxide as the substrate coating and etch stop layer during the sacrificial (porous Si) layer removal. In these structures, silicon nitride was used for a capping layer. The sacrificial porous Si material was etched out by using 5% tetramethyl ammonium hydroxide (TMAH), at either 30°C or 75°C. All layers (etch stop, sacrificial porous Si, and nitride) were produced in the same ECR tool.

MEMS
Room 309 - Session MM+BI-ThM
Bio-MEMS and Microfluidics

Moderator: P.G. Datskos, Oak Ridge National Laboratory

8:20am **MM+BI-ThM1 Microfabrication Technologies for Biomedical Applications***, **M. Ferrari**,* The Ohio State University **INVITED**

PLEASE SEND US AN ABSTRACT. Thank you.

9:00am **MM+BI-ThM3 Suppression of Blood Serum Adhesion on Quartz Inner Wall of Microcapillary Coated by Bio-compatible MPC Polymer***, H. Ogawa, A. Oki, **Y. Takamura**, S. Adachi,* The University of Tokyo, Japan*; T. Ichiki,* Toyo University, Japan*; K. Ishihara, Y. Horiike,* The University of Tokyo, Japan

We are developing the healthcare device which enables us to detect various health markers from trace amount of the blood. To suppress adhesion of proteins in a blood injected into a quartz made microcapillary, the 2-methacryloyloxyethylphosphorylcholine (MPC) polymer which is now utilized to artificial blood tube, contact lens, in-vivo sensors, etc. has been coated on the inner wall, thus leading to bio-compatibility of the quartz surface. A microcapillary with a 30 x 30 µm cross-section and 10 mm in length was fabricated in a 2cm x 2cm quartz chip by dry-etching and subsequent press-bonding of a cover quartz plate in 1% HF solution. A pH=7.4 phosphate buffered solution (PBS) was filled in the capillary and the serum was injected from one end by electroosmosis pumping. The concentrations of proteins, which were monitored by 220nm UV absorption at the point of 4mm apart from the injection, rose up rapidly when the serum arrived at this point and then were kept at a constant value in the 3 wt% MPC coated capillary, while those in uncoated capillary were decreased gradually by adhesion of proteins on the inner wall after showed maximum. To investigate the interaction of proteins with the MPC polymer coated surface, FTIR-ATR spectra for MPC coated and uncoated wall surfaces exposed by a blood serum were measured. The adsorption peaks by NH@sub x@ and C=O of proteins in the uncoated surface increased with exposure time, while the proteins did not absorb on the coated surface. These results clearly demonstrate the excellent bio-compatiblity of the MPC polymer for a blood handling capillary chip.

9:20am **MM+BI-ThM4 Biologically-Compatible Polymeric MEMS Devices Fabricated using Holographic Two-Photon Induced Photopolymerization***, **L.L. Brott**,* Technical Management Concepts, Inc.*; S.M. Kirkpatrick,* Science Applications International Corporation*; M.O. Stone,* Wright-Patterson Air Force Base

Research in the bio-MEMS field has been driven by the desire to reduce the time, complexity and equipment needed to carry out clinical diagnostic procedures. Current bio-MEMS strategies rely extensively upon externally added reagents and conventional photolithography in the fabrication of these systems. In an effort to simplify these devices even further, research has begun incorporating the reagents, i.e. enzymes, directly into the walls of the microfluidic channels. Consequently, a new polymeric material based on poly(ethylene glycol) which maintains the biological activity of the reagents and is not sensitive to aqueous environments, yet whose monomeric form accepts aqueous solutions, was developed. The microfluidic channels were patterned by photocuring the monomer using a two-photon initiated photopolymerization process at 800 nm. A rose bengal/triethanol amine initiator system was used. By using a laser as the light source, holograms were patterned onto the device resulting in well defined and complex patterns.

9:40am **MM+BI-ThM5 Patch Clamping with Microfabricated Planar Electrodes***, **K.G. Klemic**, J.F. Klemic, M.A. Reed, F.J. Sigworth,* Yale University

