MEMS and NEMS Group
Room A210 - Session MN-MoM

MEMS, BioMEMS, and MEMS for Energy: Processes, Materials, and Devices I

Moderators: B. Robert Ilic, National Institute for Science and Technology (NIST), Zenghui Wang, Case Western Reserve University

8:20am **MN-MoM-1 Piezoelectrics Meets Photonics – Acousto-Optic Microsystems**, ***Gianluca Piazza,*** Carnegie Mellon University **INVITED**

Advancements in thin film piezoelectric technology and the ability to define and pattern acousto-electric devices that support micron and sub-micron acoustic wavelengths have opened up new opportunities to integrate acoustic functionalities into photonic circuits. The field of opto-mechanics has grown from fundamental physics investigation into device applications. Acousto-optic interactions are equally interesting and will have immediate applications in facilitating miniaturization and power efficiency for radio/microwave communication, inertial sensing, photonic signal processing, optical phased arrays, and new displays for virtual/augmented/mixed reality.

In this talk, I will present preliminary work towards the demonstration of integrated acousto-optic microsystems that take advantage of the unique properties of micro-patterned piezoelectric thin films such as sputtered aluminum nitride and single crystalline lithium niobate. The talk will focus on a couple of microsystem examples and will detail the design, fabrication and experimental demonstration of high frequency acousto-optic devices that are used for the synthesis of integrated RF oscillators or high precision and high stability gyroscope sensors.

9:00am **MN-MoM-3 On-chip Silicon Photonics Radiation Sensors**, ***Nikolai Klimov,*** *Z Ahmed, R Fitzgerald, L Cumberland, I Pazos, R Tosh,* National Institute of Standards and Technology (NIST)

The last few decades have witnessed an exponential growth in photonics, driven in part by improvements in micro-electronics fabrication techniques and by increasing adoption of photonics components by the telecommunications industry. As a result, a wide variety of photonics-based devices have been recently proposed and developed [1-4]. These photonic sensors are particularly valuable due to their micro-/nanoscale footprint, ultra-high sensitivity, low power consumption, and tolerance to harsh environmental variables. One potential application of photonic sensors is ionizing radiation dosimetry. At present, primary standards for absorbed dose are based on large (m^3) water calorimeters used to link the absorbed energy from a large uniform radiation beam to the temperature rise in a ~0.5-mm sized thermistor probe. The realization of this standard requires radiation-beam uniformity on the order of centimeters. On the other hand, rapidly evolving medical and industrial applications are demanding a deployable solution capable of detecting ionizing radiation on a millimeter to micrometer scale. To address industry demand, National Institute of Standards and Technology (NIST) has recently started a program to develop the next generation radiation dose primary standards. The new proposed standard, built on a nano-photonic chip, will leverage nano-photonics and frequency metrology to provide a field-deployable solution. Our radiation sensors are based on high-Q silicon photonic resonators such as ring resonators and photonic crystal cavities. We have recently demonstrated [5] that these sensors can withstand 1 MGy (1 Gy = 100 Rad) absorbed dose in ca. 1 MeV gamma- and electron-beam irradiations with negligible degradation to device performance. In this presentation we will give an overview of the NIST photonic dosimetry program and its most recent developments. We will explain design, nanofabrication, packaging and interrogation of our devices. We will also show our preliminary results on real-time photonic calorimetry measurements in on/off cycles of the electron beam provided by a Van de Graaff accelerator at nominal dose rate of kGy/s. Comparison of the device response with the output of finite-element modelling of heat transport and dose measurements obtained by co-irradiated alanine pellets (analyzed via EPR) will also be discussed.

[1] B. Guha et al., Opt. Lett. 37 (212) 2253–2255.

[2] Oates, L.W. Burgess, Anal. Chem. 84 (2012) 7713–7720.

[3] H. Xu, et al., Opt. Express. 22 (214) 3098–3104.

[4] N.N. Klimov, et al., Sensor ad Actuators A, 269 (2018) 308-312.

[5] Z. Ahmed, et al. , Sci. Rep. 8 (2018) 13007.

