MEMS and NEMS
Room 102B - Session MN+2D+NS-ThA
Focused Session on Atomic Layer Nanomechanics and 2D MEMS

Moderators: Wayne Hiebert, National Institute of Nanotechnology & University of Alberta, Canada, Max Zenghui Wang, Case Western Reserve University

2:20pm **MN+2D+NS-ThA1 Exploring New Degrees of Freedom by Reducing Dimensions*, Lincoln Lauhon,*** Northwestern University **INVITED**

Nanomechanical resonators fabricated additively from 1-D and 2-D nanomaterials present a wealth of scientific opportunities beyond those of conventional resonators fabricated in a subtractive manner from dielectric thin films. This talk will describe the interesting mechanical behaviors of 1-D VO_2 nanowires and 2-D MoS_2 membranes measured by scanning fiber optic interferometry and modeled using finite element methods. In the first case, nanowire resonators provide a compelling platform to investigate and exploit phase transitions coupled to mechanical degrees of freedom because resonator frequencies and quality factors are exquisitely sensitive to changes in state, particularly for discontinuous changes accompanying a first-order phase transition. To that end, correlated scanning fiber-optic interferometry and dual-beam Raman spectroscopy were used to investigate mechanical fluctuations VO_2 nanowires across the first order insulator to metal transition (*Nano Lett.***14**, 1898 (2014)). Unusually large and controllable changes in resonator frequency were observed due to the influences of domain wall motion and anomalous phonon softening on the effective modulus. In addition, extraordinary static and dynamic displacements were generated by local strain gradients, suggesting new classes of sensors and nanoelectromechanical devices with programmable discrete outputs as a function of continuous inputs. The same interferometric measurement method has been extended to study thermally driven displacements in square few-layer MoS_2 membranes (*Nano Lett.***15**, 6727 (2015)). Mechanical mode frequencies can be tuned by more than 12% by optical heating with the above gap illumination, and modes exhibit avoided crossings indicative of strong inter-mode coupling. When the membrane is optically excited at the frequency difference between vibrational modes, normal mode splitting is observed, and the inter-mode energy exchange rate exceeds the mode decay rate by a factor of 15. Finite element and analytical modeling quantifies the extent of mode softening necessary to control inter-mode energy exchange in the strong coupling regime. The observation of strong coupling suggests the feasibility of coherent control of mechanical modes in TMDs resonators, which would provide novel basis for developing phononic devices or exploring mechanical motions that mimic quantum phenomena.

3:00pm **MN+2D+NS-ThA3 Manipulating Nonlinearities in 2D NEMS*, Akshay Naik,*** Indian Institute of Science, India **INVITED**

Nanoelectromechanical systems (NEMS) are exquisitely sensitive to various stimuli and make fantastic sensors. NEMS devices fabricated using top down fabrication techniques have already demonstrated the ability to measure mass of individual protein macromolecules and their potential use in mass spectrometry applications. NEMS devices fabricated using atomically thin membranes have the potential to bring the resolution of these devices down to single Dalton. However, nonlinearities in these 2D NEMS are quite prominent and can dramatically reduce the dynamic range of these sensors. It is thus imperative to employ strategies to minimize the effect of nonlinearities as well as to exploit them to improve the performance of these devices.

In this talk, I'll present two distinct ways in which we manipulate the nonlinearities in these atomically thin NEMS devices and improve their performance for sensing and oscillator applications. In the first method we manipulate bias voltages and strain in these devices to partially cancel out the nonlinearities present in the system. In the second method, we exploit the strong coupling between various vibrational modes to initiate internal resonance. The frequency stability, and thus the mass resolution, can be improved by orders of magnitude by operating these devices at internal resonances.

4:00pm **MN+2D+NS-ThA6 Wide Bandgap β-Ga_2O_3 Nanomechanical Resonators*, Xu-Qian Zheng,*** *S. Rafique, J. Lee, L. Han, C.A. Zorman, H. Zhao, P.X.-L. Feng,* Case Western Reserve University

Among wide bandgap oxide semiconductors, β-Ga_2O_3 has recently been emerging as a promising candidate for future high-power electronics. Thanks to its direct wide bandgap, E_g≈4.9eV [1,2], power devices made of β-Ga_2O_3 may provide higher breakdown voltage even than that in high-power devices based on mainstream 4H-SiC and GaN materials. In addition to its excellent chemical and thermal stability [1, 2], β-Ga_2O_3 also possesses excellent mechanical properties (Young's modulus, E_Y≈300GPa) [3], providing opportunities for creating next generation nano- and micro-electromechanical systems (NEMS and MEMS) which can be suited for operations in harsh and extreme environments.

In this work, we describe the construction of β-Ga_2O_3 nanosheets and their suspended structures, toward the first demonstration of vibrating β-Ga_2O_3 drumhead nanomechanical resonators. The nanomaterials were synthesized on 3C-SiC film covered Si substrate using a growth temperature of 950°C for 1.5hrs. No metal catalyst was used for the synthesis of the nanomaterials. The nanosheets have a width of ~2-7µm and thickness of ~20-140nm. The crystal structure and the morphology of the nanosheets were investigated by field emission scanning electron microscopy (FESEM) and transmission electron microscopy (TEM). From high resolution FESEM image, it was confirmed that the nanosheets originated from the sidewall of the nanorods. The selected area electron diffraction pattern (SAED) taken along the [10-1] zone axis reveals that the synthesized nanosheets are single crystalline β-Ga_2O_3. We investigate the elastic properties and resonant characteristics of such devices, by measuring flexural-mode resonances using ultrasensitive laser interferometry. We fabricate circular drumhead β-Ga_2O_3 resonators with a diameter of ~3µm using a dry transfer technique. Then, by measuring undriven thermomechanical noise spectra of β-Ga_2O_3 resonators, we observe the resonance characteristics of such resonators at 37MHz to 66MHz in high frequency (HF) range with quality (Q) factors ranging 100 to 420. In addition, we observe static mechanical behaviors of β-Ga_2O_3. We perform nano-indentation on these drumhead structures using AFM tips to further study the elastic modulus of β-Ga_2O_3. By combining measured elastic properties from resonances and nano-indentation, this study provides quantitative understanding of mechanical properties of β-Ga_2O_3, and paves the way for future nanomechanical devices engineering based on this new crystal.

