## MEMS and NEMS Group
## Room: 105 - Session MN-ThA

## Multi-scale Interactions of Materials and Fabrication at the Micro- and Nano-scale
**Moderator:** A.V. Sumant, Center for Nanoscale Materials, Argonne National Laboratory

2:00pm **MN-ThA1 Heterogeneous Microsystem Integration with Self-Assembly**, ***K. Bohringer***, University of Washington **INVITED**

Self-assembly is the spontaneous and reversible organization of components into ordered structures, representing an alternative to the conventional manufacture of systems made of components from milli to nano scales. First commercial applications of self-assembly have appeared in recent years, for example in the fabrication of radio frequency identification (RFID) tags.

However, the full impact of this new approach towards hetero system integration will only be realized once self-assembly can be programmed on demand. This presentation gives an overview of several projects that aim at programmable self-assembly. A key concept is the ³programmable surface² an interface whose properties can be controlled with high spatial and temporal resolution. Several crucial topics are discussed: real time control of interfacial properties; optimization of binding site designs; and algorithms for the modeling and control of self-assembly. Promising novel manufacturing methods are emerging that combine the precision and reproducibility of semiconductor fabrication with the scalability and parallelism of stochastic self-assembly and with the specificity and programmability of biochemical processes.

2:40pm **MN-ThA3 A Study of Solder Bridging for the Purpose of Assembling Three Dimensional Structures**, ***M.R. Rao***, *J.C. Lusth, S.L. Burkett*, The University of Alabama

Recently, dip soldering has been used as a mechanism for driving the assembly of three-dimensional (3D), microscale structures. Solder is deposited on adjacent metallic faces of planar polyhedral patterns, bridging the small gaps between individual faces. When all but one face of a polyhedral pattern are freed from the substrate and solder is reheated to a

liquid state (reflow), the free faces of the pattern fold upwards, out of the plane, to form the desired polyhedron. The wetting of solder with regards to coverage of metallic faces has been described previously, but the lateral bridging between the metal faces remains relatively unexplored. The goal of this work is to characterize the parameters influencing the bridging and folding process for two different ways of dip-soldering: face and edge soldering. Face soldering refers to the complete wetting of metal faces while edge soldering refers to selectively applying solder on the edges of a face that come in contact with other faces when folded. Our work explores bridging yield for various gap sizes and face thicknesses for eight different polyhedral patterns. Experiments show that the thickness and gap size strongly influence successful bridging. Experiments also show that improved control over the bridging process increases the yield of folded structures. In particular, gap size is positively correlated to face thickness for successful folding. Moreover, face soldering results in higher

yields than edge soldering for all patterns.

3:00pm **MN-ThA4 Fabricating Arrays of Graphene Nanomechanical Resonators with High, Size-Dependent Quality Factors**, ***R.A. Barton***, *A.M. van der Zande, R.B. Ilic, C.S. Ruiz-Vargas, J.S. Alden, W.S. Whitney, J. Park, P.L. McEuen, J.M. Parpia, H.G. Craighead*, Cornell University

Graphene's unparalleled strength, stiffness, and low mass per unit area make it an ideal material for nanoelectromechanical systems (NEMS), but graphene resonators have been challenging to fabricate in large numbers and have exhibited poor quality factor. Here, we present simple methods of fabricating large arrays of graphene resonators from CVD-grown graphene and discuss their properties. We focus on circular graphene resonators with diameter of up to 30 microns, for which we observe highly reproducible resonance frequencies and mode shapes, as well as a striking improvement in the membrane quality factor with increasing size. The largest graphene resonators display quality factors as high as 2400 ± 300, about an order of magnitude greater than previously observed quality factors for monolayer graphene. These measurements shed light on the mechanisms behind dissipation in monolayer graphene resonators and demonstrate that the quality factor of graphene resonators relative to their thickness is high compared to nanomechanical resonators demonstrated to date. We conclude by providing an outlook for graphene NEMS and their applications.

