Tuesday Morning, November 14, 2006

MEMS and NEMS
Room 2007 - Session MN-TuM
Material Aspects of MEMS and NEMS

Moderator: C. Zorman, Case Western Reserve University

8:00am **MN-TuM1 Controlled Fabrication of Nanotube Devices using Nanotubes of Known (n,m) Indices*, J. Hone,*** Columbia University **INVITED**

Because small changes in the crystal structure (chirality) of carbon nanotubes can produce large changes in their electrical properties, it is important to understand the relationship between structure and transport properties, both for basic science and for applications. However, detailed experimental exploration of this relationship has proved elusive so far. Using a mechanical transfer technique in parallel with efforts to combine optical scattering and structural characteriztion, we have achieved the goal of placing 'the nanotube we want, where we want it.' Long suspended tubes are first grown by CVD and inspected optically. Rayleigh scattering spectroscopy can readily discern between metallic and semiconducting nanotubes, and can be correlated with direct structural probes to provide the exact (n,m) structure. After optical characterization, a chosen nanotube can be transferred to a substrate in the desired location, and devices fabricated using standard e-beam lithography techniques. We have fabricated a number of devices in this manner and are beginning to fully explore the detailed relationship between structure and transport.

8:40am **MN-TuM3 Compensation of Strain Gradient by Varying Dopant Profile during the Growth of Polycrystalline Silicon Carbide Films*, J. Zhang,*** University of California, Berkeley*; R. Howe,* Stanford University*; R. Maboudian,* University of California, Berkeley

Polycrystalline 3C-SiC (poly-SiC) films are deposited by low-pressure chemical vapor deposition on Si(100) substrates using 1,3-disilabutane and are in-situ doped by NH@sub 3@. The effects of dopant concentration on residual strain and strain gradient of the films are investigated using microstrain gauges and cantilever beam arrays. With the increase in doping level, the tensile strain increases from 0.10% to 0.21%. The strain gradient of all films is negative with values ranging from -2 x 10@super -4@ to -5 x 10@super -4@ µm@super-1@. To compensate for the strain gradient, a bi-layer deposition scheme consisting of films with different residual strain due to varying doping is developed. With this approach, a positive strain gradient of 5 x 10@super -5@ µm@super -1@ is achieved. Discussion and further optimization of this method will also be presented.

9:00am **MN-TuM4 Characterization of APCVD and LPCVD Based Polycrystalline 3C-Silicon Carbide Resonators*, W.C. Chang*,** *C. Zorman, M. Mehregany,* Case Western Reserve University

Silicon Carbide is a promising material for RF MEMS due to its mechanical robustness, chemical inertness and high Young's Modulus-to-density ratio. While single crystalline SiC films are used for high quality devices, many MEMS devices do not require such high crystalline quality and therefore can use polycrystalline SiC films. Polycrystalline SiC can be grown at a lower temperature than single crystal films, (at or below 900°C by LPCVD), which makes the process more compatible with conventional MEMS processes. Furthermore, the deposition does not depend on a crystalline template, as it can be deposited on any substrate, whether single crystalline, polycrystalline or amorphous. This advantage enables polycrystalline SiC to be used in more complex micromechanical structures than single crystalline SiC. This paper demonstrates poly-SiC folded beam resonators fabricated by atmospheric pressure chemical vapor deposition (APCVD) and low pressure chemical vapor deposition (LPCVD). APCVD resonators were made from films grown at 1280°C using SiH@sub 4@ and C@sub 3@H@sub 8@ as precursors. SiO@sub 2@ and poly-Si were used for isolation and sacrificial layers, respectively. The LPCVD resonators were made from films deposited at 900°C using SiH@sub 2@Cl@sub 2@ and C@sub 2@H@sub 2@ as precursors. The resonator design used SiO@sub 2@ as an isolation and sacrificial layer. The devices were driven and measured by an Agilent 4395A network analyzer via a transimpedance amplifier under a reduced pressure of 30uTorr. The measured quality factors are about 22k and 10k for APCVD and LPCVD grown lateral resonators respectively. The quality factors of the poly-SiC flexural-mode resonators are the highest reported values by electrical measurement so far. To compare the intrinsic loss of the two folded beam resonators, XRD was used to compare the average grain size of poly SiC. The estimation for APCVD-grown poly SiC is 65nm and 43nm for LPCVD-grown poly SiC.