[1] S. Rafique, *et al.*, *Phys. Status Solidi (a)***213**, 1002-1009 (2016).

[2] S. Rafique, *et al.*, *Cryst. Growth Des.***16**, 511-517 (2016).

[3] M.-F. Yu, *et al.*, *IEEE Sensors J.***5**, 20-25 (2005).

[4] R. Yang, *et al.*, *J. Vac. Sci. & Tech. B 32, 061203 (2014).*

4:20pm **MN+2D+NS-ThA7 Nonlinear Mode Coupling and Internal Resonances in MoS_2 Nanoelectromechanical System*, Chandan Samanta,*** *P. Gangavarapu, A.K. Naik,* Indian Institute of Science, India

Molybdenum-disulphide (MoS_2), a layered material has attracted attention for nanoelectro- mechanical system (NEMS) applications due to its ultralow mass density and extraordinary mechanical properties. Along with this, its direct band gap of 1.8eV (for monolayer MoS_2) offers the possibility of a new kind of transducer where its mechanical properties can be strongly coupled to its optical properties in visible range. MoS_2-NEMS has been realized recently using optical detection technique. This approach has its own difficulties to drive the resonator into nonlinear regime. On the other hand, mechanical nonlinearities play a crucial role in the performance of NEMS as its dimension shrinks down to atomically thin membrane. A clear understanding of nonlinear effects and the ability to control them are important from both fundamental and application points of view. In this report, we demonstrate fabrication of few layer MoS_2-NEMS and its characterization by three distinct all electrical actuation and detection schemes. We are able to detect multiple vibrational modes in our devices using all the three schemes. We are also able to drive the devices deep into nonlinear regime. Our devices show strong nonlinear coupling between multiple modes. The nonlinear modal coupling is so strong that it leads to multiple internal resonances. Although, there is a report on internal resonance in micromechanical system (MEMS), there is no reported evidence of internal resonance in NEMS made from atomically thin membrane. The observed internal resonances in our devices open the possibility for realizing high stability oscillator in very high frequency range.

4:40pm **MN+2D+NS-ThA8 Very-High-Frequency (VHF) Molybdenum Disulfide (MoS_2) Nanomechanical Resonators Operating in Liquid**, *H. Jia, **Rui Yang**, P.X.-L. Feng,* Case Western Reserve University

Micro/nanoelectromechanical systems (NEMS/NEMS) have demonstrated versatile device technologies for sensing applications by exploiting their miniaturized dimensions and increasing sensitivities upon scaling.[1,2] However, quite limited flexural-mode resonators (mostly cantilevers and doubly-clamped beams) have been reported, with only fundamental-modes are often utilized that suffer from very low quality factors (Q<5) in viscous media.[3-6]

In this work, we experimentally demonstrate the operation of molybdenum disulfide (MoS_2) nanoscale drumhead resonators (1–5µm in diameter, 50–60nm in thickness) in fluidic environment (water), which exhibit robust multimode resonances in the high- and very-high-frequency (HF/VHF) bands. We observe ~10 flexural modes up to ~150 MHz in water. The Q factors can easily exceed 10 for fundamental modes, and achieve as high as ~30 for higher modes.

Atomic-layer MoS_2, an emerging two-dimensional semiconductor, has attracted tremendous attention due to its ultralight weight and high surface-to-volume ratio. These attributes suggest that MoS_2 nanoresonators hold potential for ultrasensitive sensing capabilities even in fluids. Meanwhile, drumhead structure exhibits sealed air cavity and multimode resonance characteristics, which help maintain device performance in liquid.

The MoS_2 resonators are directly immersed in water, and optothermally driven by an amplitude-modulated 405nm diode laser. The multimode resonances are interferometrically read out using a 603nm He-Ne laser. We observe ~10 flexural modes up to ~150 MHz with Q factors exceeding 10 for fundamental modes, and reach as high as ~30 for higher modes in water. We attribute the improved resonance performance (higher f and Q, as compared to cantilever beams) to the drumhead structure consisting of an air cavity on one side. We also demonstrate the degradation of resonance characteristics (f, Q dramatically drop) if water gradually leaks into the imperfectly-sealed nanodrum cavities.

[1] J.L. Arlett, *et al.*, *Nature Nanotech.* **6**, 2011.

[2] B.N. Johnson, *et al.*, *Biosens. Bioelectron.* **32**, 2012.

[3] J. Tamayo, *et al.*, *Ultramicroscopy* **86**, 2001.

[4] A. Vidic, *et al.*, *Ultramicroscopy* **97**, 2003.

[5]S.S. Verbridge, *et al.*, *Nano. Lett.* **6**, 2006.

[6] A.P. Davila, *et al.*, *Biosens. Bioelectron.* **22**, 2007.

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