Microelectromechanical Systems (MEMS)
Room 320 - Session MM-TuM

Development and Characterization of MEMS and NEMS Materials

Moderator: C.A. Zorman, Case Western Reserve University

8:20am **MM-TuM1 MEMS and NEMS from Chemical Vapor Deposited Nanodiamond Materials***, **J.E. Butler**,* Naval Research Laboratory **INVITED**

Nanodiamond films grown by chemical vapor deposition exhibit a number of remarkable properties desirable for MEMS and NEMS. These include high Young's Modulus, thermal diffusivity, dielectric breakdown strength, mass density, secondary electron yields, fracture toughness, optical transparency, corrosion resistance, biological stability, and more. The nucleation, growth, and doping of these films on diverse substrate materials, including Si, poly Si, SiO2, and various metals, will be described along with various methods of processing into structures and devices.

9:00am **MM-TuM3 Engineering the Surface Properties of Ultrananocrystalline Diamond for High-Performance MEMS Devices***, **A.V. Sumant**, D.S. Grierson,* University of Wisconsin, Madison*; J.E. Gerbi, J.A. Carlisle, O. Auciello,* Argonne National Laboratory*; R.W. Carpick,* University of Wisconsin, Madison

Characterization of MEMS and NEMS devices at small length scales is extremely important in order to understand the factors that dictate the performance of these devices. Ultrananocrystalline diamond (UNCD), in particular, has exceptional physical, electrical, chemical and tribological properties (nearly equivalent to those of single crystal diamond). UNCD is being considered as one of the most promising materials for the fabrication of high performance MEMS devices. However, little is known about the surface chemistry of this material, and how such surface chemistry will affect the UNCD performance, particularly in case of rolling or sliding contacts at both the micro and nano level. We have carried out detailed, systematic studies of UNCD thin films by various analytical techniques including Auger electron spectroscopy (AES), X-ray photoelectron spectroscopy (XPS), Raman spectroscopy, and atomic force microscopy (AFM) to understand the chemical nature, phase, and microstructure of the UNCD surface. We have found that there is a significant difference in the structural and chemical properties between the as-grown UNCD top surface and the underside of the film as revealed after etching away the substrate. Characterizing the underside of the film is particularly important because in most cases (e.g. micro-engines and cantilever based switches), the underside of the film makes contact with the underlying surface below. We will discuss how these properties are influenced by various aspects of the microwave PECVD growth process, including the initial nucleation pre-treatment and the gas chemistry used during growth, and how one can engineer the surface by tuning these growth parameters. Finally, we will discuss how such changes may affect UNCD performance at MEMS length scales.

9:20am **MM-TuM4 AlN-based MEMS and NEMS Resonator Devices***, **A.E. Wickenden**, L.J. Currano, M. Dubey,* U.S. Army Research Laboratory*; S. Hullavarad, R.D. Vispute,* University of Maryland, College Park

Electromechanical resonator devices using piezoelectric aluminum nitride (AlN) actuation are being developed for RF filters operating in the MHz-GHz frequency range. Composite structures are required for these micro- and nanoelectromechanical systems (MEMS, NEMS) devices, which include the piezoelectric film, metal electrode layers, and a flexural layer. AlN film quality is very dependant on the growth technique, and differences in crystallinity impact the subsequent piezoelectric response of the film. We have demonstrated the pulsed laser deposition (PLD) of highly oriented AlN thin films on Pt-terminated composite MEMS/NEMS structures. Characterization by X-ray diffraction demonstrates a FWHM of 0.2°, a ten-fold improvement over sputtered AlN films typically used in this application. Pattern transfer techniques have been developed for these composite device structures at both micro- and nano-scale. Fully released AlN MEMS beam resonator structures have been fabricated and tested. These devices demonstrate strong electromechanical response, with a 500 nm deflection observed in a fixed-fixed beam with a resonant frequency of 250 kHz. Device dimensions for resonant frequencies near 1 GHz are predicted to scale to near one micron in length and hundreds of nanometers in cross-sectional area. Free-standing 200nm wide x 150nm thick x 10µm long AlN beams with aligned metal electrodes have been demonstrated, using direct-write electron beam lithographic patterning techniques. We will present detailed harmonic and modeshape analysis of AlN MEMS resonators in the 0.15-15 MHz frequency spectrum, and highlight current results in the development of AlN NEMS resonators.

