MEMS and NEMS
Room: Santo Domingo - Session MN-ThM

Multi-scale Interactions of Materials at the Micro- and Nano-scale
Moderator: R.B. Ilic, Cornell University

8:00am **MN-ThM1 Mechanical Devices Incorporating Ultra-Thin Membranes**, ***H.G. Craighead***, Cornell University **INVITED**

We have fabricated resonant mechanical structures from different membrane materials, including single-atom-thick graphene, and explored there function as sensors and devices. Silicon nitride can be lithographically fabricated to form electromechanical devices, and these structures have been widely studied, often in the form of cantilevers, as resonators and sensors. We have explored different geometries of silicon nitride as resonant mass sensors and also studied a new stress-based resonant device for sensing atmospheric gasses. With advances in processing methods we can now create similar devices from lithographically patterned graphene atomic sheets and monitor their mechanical response by methods similar to those used for surface patterned silicon nitride. The ability to integrate membranes into nanomechanical devices and systems creates the possibility for new sensing modalities and systems.

8:40am **MN-ThM3 Functionalized CMOS Nanomechanical Resonators for Trace Explosives Detection**, ***J.W. Baldwin***, Naval Research Laboratory, *J.S. Burgess,* National Research Council, *M. Zalalutdinov, F.A. Bulat,* Global Strategies Group, *B.H. Houston*, Naval Research Laboratory

We used functionalized CMOS integrated Nanoelectromechanical (NEM) resonators to selectively detect specific families of analyte. Unfunctionalized resonators have femtogram sensitivity in air, but have little selectivity. To address this problem, our resonators have been functionalized with adsorbate groups (e.g. perfluoroalkane and hexafluoroisocarbonol). These groups were bound to the surface using a spatially selective process using UV hydrosilation reactions. This process allows for the functionalization of the resonator without functionalizing the whole surface, leading to increased sensitivity. These functionalized resonators showed enhanced selectivity towards target molecules. For example, the hexafluoroisocarbonol group showed selectivity towards nitrobenzene but not towards cyclohexane or water. The operation of these devices in air, functionalization methods, and limits of detection will be discussed. This work was supported by the Office of Naval Research.

9:00am **MN-ThM4 Performance of Nanomechanical Mass Sensors Containing Nanofluidic Channels**, ***R.A. Barton***, *R.B. Ilic, S.S. Verbridge, B.R. Cipriany, J.M. Parpia, H.G. Craighead*, Cornell University

Nanomechanical resonators operating in vacuum are capable of detecting and weighing single biomolecules, but their poor performance in liquid, a consequence of strong viscous damping, hinders many biological applications. One approach that has been demonstrated to improve the performance of resonant MEMS operating in contact with liquid, encapsulating the liquid within the resonator, had until this work not been extended to devices with effective mass smaller than ~100 ng. Here, we show that the practice of confining liquid within a resonator improves the performance of NEMS with mass as small as 100 pg. We optically actuate and detect the motion of doubly clamped beams containing fluidic channels with height 100 nm, which show quality factors as high as 800 when filled with fluid. We use these devices to measure fluid density, demonstrating a mass responsivity of 100 Hz/fg and a noise equivalent mass of 2 fg. We also demonstrate that the quality factor of the fluid-filled resonators is limited by the fluid, and discuss the physical mechanisms causing the enhanced dissipation. Our analysis suggests methods of improving the mass resolution of fluid-filled resonators and demonstrates their promise for novel biological applications.