9:20am **MN-MoM-4 Synthesis and Characterization of Nanoscale 3 dimensional Plasmonic Architectures**, ***Grace Pakeltis,*** *E Mutunga,* University of Tennessee Knoxville*; Z Hu, D Masiello,* University of Washington*; J Idrobo,* Oak Ridge National Laboratory*; H Plank,* Graz University of Technology, Austria*; J Fowlkes,* Oak Ridge National Laboratory*; P Rack,* University of Tennessee Knoxville

New breakthroughs and better understanding in the underlying theory of plasmonics has led to an increased demand for advanced design, synthesis and device integration strategies for plasmonic nanomaterials. Three-dimensional plasmonic nanostructures have the ability to advance applications such as ultra-fast communication, high density memories, and sensing while enabling further investigation into plasmonic physical phenomena. In this study, we illustrate a nanoscale synthesis process which utilizes a hybrid of direct-write 3D nanoprinting and thin film deposition to fabricate complex, free-standing plasmonic nanostructures for the investigation of 3D plasmonics. Focused electron beam induced deposition is used to deposit non-plasmonic 3D scaffolds, which are subsequently isolated with a conformal SiO_2 layer and coated with a plasmonic materials, specifically Au, to create functional 3D plasmonic nanostructures. A variety of single and dimer structures were fabricated and low-loss electron energy loss spectroscopy was utilized to characterize their full plasmonic spectra with nanoscale resolution. Complementary electron discrete dipole approximation simulations were performed to elucidate the resultant consequent electric and magnetic field distributions. This work demonstrates the flexibility FEBID scaffolds offer for the advancement of new 3D devices for applications and fundamental studies of plasmonic nanomaterials.

9:40am **MN-MoM-5 2D Raman Imaging and Characterization of Surface Acoustic Waves on GaAs Substrates**, ***Brian Douglas Rummel,*** *G Heileman,* University of New Mexico*; M Henry,* Sandia National Laboratories*; S Han,* University of New Mexico

We have fabricated Surface Acoustic Wave (SAW) devices on a GaAs (110) substrate to demonstrate the capability of 2D Raman microscopy to image and characterize acoustic waves traveling on the surface of a piezoelectric substrate. SAW devices are typically utilized in sensors and rf filters, and developing a facile technique to image the transmitted signal would be useful in characterizing device operation and optimization. SAWs are generated using a two-port interdigital transducer (IDT) platform, modified to produce free surface standing waves. These standing waves provide a means to differentiate nodes and antinodes of the acoustic wave. The frequency of SAWs does not easily allow *in situ*, real-time imaging of the waves. However, we make use of Raman peak broadening that corresponds to an averaging of the peak shifts over the integration time of the spectrometer. We have derived an analytical model to fit the peak broadening and effectively calculate the maximum strain induced by the acoustic waves, thus allowing one to characterize the SAWs and measure surface displacements on the order of picometers. The application of this research for the strain-induced fabrication of highly ordered nano/micro structures in III-V semiconductors will also be discussed.

10:00am **MN-MoM-6 Impacts of Stress and Dissipation in van der Waals Interfaces on 2D Material Nanoelectromechanical Systems**, ***SunPhil Kim,*** *A van der Zande,* University of Illinois at Urbana-Champaign

Two-dimensional materials such as graphene and MoS_2represent the ultimate limit of both nanoelectronic and nanoelectromechanical systems due to their intrinsic molecular scale thickness. While 2D materials exhibit many useful properties, many of the most exciting phenomena and applications arise at the van der Waals interface. Electrically, the van der Waals interface enables the constructing of heterostructures and molecular scale electronics. Mechanically, the van der Waals interface displays superlubricity[1] or solitons[2] depending on whether the interface is aligned. A fascinating question is how the van der Waals interface affects the mechanical properties of 2D membranes. Answering this question is important to incorporating 2D heterostructure electronics into diverse applications such as highly tunable nanoelectromechanical systems from suspended 2D membranes, stretchable electronics from crumpled 2D materials, and origami/kirigami nano-machines.

In this study, we explore the impact of the van der Waals interface by comparing mechanical resonance of electrostatically contacted circular drumhead resonators made from atomic membranes of monolayer graphene to commensurate (Bernal stacked) bilayers, incommensurate (twisted) bilayer, and graphene-MoS_2heterostructures (2D bimorph).

For Bernal stacked bilayer, we observe the creation and destruction of individual solitons manifesting as stochastic jumps in the mechanical

resonance frequency tuning. We find individual dislocation creation and destruction of single solitons lead to shifts in membrane stress of < 7 mN/m or an in-plane interlayer slip distance of < 0.7 Å. We observe similar jumps in the few layer graphene and heterostructure, but not in the twisted bilayer.