9:20am **MN-TuM5 NEMS and AFM Cantilevers Synthesized from Metal Nanocomposites*, C. Ophus*,** Univ. of Alberta, Canada*; Z. Lee,* NCEM, Lawrence Berkeley National Lab*; E. Luber, N. Nelson-Fitzpatrick, R. Mohammadi, C. Gilkison, L.M. Fischer, S. Evoy,* Univ. of Alberta, Canada*; V. Radmilovic, U. Dahmen,* NCEM, Lawrence Berkeley National Lab*; D. Mitlin,* Univ. of Alberta, Canada

While metal films, such as Ni, Ag, Pd and Al, have been used in a variety of electronic and MEMS devices, they have had limited applications in the field of cantilever-based sensing or as AFM cantilevers. Despite several major advantages over insulators and semiconductors (optically reflecting, tough-ductile, electrically conducting), metals are notoriously difficult to pattern or release due to their high stress state, large surface roughness and low strength. We were able to overcome these limitations by using room temperature co-sputtering to synthesize nanocomposite alloy films with unique microstructures and properties. The aim of this report is to describe the device applications, the mechanical properties and the microstructure of Ni-X, Ag-X, Pd-X (where X is one or more alloy addition) and Al-Mo nanocomposite thin films. We fabricated a range of compositions and microstructures of these alloys by co-sputtering from different metal targets. Nanoindentation tests indicate that the hardness of the fabricated materials is more than an order of magnitude higher than that of conventional metal films. In addition, within a certain compositional range, the nanocomposites are under relatively low stress and possess near atomic-level smoothness. The properties of the nanocomposites are discussed in relation to the materials' microstructure, as characterized by TEM, SEM, AFM and XRD analysis. Using the microstructurally optimized versions of these alloys, we fabricated free-standing nano-scale cantilevers down to approximately 4 nm thickness. These were to our knowledge the thinnest cantilevers ever achieved both for metals and for semiconductors. We tested these devices in vibrational resonance mode, as well as further processing them into AFM-usable geometries that included both the cantilever and the tip.

10:40am **MN-TuM9 Gray-scale Technology for 3-D Static and Dynamic MEMS*, R. Ghodssi,*** University of Maryland **INVITED**

The development of gray-scale technology, a batch 3-D silicon fabrication technique, has the potential to lift the vertical design restrictions that plague MEMS designers. Gray-scale technology involves two primary steps, beginning with gray-scale lithography, where partial exposure of a photoresist film creates a gradient structure in resist after development. Next, deep reactive ion etching (DRIE), is used to transfer the gradient photoresist structure into an underlying silicon substrate, where the etch selectivity determines the vertical amplification of the gray-scale photoresist structure into a final 3-D silicon structure. Research in our group has focused on investigating the limitations and tradeoffs of the core fabrication technique, as well as incorporating this technology into the design and fabrication of both static and dynamic MEMS devices. We first created an empirical model to relate the height of a photoresist feature to the local transmitted intensity through a projection lithography system. This model enables nearly arbitrary photoresist profiles to be created by simply designating the size of individual sub-resolution pixels on an optical mask. Upon creating a precise 3-D photoresist feature, extensive etch characterization during DRIE was necessary to investigate the effects of various etch parameters on the transfer of gray-scale features into silicon. Etch variables such as silicon loading, electrode power, and oxygen content were studied as they relate to etch selectivity, enabling creation of 3-D silicon structures millimeters wide and up to 100's of micrometers tall. Static MEMS structures developed during the course of this research have included: (1) a variable span micro-compressor towards increasing cycle performance of a micro-gas turbine generator device (in association with MIT and ARL), (2) 3-D substrate and interconnect technologies for MOSFET relay packaging (in association with Toshiba), and (3) x-ray silicon phase Fresnel lenses with precise profiles for increased focusing efficiency (in association with NASA - Goddard Space Flight Center). Dynamic MEMS devices benefiting from the incorporation of 3-D components have also been demonstrated by our group, such as voltage-tunable MEMS resonators and multi-axis optical fiber actuators for in-package alignment of fibers to edge-coupled optoelectronic components.