The patch clamp technique is the most sensitive way to record the small ionic currents carried by ion channels and transporters in cell membranes. To make a typical recording, the ~1 micron tip of a glass or fused-quartz micropipette, filled with saline solution, is sealed over a patch of cell membrane, electrically isolating it with a very large electrical "seal resistance" of 10-100 G@ohm@. Here we describe the first use of new materials and a new configuration for patch-clamp electrodes. We have microfabricated planar electrodes that mimic the shape of the tip of the micropipette by aniostropic etching of single crystal quartz or by micromolding the silicone elastomer, poly(dimethylsiloxane) (PDMS). The planar geometry has several advantages over the standard glass micropipette currently used for patch clamp recording. First, it permits direct integration of the first stage of amplification electronics into the electrode. Second one electrode can be easily scaled to an array of electrodes for simultaneous patch-clamp recordings from many cells, greatly expanding the discovery of new ion channel genes and new pharmacological agents directed to ion channel targets. Third, microfluidic channels can be integrated to permit fast solution exchange on both sides of the membrane, something that is not presently possible. Lastly, the electrode is designed to have a small solution volume that reduces the capacitance and thereby reduces by an order of magnitude the contribution of the electrode to the background noise. The design and fabrication of these novel patch electrodes as well as membrane current recordings using these devices will be presented.

10:00am **MM+BI-ThM6 High Sensitivity Resonant Biosensor***, **B. Ilic**, D. Czaplewski, H.G. Craighead,* Cornell University*; P. Neuzil,* Institute of Microelectronics, Singapore*; C. Campagnolo, C. Batt,* Cornell University

There is a growing demand to produce highly selective biological sensors for the detection of small quantities of biological microorganisms using micromachining. In this work, the detection of bacteria using a resonant frequency based mass detection biological sensor has been accomplished. The biological sensor under development consists of an array of resonating cantilever beams fabricated, using bulk silicon micromachining techniques, from both low pressure chemical deposition (LPCVD) and plasma enhanced chemical vapor deposition (PECVD) low stress silicon nitride. For this experiment an array of cantilevers with dimensions of varying length from 15µm to 500µm, varying width of 2µm to 20µm, thickness of 320nm for the LPCVD, and t=600nm for the PECVD nitride, were used. Escherichia coli O157:H7 antibodies were immobilized on the surface of the resonators. Devices were subsequently exposed to varying concentrations of E. Coli cells in solution and any loosely bound cells were removed. In order to determine the mass bound to the cantilever, a frequency spectra was taken before and after the binding of the cells to the cantilever. Signal transduction of the micromechanical oscillators has been accomplished by measuring the out of plane vibrational resonant mode with an optical deflection system. The measured vibrational mode was entirely due to thermal noise and ambient vibrations in air. The measured resonant frequency shift as a function of the binding of additional cells was observed and correlated to the mass of the specifically bound E. Coli O157:H7 cells. Our results indicate good agreement with the predicted theory of linear elasticity. Under ambient conditions where considerable damping occurs, we were able to detect single E. Coli cells. Methods, utilizing vacuum encapsulation and tailoring of the cantilever dimensions, for single molecule detection will be discussed.

10:20am **MM+BI-ThM7 Nanofluidic Entropic Trap Array device for DNA Separation***, **J Han**, H.G. Craighead,* Cornell University

A nanofluidic entropic trap array device@footnote 1@ for separation and analysis of long DNA molecules was constructed and tested. The device contains many constrictions (entropic traps) with dimensions smaller than the radius of gyration for the DNA molecules. The length dependent trapping of DNA and resulting electrophoretic mobility difference enables efficient separation of DNA in the range of 5kb ~ 200kb, typically within 30 minutes, in a channel as short as 15 mm without using a gel.@footnote 2@ We fabricated devices with multiple channels with the same structural parameters, for a parallel analysis of samples. Multiple DNA samples were separately introduced into the device and collected into narrow bands for launching. The amount of DNA in the launching band could be electrically controlled. Simultaneous separation of multiple samples enables one to compare electrophoregrams for calibration or direct comparison for applications such as DNA fingerprinting. A range of device parameters were tried, and the optimization of the device will be discussed. @FootnoteText@ @footnote 1@ J. Han and H. G. Craighead, J. Vac. Sci. Tech. A, 17, 2142 (1999) @footnote 2@ J. Han and H. G. Craighead, Science, in publication (2000)

10:40am **MM+BI-ThM8 Integration of Microcapillary Electroporesis and Inductively Coupled Plasma Spectrometry for Rapid Biological/Chemical Analysis***, **T. Ichiki**, T. Koidezawa, R. Taura, T. Ujiie,* Toyo University, Japan*; Y. Horiike,* The University of Tokyo, Japan