For twisted bilayer, temperature and amplitude dependent studies reveal that the resonators show a factor of 3 higher dissipation rate, leading to different nonlinear behaviors compared to monolayer graphene and Bernal stacked bilayer resonators.

These results show that van der Waals interfaces strongly affect stress and dissipation of many multilayer 2D atomic membranes; an important consideration in engineering 2D nanomechanical devices.

[1]Dienwiebel, M.; Verhoeven, G. S.; Pradeep, N.; Frenken, J. W. M.; Heimberg, J. A.; Zandbergen, H. W., Superlubricity of graphite. *Phys Rev Lett* **2004,***92*(12).

[2]Alden, J. S.; Tsen, A. W.; Huang, P. Y.; Hovden, R.; Brown, L.; Park, J.; Muller, D. A.; McEuen, P. L., Strain solitons and topological defects in bilayer graphene. *P Natl Acad Sci USA* **2013,***110*(28), 11256-11260.

10:40am **MN-MoM-8 Nanomechanical Sensing for the Life Sciences***,* ***Montserrat Calleja****,* IMN-CSIC, Spain **INVITED**

Physical and, among them, mechanical properties of biological entities as cells, bacteria, viruses and biomolecules are valuable cues to better understand human diseases. Still, this has remained an underexplored route for the development of novel biosensing and diagnostic strategies. Biosensors based on nanomechanical systems are best suited to respond to the demand for accurate physical characterization of biofilms, biomolecules and single cells. The continuous downscaling of such devices from micro- to nano- scale is providing a drastic improvement in their mass resolution, while the robustness of nanomechanical biosensors for high throughput immunodetection has reached the demands of clinical applications. Interestingly, other physical parameters than the added mass of the biological targets are at reach for nanomechanical systems. We have recently observed that thin films of DNA demonstrate a Young's modulus tuning range of about 10 GPa, by simply varying the environment relative humidity from 0% up to 70%; while upon hybridization with the complementary strand, the DNA self-assembled monolayers significantly soften by one order of magnitude. Thus, we have demonstrated direct detection without prior purification or amplification of DNA sequences for gene-based identification of pathogens and antibiotic resistances. Also, the mass, position and stiffness of analytes arriving the resonator can be extracted from the adsorption-induced eigenfrequency jumps. We have proposed that this approach serves for identification of large biological complexes near their native conformation, a goal that is beyond the capabilities of conventional mass spectrometers. The capability to describe the analytes that arrive to the resonator by two orthogonal coordinates, the mass and the stiffness, clearly enhances the selectivity of nanomechanical spectrometry and it opens the door to relevant biomedical applications, as now the important role of mechanical properties in biological processes and in pathogenic disorders is becoming increasingly clear. In this talk, several avenues to advance nanoresonators for multiparameter fingerprinting of single proteins, cells, viruses and bacteria will be reviewed.

11:20am **MN-MoM-10 Neutral Mass Spectrometry of Metallic Nanoparticles with Optomechanical Resonators***,* ***Marc Sansa****, M Defoort, M Hermouet, L Banniard, A Fafin, M Gely,* Université Grenoble Alpes, CEA, LETI, France*; I Favero,* Centre de Nanosciences et de Nanotechnologies, CNRS, Université Paris-Sud, Université Paris-Saclay, France*; G Jourdan,* Université Grenoble Alpes, CEA, LETI, France*; A Brenac,* Université Grenoble Alpes, CEA, CNRS, Grenoble INP, INAC-Spintec, France*; S Hentz,* Université Grenoble Alpes, CEA, LETI, France

Nanomechanical resonators have shown record performance in mass or force sensing thanks to their miniature sizes. Pioneering works have shown single protein mass spectrometry (MS) could be performed with nanoresonators (1). It was recently demonstrated that they are particularly well suited for the analysis of high-mass species like virus capsids (~100MDa), out of reach for any commercial instrument as of today (2). In parallel, cavity-based nano-optomechanical resonators have shown exceptional displacement sensitivities (3), opening new avenues to improve the limit of detection of nanomechanical sensors (4). Here we report the first proof of concept of mass spectrometry with a nano-optomechanical resonator, made possible by a novel resonator geometry, the combination of optomechanics with electrical actuation and advances in fabrication and assembly of the sensor.