3:40pm **MN-ThA6 Modal Dependence of Dissipation in Ultra Thin Silicon Nitride Drum Resonators**, ***V.P. Adiga***, *R.B. Ilic, R.A. Barton,* Cornell University, *I. Wilson-Rae,* Technische Universität München, Germany, *H.G. Craighead, J.M. Parpia*, Cornell University

We have fabricated up to 1 mm diameter high tensile stress (1.2 GPa) circular SiN membranes. Stoichiometric amorphous high tensile stress SiN is a useful material for nanomechanical devices and resonators made from it have shown extremely high $Q$ (> 1,000,000) at room temperature.[1] We used both optical and electron beam lithography to define circular structures and measured their resonant frequency and Q using optical interferometric detection methods. The measured mechanical $Q$ shows a strong modal dependence, indicating the influence of clamping losses. Azimuthal harmonics of circular resonators with diameter s> 200 mm show an exponential drop in dissipation within an individual modal family (n = 1,2,3.., m) apparently due to the destructive interference between the waves radiated by adjacent sections of periphery.[2] However, still higher order modes of large resonators and modes of smaller resonators are strongly influenced by a characteristic $fQ$ limit of $2 \times 10^{13}$ possibly indicating the presence of intrinsic dissipation in the high frequency limit. These findings pave the way for identifying optimum high Q modes of stressed oscillators for applications in mass sensing and fundamental research in optomechanics.

1) D. Southworth et al, PRL, 2009

2) I. Wilson-Rae et al PRL, 2011

4:00pm **MN-ThA7 Stress-based Flammable Gas Sensing with Nanocoated Resonant Microbridge at Critically-Buckled State**, ***D.J. Joe***, *Y. Linzon, V.P. Adiga, R.A. Barton, M. Kim, B. Ilic,* Cornell University, *S. Krylov,* Tel Aviv University, Israel, *J.M. Parpia, H.G. Craighead*, Cornell University

In this work we demonstrate robust flammable gas sensing using stress-based resonant microelectromechanical systems (MEMS) bridges at ambient pressure and temperature. In contrast to previously reported works, which were based on either measuring a static deflection or changes in frequency due to added mass, we report a method of tracking shifts in resonant frequency of microbridges in real time due to alteration of stress from swelling of a reactive polymer coating near the Euler buckling configuration. Experimental results clearly demonstrate that the suggested approach is efficient for selectively sensing trace vapor. We show projected vapor content sensitivity as low as ~13.4 ppm for ethanol vapor in low concentration regime, and demonstrate actualized proven sensitivity of less than 1 part per thousand, with a few seconds response time for the functionalized microbridge.

4:20pm **MN-ThA8 Rapid Serial Prototyping of Magnet-Tipped Attonewton-Sensitivity Cantilevers**, ***J.G. Longenecker***, *E.W. Moore, J.A. Marohn*, Cornell University

There is a critical need for a technique capable of non-invasive high resolution imaging of single copies of delicate biomolecules and as-fabricated semiconductor and spintronics devices. Magnetic resonance force microscopy (MRFM) is a non-invasive, three-dimensional imaging technique that employs attonewton-sensitivity cantilevers to mechanically detect electron spin resonance [1] and nuclear magnetic resonance [2]. The recent demonstration of 4 nm resolution imaging of a virus using MRFM establishes that the technique can achieve single-particle imaging with resolution competitive with cryo-electron microscopy [2]. The sample-on-cantilever geometry used in the experiment of Ref. 2, however, requires small, robust samples and is inapplicable to as-fabricated devices. We propose to image semiconductor devices by instead affixing to the cantilever the submicron magnetic particle required to achieve high spin sensitivity and spatial resolution. To minimize surface dissipation and achieve high signal to noise, the magnet must overhang the leading edge of the cantilever [3]. We recently demonstrated an approach to fabricating cantilevers with such integrated overhanging nanomagnets that achieves high yield [4]. Moreover, the novel tip fabrication method enabled the prototyping of new tip designs in less than sixteen hours of processing time [4], compared to the more than two weeks of processing time required for the best previous method [3].

Here we report harnessing this rapid prototyping technique to fabricate and characterize nickel and cobalt-iron-boron (CoFeB) nanorods. All nanomagnets are defined using electron beam lithography. The nickel nanorods are evaporated followed by liftoff, whereas the CoFeB nanorods are deposited by conformal sputtering and patterned by ion milling. The magnetic properties of the nanomagnets are determined using frequencyshift cantilever magnetometry and superconducting quantum interference device measurements. The elemental composition – paying particular attention to the extent of surface damage – is determined by scanning transmission electron spectroscopy and electron energy loss spectroscopy. We will detail work to develop a protocol for improved encasement of nanorods overhanging the cantilever leading edge to protect against damage, as well as our progress in implementing the nanomagnet-tipped cantilevers in MRFM experiments to rapidly detect single electron spins.