Rapid and sensitive elemental specification of trace amounts of samples are important for chemical, biological, environmental and clinical applications. For the goal of integration of microcapillary electrophoresis (µCE) and inductively coupled plasma (ICP) optical emission spectrometry (OES) on a chip, we have fabricated µmCE chips with a nebulizer, and have investigated conditions for generating microscale ICPs. Microcapillary and nebulizer patterns were etched onto the quartz plate in C@sub 4@F@sub 8@/SF@sub 6@ plasmas using Cr masks. The etched quartz plate was dipped in 1% diluted HF solution and then bonded together with the other quartz plate with drilled holes. These two plates were press-bonded under the load of 1.3 MPa at room temperature for 24 hours. Samples separated via electroosmotic and electrophoresis phenomena were nebulized by controlling the carrier gas flow around the nozzle located at the capillary end to achieve the injection of pico-liter droplets in the gas. Subsequently, generation of microscale VHF-ICPs was investigated. Discharge chambers of 500µm-5 mm depth and/or width were fabricated on 20 mm@super 2@ quartz plates, which was attached under the 70-mm-@phi@ circular quartz plate set on a small vacuum chamber. A 5-mm-@phi@ antenna was set on the circular quartz plate so as to locate just above the discharge chamber. The power for Ar plasma ignition and mode jump from E- to H-discharge was examined by means of spectroscopy. In the case of discharge chamber dimension of 5 mm width and more than 2 mm depth, the power for ignition was only 5 W at pressures of 0.01-1 Torr, while no mode changes were observed even at 100 W. When reducing the discharge chamber depth to 1-1.5 mm, mode change occurred around 10 W and emission intensity drastically increased by 100 times. Thus high density VHF-ICP was found to be easily attained when the characteristic length of the discharge space is around 1 mm and the pressure is 1-10 Torr.

11:00am **MM+BI-ThM9 Silicone Elastomer Microwell Arrays for High Throughput Protein Biochemical Assays***, **J.F. Klemic**, H. Zhu, M.A. Reed, M. Snyder,* Yale University

The identification of the function of large numbers of gene products is an important challenge in post-genomic research. Inexpensive, disposable microwell arrays have been developed for high throughput screening of protein biochemical activity. The microwell arrays are cast in silicone elastomer sheets and placed on top of microscope slides for compatibility with commonly available sample handling and recording equipment. Arrays consist of high density (hundreds per slide), small volume (~300nl) wells which permit high throughput batch processing and simultaneous analysis of many individual samples using only small amounts of protein. Device utility has been demonstrated through the simultaneous analysis of 120 protein kinases from Saccharomyces cerevisiae assayed for phosphorylation of 17 different protein substrates. These microwell arrays, as tested, permit the simultaneous measurement of hundreds of protein samples, however, the use of micromolded silicone elastomer allows array densities to be readily increased by several orders of magnitude. With the further development of appropriate sample handling and measurement techniques, these arrays may be adapted for the simultaneous assay of several thousand to millions of samples.

11:20am **MM+BI-ThM10 Development of a Micro Capillary Pumped Loop System for Microelectronic Device Cooling***, **H. Yun**, H. Lee, K. Cho, I. Song,* Samsung Advanced Institute of Technology, South Korea

Increasing demand for processing data leads to faster clock speeds and large integration. As a result, the heat generation of microelectronic devices is increasing at rapid rate. Current PCs generate 20~30 Watts/cm@super 2@ of heat. If this trend continues, 100 Watts/cm@super 2@ of heat generation are expected within few years. Since conventional phonon diffusion based metal heat sinks can handle only up to 10 Watts/cm@super 2@, an alternative cooling technology is desired. In this paper, a micro capillary pumped loop (CPL), which is a microfabricated, capillary pressure driven fluid cycle is proposed as an alternative means of cooling microelectronic devices with large heat generation. The heat is absorbed at the evaporator by vaporizing the circulating fluid, and released out of the system at the condenser. The capillary forces of the microfabricated wick structure at the evaporator drives the fluid. Since the fluid particle directly carries the heat out of the system, the micro CPL is expected to be more effective than the conventional diffusion-based heat sinks. A prototype of 30 Watts/cm@super 2@ cooling capacity has been built and tested. Microchannels have been etched on a silicon wafer to form the evaporator and the condenser. The prototype operated successfully under 30 Watts/cm@super 2@ heat flux while keeping the junction temperature below 400K. The maximum heat flux was 50 Watts/cm@super 2@ before the dryout at the evaporator occurred. A nonlinear dynamic model has been developed to simulate the interaction between various components of the micro CPL. The simulation model successfully captured the overall trends of the experimental data. Further research on the underlying physics are desired for better understanding of this device.