Taking advantage of the optomechanical detection, we use an ultra-thin planar sensor geometry. It displays several advantages compared to commonly used 1D-like resonators: the capture area is increased threefold while maintaining a similar mass resolution. Additionally, this planar membrane resonator is designed to be insensitive to particle position, shape or stiffness, avoiding the need for multi-mode operation (5). The resonators are fabricated using the first Very Large Scale Integration process for optomechanics, which allows the combination of standard photonic components (grating couplers, waveguides, optical cavities), electrical actuation of the resonator and a protection layer covering the optical and electrical features.

Our process and design also allow optical packaging in order for our sensor to be portable and usable in any vacuum system with optical and electrical input/outputs, such as a sputtering system containing a standard Time-of-Flight (TOF) mass spectrometer (6). This set-up allows the generation of particles of controllable mass, and the comparison of optomechanical and TOF mass spectrometry in situ. We show that the measured mass is equivalent with both techniques, while optomechanical detection is more performant at higher masses (>5 MDa), where TOF becomes less efficient. This work represents the first step towards the optomechanical addressing of large sensor arrays, which combine the advantages of nanomechanical sensors with reduced analysis times comparable to those of conventional MS.

1. M.S. Hanay et al. Nat. Nanotechnol. (2012)

2. S. Dominguez-Medinaet al. Science (2018)

3. A. Schliesser et al. New J. Phys. (2008)

4. A. Venkatasubramanian et al. Nano Lett. (2016)

5. E. Gil-Santos et al. Nat. Nanotechnol. (2010)

6. E. Sage et al. Nature Communications (2018)

11:40am **MN-MoM-11 Mass Calibration of Nanomechanical Resonators from Electrical Measurements for Mass Spectrometry Applications***,* ***Bogdan Vysotskyi****,* CEA/LETI-University Grenoble Alpes, France*; S Lai,* CEA/IRIG-University Grenoble Alpes, France*; M Defoort, M Sansa,* CEA/LETI-University Grenoble Alpes, France*; K Clement,* CEA/IRIG-University Grenoble Alpes, France*; M Gely,* CEA/LETI-University Grenoble Alpes, France*; C Masselon,* CEA/IRIG-University Grenoble Alpes, France*; S Hentz,* CEA/LETI-University Grenoble Alpes, France

Nanomechanical resonators have recently shown their potential to extend mass spectrometry towards a mass range inaccessible to commercial spectrometers [1]. The frequency shift-to-particle mass conversion requires precise knowledge of the resonator's effective mass. When using a single resonator, uncertainty on the effective mass translates into a shift into central mass of the measured mass profile. If this resonator can be used for a large amount of time, time and effort can be spent into proper morphological characterization such as scanning electronic microscopy or local stress measurement. While these techniques can be suitable for MEMS-type devices [2], they prove much more complex and less effective in the case of nanomechanical resonators due to limited precision (*c.a.* 5 to 10nm). Moreover, the issue becomes way more acute when using arrays of resonators [3]: in this case, effective mass uncertainty and variability within the array leads to shifts in central mass, but also changes in mass profile. Lastly, routine particle measurements demand frequent changes in devices and time-effective calibration techniques are required. This crucial issue for mass spectrometry applications is very little discussed in the literature, or is addressed with complex procedures [4]. FEM simulations show that two main parameters impact effective mass assessment in the case of our monocrystalline silicon resonators (160nm thickness, 300nm width and *c.a.* 10um long): width and residual plane stress. The resonance frequencies of all resonators in the array are measured, thus both deviation from the theoretical frequency spacing and absolute frequency of our 20 resonators in the array are used for calibration of effective mass. A two-step optimization routine is used in conjunction with a physical model and internal stress and beam width are deduced. With this method an extremely low absolute mass error (<1%) is demonstrated to be reached. This non-destructive technique based on electrical measurement is amenable to the future use of very large arrays (>1000 resonators) for very short analysis time. This method can be extended for non-destructive characterization of nanomechanical resonators for different applications.

[1] S. Dominguez-Medina et al., Science 362, 918-922 (2018)

[2] A. Brenes et al., Mechanical Systems and Signal Processing 112, 10-21 (2018)

[3] E. Sage et al., Nature Communications 9 : 3283 (2018)

[4] O. Malvar et al., Nature Communications 7 : 13452 (2016).

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