[1] EW Moore *et al.*, *Proc. Natl. Acad. Sci.* **106**(52), 22251 (2009).

[2] C Degen *et al.*, *Proc. Natl. Acad. Sci.* **106**(5), 1313 (2009).

[3] SA Hickman *et al.*, *ACS Nano* **4**(12), 7141 (2010).

[4] JG Longenecker *et al.*, *J. Vac. Sci. Technol. B*, in press.


4:40pm **MN-ThA9 Microfabrication of On-Chip Electrodeposited CoNiP Micromagnets and Integration into MEMS Sensors**, ***D. Schreiber***, *O. Berkh, S. Krylov, Y. Shacham-Diamand*, Tel Aviv University, Israel

Motion sensing of microelectromechanical systems (MEMS) devices is often a problem due to limited available chip footprint. On-chip thin film hard magnetic materials, when used as elements of integrated induced current displacement sensors, can help significantly simplify the designs and reduce device footprint due to the relatively high field density attainable. Device element spacing can also be increased thereby reducing fabrication tolerance requirements and improving robustness.

Electrochemical deposition is an attractive method for batch processing of magnetic films in patterned structures. Electroplating is a relatively simple process with a wide variability and control of film thickness and good scalability and compatibility with most of the MEMS microfabrication processes. Additionally, electrochemical deposition allows for the controlling of magnetic film anisotropy a key factor for the design of devices that operate in-plane or out-of-plane. Interest has been shown in CoNiP thin films for use in a number of MEMS applications however, the issues of integration were not addressed.

The integration of CoNiP magnetic films into MEMS sensors was studied. Through-mask electrodeposition of 1-2 µm thick magnetic films from concentrated ammonium chloride electrolyte was carried out at current densities of 30-150 mA/cm2 using both direct current and pulse plating modes. The effects of current density, seed layer, passivation layer, pattern size and geometry on magnetic properties and feature-scale thickness distribution were investigated. Geometries included various arrays of micron scale stripes and dots, and large 1-4 mm2 square areas. Feature scale profiles and magnetic properties of the films are influenced by current density as well as by feature size and geometry. Magnetic properties of CoNiP films after post-electrodeposition processing remain in the range suitable for sensor operation and are therefore shown to be suitable for integration in MEMS sensor.

Micropatterned CoNiP magnetic thin films have been integrated into silicon-on-insulator (SOI) MEMS devices. The patterned micromagnets – large square areas, stripes and dots – were characterized for feature-scale thickness distribution in relation to pattern geometry and current density, the effects on magnetic properties due to post-electrodeposition processing and their compatibility with standard MEMS process chemicals. Thickness distribution is strongly correlated with pattern geometry and current density. Magnetic properties remain in a range suitable for integration into MEMS devices following post-electrodeposition fabrication processes such as lithography, sputtering and etching.

5:00pm **MN-ThA10 Towards an Integrated Nano-optomechanical Platform for Molecular Sensing and Magnetometry**, ***W.K. Hiebert***, *Z. Diao, J.N. Westwood, V.T.K. Sauer, M.R. Freeman*, National Institute for Nanotechnology (NRC Canada) and University of Alberta, Canada

Nanoelectromechanical systems (NEMS) have exquisite potential in fields ranging from quantum measurement to ultrasensitive mass sensing. Signal transduction has remained an important challenge for NEMS where applications demand fast, parallel, sensitive, and low-noise drive and detection of motion in ever smaller and faster devices. The burgeoning field of nanooptomechanical systems (NOMS) has offered a promising solution to this challenge in the form of unprecedented displacement sensitivity with almost unlimited bandwidth. Nanophotonic circuits provide strong local concentration of optical forces and optical phase changes interacting with embedded NEMS devices. The combination is fully integratable with modern opto-electronic and semiconductor technology paving the way to large-scale-integrated lab-on-a-chip NEMS sensing arrays.

We will present our preliminary efforts in building an integrated NOMS platform for molecular sensing and for magnetometry applications. The results include a novel measurement geometry that allows accessing nanophotonic NOMS chips in vacuum via free-space focusing onto grating couplers. The external-to-vacuum optics arrangement gives independent control over the position and input/output angles of both the input and output laser beams. This geometry allows us to directly compare photonic readout of NEMS motions with conventional free-space Fabry-Perot interferometry. Finally, we will update our progress in 3D integration of NEMS and photonics.

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