11:40am **MM+BI-ThM11 Design, Fabrication, and Testing of Cross Flow Micro Heat Exchanger***, **C.R. Harris**, M. Despa, K.W. Kelly,* Louisiana State University

A cross flow micro heat exchanger was designed and fabricated to maximize heat transfer from a liquid to a gas (air) for a given frontal area and pressure drop of each fluid. To accomplish the goal of high heat transfer, micro channels with scales ranging from 200 µm to 500 µm were utilized. By constraining the flow to narrow channels, heat transfer is enhanced since the convective resistance at the solid/fluid interfaces is reduced. To minimize the pressure drop associated with micro channels, air passes through the plane of the heat exchanger via thousands of parallel short channels. Heat is transferred to the air from liquid that passes in cross flow through tens of parallel channels. Predicted design performance for plastic, ceramic, and aluminum micro heat exchangers are compared to one another and to current innovative car radiators. The micro heat exchangers can transfer greater heat per mass or volume than existing heat exchangers within the context of the design constraints specified. Important applications of this technology include automotive, home heating, and aerospace fields. The heat exchanger designed for plastic was fabricated by aligning and bonding two identical polymer (PMMA) parts that had been embossed using the LIGA process. After heat exchanger assembly, liquid was pumped through the heat exchanger with no leaks. Heat transfer and pressure drop tests were performed on the fabricated polymer heat exchanger. The experimental data is compared to the design calculations and to other heat exchangers.

MEMS
Room 309 - Session MM-ThA
Material Science of MEMS

Moderator: C.C. Wong, Sandia National Laboratories

2:00pm **MM-ThA1 Stress Measurement in MEMS Devices*, L.A. Starman,*** Air Force Institute of Technology*; J.D. Busbee,* Air Force Research Laboratory Materials Directorate*; J. Reber,* Wright State University*; J.F. Maguire, W.D. Cowan,* Air Force Research Laboratory Materials Directorate

Due to the unique structure and small scale of Micro-Electro-Mechanical Systems (MEMS), residual stresses during the deposition processes can have a profound affect on the functionality of the MEMS structures. Typically, the material properties of thin films used in surface micromachining are not controlled during deposition. Currently, few techniques are available to measure the residual stress in MEMS devices, with each having a limited degree of validity. In this paper, Raman imaging spectroscopy is utilized to examine the residual and induced stress in silicon MEMS test structures. As MEMS structures become more complicated, images generated from Raman spectroscopy can provide valuable information on stress fields in the structure. Since the Raman methodology is directly sensitive to stress in the deposited material, the potential exists for this technology to be used both as an in situ quality control device and for the control of gradients in the batch processing. Successful implementation of this technique allows the validation of MEMS designs. We report here the mapping of the complete stress field across a micromirror flexure. Vertical displacement measurements obtained using an interferometric microscope allow the applied stress in the device flexures to be calculated as a conformation of the stress image.

2:20pm **MM-ThA2 Issues in MEMS Reliability and Characterization*, S. Brown,*** Exponent, Inc. **INVITED**

This presentation addresses MEMS failure modes that are either unexpected or judged insignificant on a macroscale. Although MEMS devices can fail from typical "macro" effects such as overload, fatigue, or corrosion, in many instances these phenomena are accentuated once one addresses micron sized devices. Examples cited include stress corrosion of silicon, creep of membrane and thin film structures, electrostatic accumulation, shock resistance, and strength reduction due to processing effects. Possible countermeasures are included with each example, and suggestions are provided for additional investigation on MEMS reliability.

3:00pm **MM-ThA4 MOCVD PZT as a Pathway to Integrated Piezoelectric MEMS*, I.-S. Chen,*** *J.F. Roeder,* ATMI*; D.-J. Kim, J.-P. Maria, A.I. Kingon,* North Carolina State University

Development of reliable actuation methods is one of many challenges in thin film MEMS devices. Piezoelectric actuation using bulk ceramic materials is well known, but widespread use in MEMS requires suitable deposition and integration methods that are compatible with large-scale manufacturing. One primary factor limiting the development of piezoelectric MEMS has been the lack of a suitable thin film piezoelectric material. PZT and its derivatives have excellent piezoelectric properties and therefore are a logical choice for MEMS applications. Metalorganic Chemical Vapor Deposition (MOCVD) offers a unique combination of precise composition control, uniformity over large areas, and relatively low process temperatures that are compatible with integrated Si processing. We have developed MOCVD processes to prepare PZT films on advanced electrodes with longitudinal piezoelectric coefficients (d@sub 33@) up to 50pm/V. Robust electrode stacks were developed to suppress diffusion of reactive / mobile species into the silicon substrate during PZT deposition. The electrode stacks are fully compatible with substrates typically used in bulk micromachining, namely silicon wafers coated with either silicon nitride or boron-doped epitaxial silicon as an etch stop. For temperature-critical surface-micromachined structures, process temperatures as low as 450 °C have been successfully demonstrated.