9:20am **MN-ThM5 Fabrication of Integrated Nanomagnets Overhanging Batch-Fabricated Attonewton-Sensitivity Cantilevers**, ***J.G. Longenecker***, *S.A. Hickman, E.W. Moore, S.G. Lee, S.J. Wright,* Cornell University, *L.E. Harrell,* United States Military Academy, *J.A. Marohn*, Cornell University

Mechanical detection of magnetic resonance opens up exciting possibilities for characterizing soft materials and biomolecules with elemental specificity at nanometer-scale, and potentially atomic-scale, resolution. Achieving atomic-scale resolution requires using cantilevers with a low minimum detectable force at small tip-sample separations and fabricating magnetic tips with only a few nanometers of damage at the leading edge. We address these challenges by 1) fabricating cantilevers with overhanging magnetic tips, 2) protecting the nanomagnet leading edge by atomic layer deposited (ALD) alumina, and 3) characterizing the extent and chemical mechanism of damage by nanometer-resolution electron energy loss spectroscopy (EELS).

After determining by EELS analysis that the nickel magnet leading edge incurred substantial damage during processing, we introduced tantalum and ALD alumina interdiffusion barriers into our forty-two step fabrication process. We demonstrate that these modifications have significantly reduced the damage layer thicknesses. The nanomagnet grain structure, point-by-point relative atomic concentrations at the leading edge, and magnetization are determined by high-resolution transmission electron microscopy (TEM), EELS, and frequency-shift cantilever magnetometry, respectively. We will also detail ongoing work to reduce the number of processing steps after magnet deposition, which could greatly improve magnet yield and quality. Our findings suggest that fabricating a cantilever suitable for single proton detection, while a materials processing challenge, should be possible.

9:40am **MN-ThM6 Fabrication and Characterization Ultra-Sensitive, Nickel-Tipped Silicon Cantilevers for Magnetic Resonance Force Microscopy**, ***S.A. Hickman***, *E.W. Moore, S.G. Lee, S.J. Wright,* Cornell University, *L.E. Harrell,* United States Military Academy, *J.A. Marohn*, Cornell University

Magnetic Resonance Force Microscopy is a technique which combines the elemental discrimination and three-dimensional imaging of magnetic resonance with the spatial resolution of scanned probe microscopy. Key to this technique is attonewton-sensitivity mechanical oscillators with magnetic particles at the tip.

The aim of this work was to create silicon cantilevers with nickel magnets which extended past the tip of the cantilever body - a design conceived to minimize surface-induced force noise.

The fabrication challenges of this design, including alignment across multiple lithographic modes and silicide prevention, will be covered. As well, characterization data of successfully produced devices will be presented.

10:40am **MN-ThM9 Parametric Excitation of Large Amplitude Out-of-Plane Vibrations of Micro Beams By Fringing Electrostatic Fields**, ***S.L. Krylov***, Tel Aviv University, Israel, *N. Molinazzi*, Medica Group, Italy, *T. Shmilovich, U. Pomerantz, S. Lulinsky*, Tel Aviv University, Israel

We report on an approach for efficient parametric excitation of large amplitude flexural out-of-plane vibrations of cantilever and double-clamped micro beams and present results of theoretical and experimental study of the suggested principle. An actuating electrode is located symmetrically at the two sides of the beam and is fabricated from the same layer of the wafer. The beam is free to deflect in the out-of-plane direction, whereas its stiffness in the lateral in-plane direction is significantly higher. The distributed electrostatic force, which is zero in the initial configuration, is engendered by the asymmetry of the fringing fields in the deformed state and acts in the direction opposite to the deflection.

The force can be effectively viewed as a reaction of an elastic foundation, which increases the stiffness of the system. The time-varying voltage applied to the electrode results in the modulation of this electrostatic stiffness and consequently in the parametric excitation of the structure. The device is distinguished by a simple single-layer architecture and may exhibit large vibrational amplitudes, which are not limited by the pull-in instability common in close-gap actuators. In contrast to previously reported devices excited by the fringing fields, the force considered here is of distributed character. The reduced order model was built using the Galerkin decomposition with undamped linear modes as base functions and the resulting system of nonlinear differential equations was solved numerically. The electrostatic forces were approximated by means of fitting the results of three-dimensional numerical solution for the electric fields. The devices fabricated from a silicon on insulator (SOI) substrate using deep reactive ion etching (DRIE) based process combined with the critically timed etching were operated in ambient air conditions and the responses were registered by means of Laser Doppler Vibrometry. The experimental resonant curves were consistent with those predicted by the model. Theoretical and preliminary experimental results illustrated the feasibility of the suggested approach.

