MEMS and NEMS
Room: 211A - Session MN+MG-TuM

Multiscale Phenomena & Interactions in Micro- and Nano-Systems (8:00-10:00 am) & Optical MEMS/NEMS, Photonics, and Quantum Nanosystems (11:00 am-12:20 pm)

Moderator: Robert Davis, Brigham Young University, Robert Ilic, National Institute of Standards and Technology (NIST), Meredith Metzler, University of Pennsylvania

8:00am **MN+MG-TuM1 Microengineering for Mechanobiology**, ***Beth L. Pruitt***, Stanford University **INVITED**

Living organisms generate and respond to mechanical forces and these forces are sensed and created by specialized cells in the body. Force generation and sensing, or more broadly the mechanobiology coupling tissue (cell) mechanics and biology, are essential in normal development, wound healing, and tissue homeostasis. Our mechanical senses of hearing and touch allow us to navigate our environment and interact with one another, yet they remain the least understood of our perceptive senses. Basic life sustaining functions such as breathing, circulation, and digestion are driven autonomously by coordinated contraction of specialized muscle cells, yet how these functions incorporate active feedback via force sensing at the cellular level is an area of active study. Meanwhile, a variety of specialized stretch activated receptors and mechanically mediated biochemical signaling pathways have been identified in recent years. Importantly, defects in proteins of these mechanically mediated pathways and receptors have been implicated in disease states spanning cardiovascular disease, cancer growth and metastasis, neuropathy, and deafness. Thus, understanding the mechanical basis of homeostasis (health) and defective cell renewal function (disease) increasingly requires us to consider the role of mechanics. To study how cells and tissues integrate mechanical signals, we and others have developed specialized cell cultures systems and micromachined tools to stimulate and measure forces and displacements at the scale of proteins and cells. A key feature of such experiments is the ability to observe cell outputs such as morphological changes, protein expression, electrophysiological signaling, force generation and transcriptional activity in response to mechanical stimuli.

8:40am **MN+MG-TuM3 Introducing Students to MEMS: A Practical Process for the Fabrication and Testing of Piezoresistive Cantilevers**, ***Frederic Loizeau***, *E. Sadeghipour, T. Larsen, J.Y. Sim, C. Roozeboom, E. Mazzochette, B.L. Pruitt*, Stanford University

We present a laboratory course to introduce students to Micro-Electro-Mechanical Systems (MEMS) through fabrication and characterization of piezoresistive cantilevers. We developed a process flow comprised of only three photolithography steps to minimize time spent by the students in the cleanroom and workload of the teaching team. Students performed hands-on work on over 80% of the fabrication process and thus earned qualification status to operate the standard tools in our cleanroom. The course included practical experience with signal conditioning, noise, and sensitivity measurements. The lab component spanned six sessions of 4.5 hours each and is ideal for integration in a lecture course or a two-week standalone mini-course.

The hands-on laboratory component was paired with lectures covering cleanliness, process selection, and device design and characterization. Six lab sessions of 4.5 hours each covered the fabrication and characterization of piezoresistive cantilevers. In each session, teams of five students learned fundamental MEMS processes and equipment use while fabricating pre-designed devices. Weekly homework reinforced design, process, and testing concepts, e.g., predicting device performance, completing lithography steps, or building a measurement circuit. Device fabrication was completed in the first four lab sessions. Modest process support was provided outside of class by the teaching team for batch processes such as wafer preparation, metallization, and final HF release. The yield of the fabrication process was >90%. Each team built their own Wheatstone bridge and amplifier circuit to readout the piezoresistor signal prior to lab sessions 5 and 6 for device characterization. In session 5 they learned to use a dynamic signal analyzer to measure the Hooge and Johnson noise. In session 6, the students measured the power spectral density of cantilever tip deflection due to thermomechanical noise using a laser-Doppler vibrometer (LDV). From these measurements, they estimated the spring constants, resonant frequencies and quality factors of the cantilevers. Using a piezoelectric shaker and the LDV, students simultaneously measured the cantilever deflection and the piezoresistor bridge output and then used this to calculate cantilever sensitivity and resolution. Finally, experimental measurements were compared with theoretical predictions.

9:00am **MN+MG-TuM4 Deflection Control of an Electroactive Polymer Bimorph Actuator by Carrier Frequency Modulation**, ***Leeya Engel***, Tel Aviv University, Israel, *K. Van Volkinburg*, University of California Irvine, *Y. Shacham-Diamand*, Tel Aviv University, Israel, *G.N. Washington*, University of California Irvine, *S. Krylov*, Tel Aviv University, Israel

In microelectromechanical systems (MEMS), actuator deflections are typically controlled by varying the voltage used to drive the active element. In this work, we use the frequency sensitivity of the permittivity of relaxor ferroelectric polymer poly(vinylidene fluoride-trifluoroethylene chlorotrifluoroethylene (P(VDF-TrFE-CTFE)) as an additional parameter for controlling the deflections of an electroactive polymer bimorph actuator.