3:20pm **MM-ThA5 Deposition of Highly Oriented LiCoO@sub 2@ Thin Films for Use as Cathodes in Thin Film Batteries*, J.A. Ruffner,*** *T.J. Boyle, D. Ingersoll, K.P. Peters, M.A. Rodriguez, J. Liang,* Sandia National Laboratories

Presently micro-and meso-machines (MEMS) are powered by sources that are large in comparison to the actual MEMS devices. Development of small-scale power sources is critical if these devices are to reach their full usefulness. A prototype all-ceramic thin film battery that consists of a LiCoO@sub 2@ cathode, surface modified silica film composite electrolyte, and SnO@sub 2@ anode is presently under development at Sandia National Labs. Deposition of well-oriented, crystalline LiCoO@sub 2@ thin film cathodes is a critical step to achieve the highest capacities possible for these batteries. LiCoO@sub 2@ thin films deposited at ambient temperature using rf sputtering are generally amorphous in their as-deposited state. Post deposition annealing at temperatures > 300 °C results in melting and subsequent crystallization.@footnote 1@ However, it may be possible to promote crystallinity in the desired orientation [(101), (100) or (104) planes parallel to the substrate] by using a substrate or appropriate seed layer which is epitaxially matched to the desired LiCoO@sub 2@ orientation. Single-crystal metal substrates, such as Au (110), Re (100), or Ti (100), have lattices that are well-matched to LiCoO@sub 2@ lattices. However, these substrates are expensive and, in the case of Ti, readily oxidized. Instead, we deposited thin films of these metals as seed layers on more readily available single-crystal dielectric substrates (i.e. quartz) in order to test their effectiveness in promoting crystallization of subsequently deposited LiCoO@sub 2@ thin films in the desired orientation. We report on the orientation and properties of LiCoO@sub 2@ thin films deposited using rf sputter deposition versus solution chemistry. 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. @FootnoteText@ @footnote 1@ P. da Fonseca et al., J. Power Sources (1999), 81-82, 575-580.

3:40pm **MM-ThA6 Microstructure and Mechanical Properties of Polysilicon and Poly-SiC Films for MEMS*, H. Kahn,*** *A.H. Heuer,* Case Western Reserve University **INVITED**

Polysilicon films deposited via LPCVD are the current mainstay structural material for MEMS. It is well known that the microstructures and residual stresses of these films are influenced by deposition temperature. We have developed a novel processing approach (the MultiPoly process) which exploits this concept by using polysilicon multilayers in order to create flat structures, as well as structures with controlled curvatures. The effect of microstructure on mechanical properties is less well known. We have also developed a surface-micromachined electrostatic microactuator capable of generating 0.7 mN of force. The microactuator can be integrated with on-chip fracture mechanics specimens, and these devices have been used for studying strength, toughness, and fatigue resistance of polysilicon. Similar studies have also been done on poly-SiC films.

4:20pm **MM-ThA8 Comparison of In-situ Boron-doped and In-situ Phosphorus-doped Polysilicon Films for Microelectromechanical Systems*, J.J. McMahon,*** *J.M. Melzak, C. Zorman, J. Chung, M. Mehregany,* Case Western Reserve University

In order to produce thick polysilicon films for MEMS applications, a single step, high deposition rate, APCVD process was developed and used to deposit in situ boron-doped, undoped, and in situ phosphorus-doped polysilicon films at susceptor temperatures ranging from 625C to 850C. For doped and undoped films alike, the deposition rate increases with increasing susceptor temperature, with boron-doped films exhibiting the highest deposition rate at each temperature setting. The highest deposition rates occurred at 850C, with boron-doped films being deposited at a rate of 733A/min, undoped films at a rate of 716A/min, and phosphorus-doped films at a rate of 622 A/min. Spreading resistance and SIMS measurements performed on the boron-doped samples indicate that the boron concentrations are generally constant throughout the thickness of the films, with the highest boron concentrations found in films deposited at 625C. Wafer curvature measurements on boron-doped films indicate that the films are in compression over the entire temperature range, with the magnitude of the stress decreasing with increasing temperature. In contrast, the undoped films are in tension at lower temperatures, but become compressive as the deposition temperature is increased. TEM analysis shows that film microstructure strongly depends on the deposition temperature, with equiaxed grains forming at low substrate temperatures and columnar grains forming at higher temperatures. Surface micromachined cantilevers, strain gauges, and lateral resonators were successfully fabricated from 5.0 micron-thick doped films grown at 850C. The extended paper will detail the process used to deposit the doped and undoped films, present a summary of the characterization study, and highlight the performance of micromachined structures and devices.