9:40am **MM-TuM5 Anchor Optimization for Quality Factor Improvement in Microresonators***, **L.J. Currano**, A.E. Wickenden, M. Dubey,* U.S. Army Research Laboratory

Arrays of microresonators are of considerable interest for low-cost, high precision RF filters. The quality factor (Q) of a resonator is the figure of merit which determines the amount of signal lost from input to output as well as the slope of the cutoff of a bandpass filter. Some of the factors that degrade the quality factor in mechanical resonators are geometry and material properties, thermoelastic noise, and the transduction mechanism.@footnote 1@ Several discussions of the noise and dissipation mechanisms in microresonators have been published.@footnote 2@ One of the most important loss mechanisms is the transmission of mechanical strain energy to the substrate. The magnitude of strain energy transmitted to the substrate can be manipulated by changing the geometry of the interface between device and substrate. The quality factor for similar PZT-based clamped-clamped beam resonator devices has been found to double by changing the geometry of the anchor slightly. New models are necessary for reducing mechanical losses in the simplest resonator structure, a doubly clamped beam. Finite element analysis provides a vehicle for examining the losses due to transmission of strain energy from the resonator into the substrate and a window into some of the design methods that can be used to minimize mechanical losses. A finite element model which calculates the strain energy transmitted to the substrate in a clamped-clamped resonator beam has been devised, and the results show that the losses steadily decrease with anchor width. Results from the model along with results from electrical testing of PZT resonator devices will be presented. @FootnoteText@@footnote 1@A. N. Cleland and M. L. Roukes, "Noise processes in nanomechanical resonators," Journal of Applied Physics, vol. 92 pp 2758, 2002.@footnote 2@J. R. Vig, "Noise in microelectromechanical systems resonators," IEEE Trans. on Ultrasonics, Ferroelectrics, and Frequency Control, vol. 46 pp. 1558, 1999.

10:00am **MM-TuM6 Chemical Control of Mechanical Energy Dissipation in Micromechanical Silicon Resonators***, **Y. Wang**, J.A. Henry, M.A. Hines,* Cornell University

Why are we unable to predict the dynamical performance of nanoscale devices from the well-known properties of macroscopic materials? For example, the quality (or Q) of micromechanical resonators plummets as the size of the device is reduced. We will show that the role of surface effects on energy loss cannot be ignored at this length scale. To investigate the role of surface dissipation, we have fabricated silicon torsional resonators with predominantly Si(111) faces. The resonators' surfaces are then chemically modified and characterized by infrared spectroscopy. Resonators terminated by an atomic layer of hydrogen have the lowest energy loss but the quality of the resonator decreases with time even in high vacuum (10@super -8@ Torr). Quantitative analysis of the time-dependent frequency shift suggests that the increased losses observed in vacuum are correlated with chemical adsorption. The quantitative effects of a variety of adsorbates will also be discussed. When the H-monolayer is replaced by one type of self-assembled monolayer (SAM), a small decrease in initial quality is observed; however, SAMs-terminated devices are much more stable with time. This stability is attributed, in part, to increased chemical resistance; however, aggressively oxidizing environments still lead to performance degradation. A second type of SAM leads to much higher energy losses. The chemical origins of this difference will be discussed.

10:20am **MM-TuM7 Vapor-Phase Lubricants: Nanometer-scale Lubrication Mechanisms and Uptake on Silicon***, **W. Neeyakorn**, M.R. Varma, J. Krim,* North Carolina State University

The concept of lubricating high temperature bearing surfaces with organic vapors which react with a surface to form a solid lubricating film has existed for at least forty years, with substantial efforts beginning in the 1980's and continuing to the present day. While vapor-phase lubricants have primarily been studied within the context of macroscopic system performance, they may well prove to be of critical importance to tribological performance in sub-micron mechanical systems as well. This is because the vapor phase may ultimately prove to be the most effective, if not only, means to deliver and/or replenish a lubricant that can withstand a variety of extreme environmental conditions that a MEMS device is likely to encounter. In order to investigate the viability of vapor-phase lubrication for MEMS applications, we have studied molecular scale tribological properties and gas uptake rates for four known organophosphate lubricants in controlled environments on silicon and gold substrates. The first study involves Quartz Crystal Microweighing investigations of the uptake rates of lubricant vapors from the vapor phase in vacuum conditions. With the intent of modelling actual MEMS contacts, we have also constructed a simple nanomechanical system consisting of a Scanning Tunneling Microscope tip dragging on the surface of a Quartz Crystal Microbalance electrode. This system allows us to monitor lubricant performance in realistic sliding conditions of up to 2 m/s. Finally, work is in progress to study the effect of these vapor-phase lubricants on actual MEMS devices with contacting silicon surfaces.@footnote 1@ @FootnoteText@@footnote 1@ Work supported by NSF and AFOSR.

10:40am **MM-TuM8 Can We Predict Friction and Wear in MEMS?*, E.E. Flater,*** University of Wisconsin - Madison*; A.D. Corwin, M.P. DeBoer,* Sandia National Laboratories*; C.K. Bora, M.E. Plesha, R.W. Carpick,* University of Wisconsin - Madison

The design of reliable MEMS devices that involve sliding or rolling surfaces requires a predictive capability for friction and wear. We will describe our efforts to predict friction in MEMS by connecting single asperity friction measurements via atomic force microscopy (AFM) with multi-asperity friction measurements in a newly-developed MEMS friction test device through the use of analytical models of contact between rough surfaces. We will show that AFM resolves critical roughness features of MEMS surfaces from the nm-to-Âµm scale. From this information, we derive surface roughness parameters that are used as inputs to predict the interfacial mechanics using generalized models based on the Greenwood-Williamson approach and fractal surface models, respectively. We will discuss the validation of these approaches with reference to single-asperity AFM experiments and multi-asperity MEMS friction test device experiments.

