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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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