4:40pm **MM-ThA9 Investigation of the Friction and Adhesion Properties of BPT and BPTC Self-assembled Monolayers by AFM**, ***H. Liu***, *B. Bhushan,* The Ohio State University; *W. Eck, V. Stadler,* University of Heidelberg, Germany

Self-assembled monolayers (SAMs) are considered to be good candidate lubricants for microelectromechanical systems (MEMS). It is important to understanding the relationship between the structure and tribological performance for molecular tailoring to achieve efficient lubrication. For this purpose, biphenyl-4-thiol (BPT), and cross-linked biphenyl thiol (BPTC) were prepared on a gold sublayer. The cross-linking of BPT was carried out by low energy electron irradiation. Structure characterization shows that cross-links were formed between neighboring phenyl groups. The topography, adhesion, and friction properties of Si, Au, BPT and BPTC were studied by atomic force microscopy (AFM) with silicon nitride tip. It was found that both BPT and BPTC exhibited lower adhesion and friction than Si. But the coefficient of friction of BPTC are higher than BPT. The larger coefficient of friction of BPTC is believed to be caused by its rigid cross-linked structure. The study also found that the topography of different films have different contribution to the frictions of films. For Au and BPTC, friction is affected by surface slope, but for BPT the higher surface areas have low friction. A relationship between wear resistance of the low friction phase of BPT and its size was found.

5:00pm **MM-ThA10 Viewing a Moving Surface Contact: An STM-QCM Study of Vapor Deposited Films on Metal Surfaces**, ***B. Borovsky***, *M. Abdelmaksoud, J. Krim,* North Carolina State University

With the emergence of MEMS technology and the problems of high friction and mechanical failure encountered in the operation of such devices, new experimental techniques are needed which are able to probe nanometer scale contacts under sliding conditions relevant to MEMS. By combining a Scanning Tunneling Microscope (STM) with a Quartz Crystal Microbalance (QCM), we have constructed a nanotribological test set-up in which a single asperity contact is subject to contact pressures and sliding speeds relevant to both MEMS and macroscopic devices. We have applied STM-QCM to the study of vapor phase lubricants, which may prove to be an effective, and perhaps exclusive, means of lubricating MEMS devices. The STM allows direct imaging of the surface contact under both stationary and vibrating conditions, and is able to track changes in the conductivity and mobility of molecularly thin lubricant films. Surprisingly, the amplitude and speed of the sliding contact may be directly measured using STM images of the vibrating QCM surface. We show that the QCM achieves sliding speeds over 1 m/s and senses changes in sliding friction as a function of normal load upon application of a lubricant film to a bare metal surface. Together, our nanometer scale STM-QCM results are highly suggestive of the known macroscopic lubricant properties of the applied films. By performing rubbing-and-imaging experiments with this combined apparatus, dramatic changes in the properties of the contact are observed which are highly localized to the region of rubbing. Such investigations provide evidence of possible tribochemical effects, the observation of which is associated with the realistic sliding conditions attained with the STM-QCM. Research supported by the NSF and the AFOSR.

MEMS
Room 309 - Session MM+VT-FrM
MEMS Actuators, Pumps, Power Devices, and Tribology

Moderator: R. Robbins, Texas Instruments

8:20am **MM+VT-FrM1 Micromechanical Devices for Force Measurement***, **T.W. Kenny,*** Stanford University **INVITED**

In recent years, many researchers have adapted lithography, deposition and etching techniques from the IC processing community to the fabrication of micromechanical sensors. Many of the signals that these sensors are intended to detect are expressed as forces which stress or deflect the micromechanical structure. As sensors are miniaturized, these forces naturally become smaller, and techniques for detection are required to improve. Our research group has been engaged in a variety of activities, all of which share an interest in improving the force detection capability of microinstruments. In this talk, an overview of these activities will be presented, beginning with simple strain-gauge sensors (micronewtons), sensors based on tunneling displacement transducers (nanonewtons), AFM cantilevers (piconewtons), and ultra-thin force sensing cantilevers (attonewtons). Opportunities for exciting scientific measurements will be highlighted, and challenges for application of MEMS devices to these measurements will be discussed.

