MEMS and NEMS
Room: 210B - Session MN-ThM

Atomic Layer Nanostructures and 2D NEMS
Moderator: Tse Nga (Tina) Ng, PARC (Palo Alto Research Center), a Xerox Company

8:00am **MN-ThM1 Piezoelectric and Phase Change Properties of Two-Dimensional Materials**, ***Evan Reed***, Stanford University **INVITED**

Some of the most dramatic accomplishments with 2D materials have been enabled by properties that emerge only at the single or few-layer limit and are not found in bulk forms. Using and developing a variety of atomistic modeling methods, we have predicted that many of the commonly studied single-layer and few-layer transition metal dichalcogenide (TMD) materials (e.g. MoS_2) exhibit substantive electromechanical coupling in the form of piezoelectric and flexoelectric-like effects, unlike their bulk parent crystals.[1] I will describe the first recent observations of some of these effects in the laboratory by several research groups.

Single-layers of two-dimensional Mo- and W-dichalcogenide compounds differ from graphene in an important respect: they can potentially exist in more than one crystal structure. Some of these monolayers exhibit hints of a poorly understood structural metal-to-semiconductor transition with the possibility of long metastable lifetimes. If controllable, such a transition could bring an exciting new application space to monolayer materials. We have discovered that mechanical deformations provide a route to switching thermodynamic stability between a semiconducting and a metallic crystal structure in some of these monolayer materials.[2] Our DFT-based calculations reveal that single-layer $MoTe_2$ exhibits a phase boundary at a few percent tensile strain. The potential application space for this work ranges from information and energy storage to electronic and optical electronic devices.

[1]Karel-Alexander N. Duerloo, Mitchell T. Ong, and Evan J. Reed, Journal of Physical Chemistry Letters **3** (19), 2871 (2012); Karel-Alexander N. Duerloo and Evan J. Reed, Nano Letters (4), 1681 (2013).

[2]Karel-Alexander Duerloo, Y. Li, and E. J. Reed, Nature Communications **5**, 4214 (2014).

8:40am **MN-ThM3 Novel Graphene Devices Based on Laser-Scribing Technology**, *H. Tian, **Qian-Yi Xie**, N.-Q. Deng, L.-Q. Tao, X.-F. Wang, W.-T. Mi, Y.-X. Li, H.-M. Zhao, Y.-T. Li, Y. Shu, Y. Yang, T.-L. Ren*, Tsinghua University, China **INVITED**

Wafer-scale graphene devices could be fabricated by one-step laser-scribing technology. Six kinds of novel graphene devices have been developed, including in-plane transistor, resistive memory, photo detector, earphone, strain sensor and pressure sensor. The in-plane graphene transistor has a large on/off ratio up to 5.34 with simpl e structure. The graphene resistive memory has a Fin-like structure with forming-free, stable switching, reasonable reliability and potential for 2-bit storage. The 1D and 2D arrays of graphene photo detectors were achieved with photo responsivity as high as 0.32 A/W. The graphene earphone realizes wide-band sound generation from 100 Hz to 50 kHz, which can be used for both human and animals. The strain sensor based on graphene micro ribbon has the gauge factor up to 9.49. The sensitivity of the graphene pressure sensor is as high as 0.96 kPa-1 in a wide pressure range (0~50 kPa). These results demonstrated that the laser-scribed technology could be used as a platform to develop novel graphene devices.

Keywords: Graphene Devices; Laser-Scribing; Wafer-scale; Transistors; Memory; Sensors and Actuators

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9:20am **MN-ThM5 Ultrathin Hexagonal Boron Nitride (h-BN) Nanomechanical Resonators**, ***Xu-Qian Zheng**, J. Lee, P.X.-L. Feng*, Case Western Reserve University

Among recently emerged two-dimensional (2D) materials, hexagonal boron nitride (h-BN) possesses some unique properties, including a wide bandgap (5.9eV) [1] and electrical insulation, excellent thermal stability, and superb inertness [2]. It also has very high elastic modulus (E_Y ~810GPa) which is on the same order with that of graphene [3]. Similar to graphene, h-BN also has very high fracture strain limits [4] that are far beyond achievable values in conventional 3D crystals. In particular, h-BN offers piezoelectricity in an ultrathin 2D platform [5]. Therefore h-BN is an attractive structural material for 2D nanoelectromechanical systems (NEMS), especially as resonant transducers in harsh environment applications.

In this work, we describe the construction of h-BN drumhead structures and the first demonstration of vibrating h-BN 2D NEMS resonators. We investigate the elastic properties and resonant characteristics of such devices, by measuring flexural-mode resonances using ultrasensitive laser interferometry. We first fabricate circular drumhead h-BN resonators with thickness ranging from 9nm to 292nm and diameter of ~10μm using a completely dry transfer technique [6]. Then, by conducting both undriven and driven measurements on h-BN resonators, we observe and study the multimode resonances up to 7 modes, in high frequency (HF) and very high frequency (VHF) range. We further conduct spatially resolved measurements to attain the mode shapes of the multimode resonances. We then investigate the multimode frequency scaling of h-BN nanomechanical resonators with different thickness and analyze the experimental results to extract the elastic properties, structural and geometric effects. Finally, in comparison with the previously studied graphene and MoS_2 2D NEMS resonators, we identify potential applications of these new h-BN devices in the 2D NEMS family.

[1] Y. Kubota, *et al.*, *Science* **317**, 932-934 (2007).

[2] A. Pakdel, *et al.*, *Chem. Soc. Rev.* **43**, 934-959 (2014).

[3] C. Lee, *et al.*, *Science* **321**, 385-388 (2008).

[4] L. Song, *et al.*, *Nano Lett.* **10**, 3209-3215 (2010).

[5] K.-A. Duerloo, *et al.*, *J. Phys. Chem. Lett.* **3**, 2871-2876 (2012).

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

9:40am **MN-ThM6 Microfabricated MoS_2 and MoS_2/Graphene Aerogel based Sensor for NO_2 Gas Detection**, ***Hu Long***, University of California at Berkeley, *M. Worsley*, Lawrence Livermore National Laboratory, *A. Harley-Trochimczyk, C. Carraro, R. Maboudian*, University of California at Berkeley

Two dimensional layered materials, such as graphene and transition metal dichalcogenides (TMD) have great potential for gas sensing applications. Ultrasensitive chemical detection using single-layer graphene and single- and few-layer MoS_2 has been reported. However, many of these sensors suffer from slow response and recovery. The difficulty of the fabrication process also hinders the broader application of these materials. In this paper, we report on MoS_2 and MoS_2/graphene aerogels for chemical sensing applications. The aerogels are integrated onto a microfabricated transducer and a ppb level detection limit for NO_2 at room temperature is achieved. The performance of the sensors is comparable to the results reported for single or few-layer MoS_2 devices but follows much more scalable synthesis and device fabrication processes.

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