11:20am **MN-TuM11 Effects of Tensile Stress and Viscous Damping on the Resonance of Nanomechanical Beams and Cantilevers*, S.S. Verbridge*,** *L.M. Bellan, R.B. Reichenbach, J.M. Parpia, H.G. Craighead,* Cornell University

Mechanical flexural resonators with cross-sectional dimensions on the scale of 100 nm have been studied. Devices have been fabricated in silicon nitride, covering a wide range of tensile stress values, from 0 to 1200 MPa. It is shown that the devices with the highest stress exhibit the highest frequencies, as well as the highest quality factors, for devices of a given size. The former result is expected based on traditional considerations of stressed vibrating beams, while the latter is more surprising. Quality factors as high as 200,000 have been attained at room temperature and at high vacuum for doubly-clamped nanoresonators, with MHz range frequencies. We will discuss the various loss mechanisms which might contribute to the quality factors exhibited by these resonators, and will show that the high stress state appears to be relieving certain of these mechanisms, resulting in nanoresonators with losses approaching the thermoelastic limit. We will also briefly discuss the operation of these resonators in environments in which viscous damping becomes the dominant loss mechanism, with applications for chemical and biological sensing. Resonators with 100 nm cross-sections and frequencies as high as 100 MHz have been operated in air, as well as viscous liquids including alcohol and water, using an optical drive technique.

11:40am **MN-TuM12 Piezoelectric-Diamond Hybrid Heterostructures for High Performance MEMS/NEMS Devices***, S. Srinivasan, J. Hiller, O. Auciello,* ***A.V. Sumant****,* Argonne National Laboratory

Novel microelectromechanical and nanoelectromechanical system (MEMS/NEMS) devices, including sensors and actuators represent a technological revolution similar to the microelectronics revolution of the 20th Century. Development of these new generation multifunctional devices involves new materials, dissimilar materials integration strategies, and micro and nanofabrication processing techniques for optimum device performance. Most MEMS devices are currently based on silicon because of the available surface micromachining technology. However, the poor mechanical and tribological properties of Si are not suitable for high-performance Si-based MEMS devices. On the other hand, diamond as a super-hard material with exceptional mechanical and tribological properties exhibits tremendous potential for new generation of high-performance MEMS/NEMS devices. Among various forms of diamond, ultrananocrystalline diamond (UNCD), based on a novel thin film technology using argon plasma chemistry, exhibits superior mechanical properties compared with single crystal diamond, microcrystalline diamond (MCD), and nanocrystalline diamond (NCD) in terms of properties and adaptability for MEMS/NEMS applications. Piezoelectric-based MEMS attracts much attention due to their high sensitivity and low electrical noise in sensing applications and high-force output in actuation applications. Pb(ZrxTi1-x)O3 (PZT) thin films have stimulated intensive studies over the past decade due to its potential applications in a wide variety of devices, namely piezoelectrically actuated MEMS/NEMS devices. Therefore, the integration of functional PZT thin films with the UNCD films opens up the tantalizing possibility of advanced MEMS/NEMS devices. However, the integration of PZT and UNCD is challenging, mainly due to the PZT/UNCD interface. In this research, we explore such an integration to achieve high quality devices.

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