9:00am **MM+VT-FrM3 Developing MEMS Vacuum Pumps***, **E.P. Muntz,*** University of Southern California **INVITED**

There are no satisfactory MEMS vacuum pumps; particularly unavailable are vacuum pumps that can handle the flow required for MEMS scale, continuous sampling instruments. The two obvious paths to creating such pumps, adapting current technology to MEMS scales or inventing new MEMS friendly technology, are discussed. The first path has been tried to some extent and not been successful, the second has been studied and a few possibilities are under investigation. A generic scaling study of expected trends in vacuum pumping performance as size is reduced to the MEMS scale is presented. It indicates that in practically all cases present vacuum pumps scaled to MEMS dimensions are not very attractive. New technologies that may offer more attractive possibilities are discussed. The degree of attraction is measured in terms particularly applicable to MEMS devices; the energy required per unit of upflow in the pump and the pump volume per unit of upflow. Both of these need to be sufficiently small to permit self consistency in energy use and size in order to allow local integration of the pumps with the MEMS devices that require vacuum pumping. For instance the full potential of instruments such as a MEMS sampling mass spectrometer can only be achieved if the pumps have power or space requirements equal to or preferably significantly less than the instrument itself. It is concluded that with new pumping technologies that have been identified, it may be possible to provide satisfactory MEMS vacuum pumping performance. However, this will only come to pass if a determined research and accompanying development program is created.

9:40am **MM+VT-FrM5 Miniaturized Fuel Cell for Portable Power***, **H.L. Maynard,** J.P. Meyers,* Lucent Technologies, Bell Laboratories

We are developing a silicon-based miniaturized fuel cell to power 0.5-20 W portable telecommunication, computing, and personal entertainment devices. Fuel cells provide a 5-10x improvement in energy storage over advanced rechargeable batteries, allow "instant recharge" (with the insertion of a fuel cartridge), and enable sustained operation away from the power grid. The fuel cell is a methanol-based proton-exchange membrane (PEM) device. Our design is implemented in silicon to leverage advanced silicon processing technology, expertise and facilities. Applying silicon processing techniques to the fuel cell structure enables precise control over the thin-film properties and interfaces, enabling optimization of the critical three-phase region of ionic conductivity, electronic conductivity and gas and/or fluid permeability. Additionally, using a wafer-based approach minimizes production costs, instead of individually constructing and assembling the components. The advantages and disadvantages of two designs will be discussed: a two-wafer bipolar design and a single-wafer integrated monolithic structure. We discuss key integration issues including: thermal management, water control, air movement, fuel delivery, and power conditioning. We will also present preliminary experimental results.

10:00am **MM+VT-FrM6 Nanotribology and Stiction Studies of Surface Micromachined Electrostatic Micromotors Using An Atomic Force/Friction Force Microscope***, S. Sundararajan, **B. Bhushan,*** The Ohio State University **INVITED**

Microelectromechanical systems (MEMS) which involve relative motion often encounter tribological problems that undermine and sometimes even prevent device operation. One such problem is that of static friction or stiction. An atomic force/friction force microscope (AFM/FFM) allows for direct measurements on fabricated devices, components and their surfaces. The AFM can be used to study tribological properties of surfaces that exhibit stiction. Nanotribological studies have been conducted on surface micromachined polysilicon micromotors for the first time using a commercial AFM/FFM. Surface roughness parameters (RMS, peak-to-valley distance, skewness and kurtosis) and nanoscale adhesion and friction properties of various surfaces of the motor were measured. Different surfaces of the motor components exhibit different surface roughness and friction properties. A novel technique to measure the stiction encountered in these motors using an AFM has been developed and is described. Using this technique, the effects of humidity and rest time on stiction in the motors have been studied. The mechanisms responsible for stiction in such devices are discussed. Meniscus forces between the mating surfaces of the motor may be the cause of the observed stiction. The real area of contact between the mating surfaces is an important factor affecting meniscus forces. The use of perfluoropolyether (PFPE) liquids as lubricants to reduce friction and stiction for such MEMS devices is investigated.

10:40am **MM+VT-FrM8 Characterizing Coupled MEM Oscillators for Array Applications***, **R. Baskaran,*** Cornell University*; K.L. Turner,* University of California, Santa Barbara

MEM Oscillators have been successfully used as accurate sensing and actuation elements. We present a system of electrostatically coupled (by interdigital placement of the movable combfingers) torsional MEM oscillators. This design aims at studying the electrostatics of torsional systems and dynamics of variable coupling strength oscillators for distributed systems applications.@footnote 1@ The configuration allows design of elements with out-of-plane motion at locations across a large area without long springs/suspended structures, eliminating complex modes of oscillations close to operating frequencies and processing issues of large released structures. By design, each of the oscillators can be used for either capacitive sensing or actuation,like in a distributed control network. With integrated tips, the present design also lends itself to applications like AFM/STMs. We have designed, fabricated (with the SCREAM process) and characterized a 2-oscillator system. A high-accuracy(~4nm) laser vibrometry technique is used to get phase and amplitude of the displacement and velocity for various forcing voltages. Experiments have been performed to extract the electrostatic and dynamical parameters (represented by a coupled harmonic model) of the system. Experimental results show a near complete energy sharing (equal area under the Amplitude-Frequency curve) between the two oscillators in the primary resonance.'Beat' phenomenon i.e Amplitude modulation, typical of coupled systems, was observed in the impulse response as well as in the amplitude 'build up' to resonance. The phase relationship between the two oscillators will be useful to characterize the coupling mechanism and is presently under investigation. Future work involves extending the system to multiple oscillator arrays. @FootnoteText@ @footnote 1@Gabriel.K., Jarvis.J., Trimmer.W "Small machines, Large opportunities" Micromechanics and MEMS Classical and Seminal papers to 1990(IEEE).

