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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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