The amplitude of the tip deflection of the electroactive polymer bimorph actuator, whose active layer comprised a thin film of P(VDF-TrFE-CFE), increased with the voltage applied at constant frequency, as expected. When the peak-to-peak displacements of the beam were plotted as a function of frequency at constant peak-to-peak voltage, a nonlinear decrease in tip deflection with increasing frequency was observed, independent of the resonance of the device. Electrical characterization of the material shows that the real component of the permittivity is ~55.5 at 100 Hz, but at radio frequencies, it decreases to 4. Dielectric losses are high at frequencies on the order of kHz–GHz with a coefficient of loss above 60% around MHz frequencies. Thus, the decrease in magnitude of electromechanical displacement with frequency can be attributed to the decrease in the permittivity-dependent electric field related electrostrictive coefficient with frequency. Deflections were recorded using both a laser Doppler vibrometer (LDV) and by interpreting the potential difference that formed across an integrated layer of piezoelectric polymer PVDF during actuation. In addition to adding mechanical sensing capabilities to the device, the PVDF layer also functioned as the passive layer of the bimorph structure.

This work directly demonstrates the dependence of the electromechanical behavior of an electroactive polymer actuator on the dielectric properties of P(VDF–TrFE–CFE) and our ability to exploit that dependence for an additional control parameter of the device. Frequency modulation of polymer beam deflections and integration of sensing capabilities can benefit the developing field of polymer microactuators, in applications such as "smart" prosthetics and implants, targeted drug delivery, tools for less invasive surgery, microfluidics, and on-chip cooling.

9:20am **MN+MG-TuM5 Solder Based Self-Assembly Method For 3D Integration Using Poly-Acrylic Acid**, ***Connor Smith***, *Y. Feng, S.L. Burkett*, The University of Alabama

The use of Solder Based Self-Assembly (SBSA) in fabricating 3D structures on the microscopic scale is a process with numerous potential applications. This method involves creating copper plated 2D flat patterns of various shapes on a silicon substrate. Then, upon dip soldering these patterns and re-flowing the solder with hydrochloric acid, surface tension pulls up on these shapes to form a 3D structure. However, the use of a SiO2 sacrificial layer in performing this method results in the need for hydrofluoric acid (HF) during the etching phases, which has many dangerous hazards associated with it. The goal of this research is to develop a new process in which a water-soluble polymer, poly-acrylic acid (PAA), may be used as a sacrificial layer instead of SiO2--thus making the micro-fabrication process much safer. By working through the original SBSA method, and overcoming the various obstacles created by needing to protect the PAA from being exposed to water earlier than desired, an effective procedure has been developed. Through completing this project, future attempts to fabricate microscopic 3D structures using the SBSA method will be safer and less prone to dangerous HF exposure. Furthermore, removing HF etching from the procedure will reduce the time required to move through the process as a whole, thus increasing its efficiency.

11:00am **MN+MG-TuM10 Mechanics and Spins in Diamond**, *A. Bleszynski Jayich*, ***Donghun Lee***, University of California at Santa Barbara **INVITED**

Single crystal diamond mechanical resonators have recently emerged as a promising platform for hybrid quantum systems comprising spins and phonons. Diamond mechanical resonators exhibit exceptionally high quality factors[1] and diamond plays host to a highly coherent spin system: the nitrogen vacancy (NV) center. The NV center is an atom-sized defect in diamond that is a remarkably good sensor of magnetic, electric, thermal, and strain fields on the nanoscale. Because of its strain sensitivity, the NV can be easily coupled to a mechanical degree of freedom. We have recently characterized the sensitivity of the NV's ground state spin to strain by controllably applying dynamical strain to NV centers embedded inside high quality factor diamond mechanical resonators[2]. We have also recently demonstrated strain-mediated coupling to the optical transitions of single NV centers. Through strain coupling, we show that coherent mechanical control of individual spins in diamond is possible. These results are encouraging for proposals to use such a spin-mechanical platform for spin-squeezing, phonon-mediated spin-spin interactions[3], and phonon cooling of macroscopic mechanical resonators[4]. We discuss the necessary steps needed to reach these goals and current progress including improvements in diamond fabrication, NV formation, and readout techniques.

1. Ovartchaiyapong, P., Pascal, L. M. A., Myers, B. A., Lauria, P. & Bleszynski-Jayich, A. C. High quality factor single-crystal diamond mechanical resonators. *Applied Physics Letters* **101,** 163505 (2012).

2. Ovartchaiyapong, P., Lee, K. W., Myers, B. A. & Jayich, A. C. B. Dynamic strain-mediated coupling of a single diamond spin to a mechanical resonator. *Nat Comms* **5,** (2014).

3. Bennett, S. *et al*. Phonon-Induced Spin-Spin Interactions in Diamond Nanostructures: Application to Spin Squeezing. *Physical review letters* **110,** 156402 (2013).