11:00am **MM+VT-FrM9 Tunable Mechanical Oscillator***, **M.K. Zalalutdinov,** B. Ilic, A. Zehnder, J.M. Parpia, H.G. Craighead,* Cornell University

It has been demonstrated that cantilever beam can resonate at various frequencies when driving force is applied locally, at different points along the beam. The tip of a scanning tunneling microscope (STM) engaged at the cantilever surface is driven in the Z-direction, acting as driving point-source with a subAngstrom amplitude. Cantilever motion was detected by the Scanning Electron Microscope incorporated into a UHV STM system and a spectrum analyzer was used to monitor the modulation of the videosignal, actuated when electron beam crosses the vibrating cantilever. Low stress silicon nitride cantilevers were fabricated using conventional bulk silicon micromachining techniques and coated with a 300Å Au/Pd film in order to provide good tunneling conditions. In this paper we present the results obtained with a 225x20x0.6 µm cantilever. When the driven STM tip was positioned above the bulk part of the sample, near the base of the beam, the conventional cantilever mode was excited with the resonant frequency

9,7kHz. When the STM tip is moved so that it engages the cantilever surface, an additional local constraint is placed on the beam's motion, altering the vibrational mode and causing the shift of the eigenfrequency. We detected a continuous increase of the resonant frequency (up to 25kHz) as the STM tip was moved along the center line from the base to the middle of the beam. This continuous variation of the resonant frequency has numerous possible applications, and was accomplished without a significant change in the Q. We have analyzed the measured deflection vs position using a model of the beam motion and found good agreement over the range we have studied. Possible realization of tunable micromechanical oscillators, based on the concept of a drive induced by the application of the local stress will be discussed.

11:20am **MM+VT-FrM10 Thermal Characteristics of Microswitch Contacts***,* ***X. Yan****, N.E. McGruer,* Northeastern University*; S. Majumder,* Analog Devices*; G.G. Adams,* Northeastern University

Electrostatically actuated microswitches and relays have been developed at Northeastern University.@footnote 1@,@footnote 2@ Devices are approximately 100 @micron@ x 100 @micron@ in area and operate with an actuation voltage of 50-60 V, corresponding to a contact force of 100-150 microNewtons. The contact resistance varies less than 0.5 @ohms@ over 10@super 7@ cycles, with 4-10 mA current cold-switched. Switches have also been tested up to 10@super 9@ cycles with less than 0.5 @ohms@ variation in contact resistance, and with 330 mA of current for up to 18 cycles. The contacting bodies are a "drain" electrode approximately 0.2 @micron@ thick, and a pair of cylindrical bumps 1 µm in radius protruding from a 6 µm thick cantilever. The actual contact area is much smaller and consists of one or more small asperities. In this paper we study the microswitch contact properties at high currents. Finite element electrical and thermal models have been developed using ANSYS, and the modeled current handling limits are compared with experiments. Modeling shows that for a range of switch designs with thin-film drains, the highest temperature is located within the drain rather than at the contact interface, and this location moves further away from the contact interface as the drain thickness decreases or the length of the drain trace increases. Experiments confirm these trends, and show that switches fail catastrophically due to evaporation of the drain trace metal. SEM analysis of contact surfaces at various current densities is also presented. SEM analysis shows that even at the highest currents at which the trace metal evaporates, the contact surfaces typically show relatively little damage, mainly material transfer from one contact surface to the other. @FootnoteText@ @footnote 1@ S. Majumder, N. E. McGruer, "Study of Contacts in an Electrostatically Actuated Microswitch", Proceedings of 44th IEEE Holm Conference on Eletrical Contacts, pp 127-132 (1998) @footnote 2@ P.M. Zavracky, S. Majumder, and N.E. McGruer, "Micromechanical Switches Fabricated Using Nickel Surface Micromachining," J. Microelectromechanical Systems, Vol. 6, pp 3 (1997)

Author Index

Bold page numbers indicate presenter