11:00am **MN-ThM10 The Effect of Temperature on Etch Rate and Surface Roughness for Si Etched with Vapor Phase XeF_2**, *Z.C. Leseman*, ***J. Butner***, University of New Mexico

In this work we present results from a pulsed etching system with XeF2 for an expanded temperature range while at the same time determining the roughness of the substrate left behind. The experimental apparatus used for the work presented in this paper is capable of temperature ranges from approximately 100 K to 800 K. Data was taken at a constant etching pressure (1 Torr) so the effect of temperature on etch rate and roughness could be studied. Etch rates were determined by varying the duration of the pulse and surface roughness was characterized using an AFM.

11:20am **MN-ThM11 Fabrication of High Density Single Crystal Silicon Nanowires for Ensemble Measurements**, ***D.A. Czaplewski***, *L.E. Ocola*, *M.V. Holt*, Argonne National Laboratory

Silicon nanowires have shown promise in applications such as photovoltaic cells, lithium storage for batteries, transducers, sensors, and many more. Single crystal silicon nanowires (SCSN) have been used to study materials and electrical properties of Si as the nanowires have been scaled down towards several nanometers. These experiments have been designed to test the classical predictions of materials behavior as the assumption of continuum mechanics starts to break down. Due to the small sizes of SCSNs, measurements of materials properties have been inconsistent due to the variation in dimensions and fabrication methods from wire to wire. Typically, SCSNs are fabricated at very low densities, which make measurements of ensembles very difficult. Here we present two top-down processes to create SCSNs at relative densities approaching 50% of a continuous film with dimensions as small as 30 nm. Both fabrication processes start with e-beam lithography. In the first fabrication process, a positive e-beam resist is patterned and developed. The resist is exposed to a second dose of electrons to increase the etch selectivity during reactive ion etching. The silicon structures are reactive ion etched in a CHF3-O_2 plasma chemistry to define the structures. In the second approach, a negative e-beam resist, hydrogen silsesquioxane (HSQ), is patterned and developed on a thin thermally-cured HSQ layer. After development, the pattern is transferred into the silicon via a reactive ion etch using a Chlorine chemistry followed by a HBr-O_2 chemistry. After the wires are defined, they are subsequently released in a dilute HF-DI water mixture and then dried using a super critical CO_2 drying technique. The released structures are being used for studies of coupled mechanical oscillators and to study materials and electrical properties in ensembles of 1-D wires.

11:40am **MN-ThM12 Analysis of a Dip-Solder Process for Self Assembly**, ***M.R. Rao***, *J. Lusth*, *S.L. Burkett*, University of Alabama

Dip-soldering is a crucial step in forming certain self-assembled metal structures. However, this particular use of dip-soldering is not well described in the literature. The goal of this work is to characterize the thickness and roughness of solder layers deposited by dipping metallic films into solder melt over a range of temperatures. Control of the solder thickness and roughness will improve the yield of structures whose self-assembly is driven by surface area minimization during solder reflow. Film thickness and overall film roughness for four solder alloys, each with different melting points, were measured on unpatterned and patterned copper films. Additionally, two variations in flux treatment were investigated: flux maintained at room temperature and flux preheated to 98 °C. Findings include the determination of critical temperatures, particular to each alloy, above which the roughness and thickness of the deposited solder dramatically decreases. Preheating the flux improves the nature of the deposition below these critical points. Above the critical points, thickness and roughness of the solder vary little and preheating the flux does not provide significant improvements. This study provides insight into designing a process flow that optimizes the folding characteristics of self-assembled metal polyhedra by controlling the volume and quality of the solder layer.

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