11:00am **MM-TuM9 Nanomechanical Characterization of Digital Micromirror Devices*, G. Wei,*** *B. Bhushan,* The Ohio State University*; J. Jacobs,* Texas Instruments, Inc.

The Digital Micromirror Device (DMD) lies at the heart of Texas Instruments' Digital Light Processing@super TM@ (DLP@super TM@) technology, enabling the next generation of bright, lightweight projection displays. The DMD comprises a surface-micromachined array of up to 2.07 million mirrors fabricated on top of an SRAM array. The nanomechanical properties of the thin-film structures formed in the manufacturing process are important to the performance of the DMD. In this paper, the nanomechanical characterization of various materials used in the manufacture of the DMD has been performed using a nanoindentation technique. Properties including Young's modulus, hardness, scratch resistance, fatigue, and fracture toughness of the corresponding materials have been measured and analyzed. The impact of these properties on mirror performance is discussed.

11:20am **MM-TuM10 Measurement of Mechanical Properties of Silicon Nitride Thin Film at Cryogenic Temperatures*, W. Chuang,*** *T. Luger,* University of Maryland, College Park*; R. Fettig,* NASA Goddard Space Flight Center*; R. Ghodssi,* University of Maryland, College Park

Mechanical properties of MEMS materials at cryogenic temperatures are investigated to extend MEMS sensors and actuators into space and low temperature applications. Two-dimensional micro-shutter arrays, made in silicon nitride thin film, are being developed at NASA Goddard Space Flight Center (GSFC) for use in the James Webb Space Telescope (JWST). Reliability and exact mechanical properties of silicon nitride thin film at cryogenic temperatures are crucial in the development of the JWST. We have developed and installed a measurement setup inside a focused ion beam (FIB) system, which can provide scanning electron microscopy (SEM) and mask-less ion milling, to measure the mechanical properties of MEMS materials from room to cryogenic temperatures. A variety of low-stress silicon nitride T-shape cantilevers suspended on silicon micromachined v-grooves are fabricated as test devices. The resonant frequency method is used in experiments to minimize the required calibration in the measurement setup at different temperature ranges. A lead-zirconate-titanate (PZT) translator and a silicon diode are utilized as the actuator and temperature sensor in the measurement setup, respectively. Experiments are performed to measure resonant frequency, damping, coefficient of thermal expansion, Young's modulus, fracture strength and fatigue properties of the test devices from room to cryogenic temperatures. The measured resonant frequencies are varied from 15.81 kHz at 25.5 K to 14.61 kHz at 298 K (room temperature). The higher resonant frequency is consistent with the expected increased Young's modulus of silicon nitride thin film at cryogenic temperatures. The preliminary measurement results, detailed fabrication process and configuration of the measurement setup will be presented.

11:40am **MM-TuM11 Pointwise Strain Mapping a Multilayer MEMS Mirror Using Synchrotron Radiation*, Y.N. Picard,*** *S.M. Yalisove, E. Dufresne, C. Cionca, J. Guzman, R. Clarke,* University of Michigan, Ann Arbor*; D. Walko,* Argonne National Laboratory*; O.B. Spahn, D.P. Adams,* Sandia National Laboratories

Precise control over surface curvature of micromirror devices is critical for developing communications and power delivery applications. Furthermore, the control of this curvature must be maintained over time and in a range of operating conditions. Curvature control ultimately requires understanding of how stress in reflective coatings and thermal-stress compensation layers affect the ultimate performance of a variety of micromirror designs (different geometries, thickness, clamping arrangements, etc). Highly localized, non-destructive strain measurement techniques are required to assess variations in stress across and through micromirror coating layers on the actual device. We present results of strain mapping across a metal-coated polysilicon micromirror using a micron-sized x-ray beam at the Advanced Photon Source. Prior to x-ray analysis, a high reflectivity, low stress film of 10 nm Ti/150 nm Au was deposited by DC planar magnetron sputtering on a 2.25 micron thick, 500 micron diameter polysilicon mirror that had been etch-released prior to film deposition. A 10keV x-ray beam was focused down to a 5.3x12.8 micron spot size using two bendable Kirkpatrick-Baez mirrors and then used for point-by-point detection of Au and Si diffraction peaks. The peak positions were then measured and used to determine strain in the respective thin film after comparison to a standard powder sample. Because the freestanding micromirror was still clamped to the substrate, variations in strain were anticipated and indeed detected. Results of measured in-plane and out-of-plane strain for both the Au film and the polysilicon mirror will be presented, where an up to 23% variation in strain is detected from the center to the constrained edges of the micromirror. We also discuss strain resolution by this method and estimate that 3-5 MPa of stress can be resolved point-to-point within each material layer.

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