4. Kepesidis, K. V., Bennett, S. D., Portolan, S., Lukin, M. D. & Rabl, P. Phonon cooling and lasing with nitrogen-vacancy centers in diamond. *Physical Review B* **88,** 064105 (2013).

11:40am **MN+MG-TuM12 Nano-Optomechanical Fin Resonators Designed for Sensing in Liquid Environments**, ***Jocelyn Westwood-Bachman***, *W.K. Hiebert*, University of Alberta and The National Institute for Nanotechnology, Canada

Nanomechanical systems are well known for their mass sensitivity, and are often used as mass sensors [1]. However, nanomechanical sensors tend to operate poorly in liquid environments due to viscous damping by the surrounding fluid. This drawback is particularly challenging for biological and related clinical sensing applications, where it is ideal to detect molecules within a liquid environment [2]. Here, we show the design of a fin-like nanomechanical resonator specifically for use in liquid environments. This design features a cantilever pointing out of the plane of the silicon device layer. This is in contrast to typical cantilevers that are in the silicon plane. The length of the cantilever is determined by the thickness of the silicon layer used, and the thickness of the resonator is designed to achieve specific resonance frequencies. The motion of these fin-like resonators is read out by an adjacent photonic microring resonator [3]. This microring resonator also provides an avenue for optical actuation of the fin resonator. The benefit of this design over existing designs is twofold. Firstly, our integrated photonics detection and actuation scheme provides higher displacement sensitivity than interferometric techniques [4]. Secondly, the fin is designed to operate at high frequencies (above 500 MHz) but can still have comparable surface area to nanoscale cantilevers as the width can be made arbitrarily large. This increases the sensing area while reducing the overall dissipation [5]. We will illustrate our design methodology and show the first generation of devices. As the as-fabricated devices have larger-than-desired feature sizes due to the limitations of photolithography, we will also discuss potential methods of tuning the device size post-fabrication. Specifically, we explore the possibility of trimming the fin resonator using Ga and He ion milling.

[1] M S. Hanay *et al*, Nature Nanotech. **7**, 602 (2012)

[2] J. Tamayo *et al*, Chem. Soc. Rev. **42**, 1287 (2013)

[3] V. T. K. Sauer *et al*, Nanotechnology, **25**, 055202 (2014)

[4] Z. Diao *et al*, Appl. Phys. Expr. **6**, 065202 (2013)

[5] K. L. Ekinci *et al*, Lab Chip **10**, 3013 (2010)

12:00pm **MN+MG-TuM13 Directed Magnetic Optical Resonator Microballoons for Particle Imaging Manometry in 3D Environment**, ***Niladri Banerjee***, University of Utah

Measurement of velocity and pressure field in microfluidic 3D environment is vital in complete characterization of any fluid flow for capillary networks, flow-based separators and microchips for different biological applications. Particle imaging velocimetry though is the gold standard for measuring in-flow velocity, there has been no equivalent technique to perform pressure mapping. Recently hollow spherical micro-particles were fabricated to perform pressure measurement inside microfluidic channels. But lack of control on the trajectory of these particles inside micro-channels resulted in the ability to perform on-the-fly in-flow pressure mapping by spectroscopic method at any arbitrary location.

In this paper, we present the design, fabrication and testing of engineered magnetic micro-balloon pressure sensor particles. These directed particles, when injected into the flow-stream of any microchip, can be localized at any specific location of interest for dynamic pressure measurement. Each particle consists of a vacuum sealed spherical cavity along with a gold-nickel-gold magnetic tail attached to a polymeric support stem. The hollow cavity sealed by a thin polymeric shell, behaving as a Fabry-Perot interferometer, changes in size due to external pressure variation, which is detected by spectroscopic technique. Moreover the magnetic tail enables temporary immobilization of these particles at any position in the channel by the application of external magnetic field. The fabrication of these particles is based on buried sphere technology (BST). The fabrication starts with patterning of circular holes on thermally oxidized silicon. A trench 10-15 µm deep into the substrate is etched by DRIE. Next we oxidize the sample to grow 100 nm of oxide in order to protect the sidewalls of the trench. On selectively etching oxide from trench-bottom wall, spherical cavity of 6 µm radius is etched by XeF_2. Then the spherical cavity is smoothened and hole necked down by subsequent oxidation and poly-deposition process steps. Al_2O_3 is then deposited by ALD forming a gas leakage-stop layer followed by parylene-C, to form the micro-balloon wall. Then a gold-nickel-gold (0.2-0.5-0.2 µm) sandwich is sputtered and encapsulated using another 1 µm layer of parylene-C. Real-time in-flow pressure measurement using 0.1T permanent magnet is performed at 8 magnet-specified locations with particles dispersed in IPA inside a serpentine test-chip. Spectral reflectance measurement indicates a pressure sensitivity of 37nm/psi. The paper will discuss the fabrication and test of the magnetic particles in detail with additional internal pressure measurement examples.

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