MEMS and NEMS Group
Room: 16 - Session MN+2D-WeM

2D NEMS
Moderators: Zenghui Wang, Case Western Reserve University, Zhu Diao, Halmstad University/Stockholm University

8:00am **MN+2D-WeM1 Micro-patterned Graphene Temperature Sensors on Different Substrates**, *B. Davaji,* Marquette University, Cornell University*, H.D. Cho*, Dongguk University*, **Jong-Kwon Lee**,* National Nanofab Center in Korea*, T.W. Kang*, Dongguk University*, C.H. Lee*, Marquette University

Since the performance of electronic devices suffers from elevated temperatures as a result of self-heating, outstanding thermal properties of graphene are considered to be suitable for both instrumentation and integrated microelectronic applications [1]. Also, recently developed techniques for fabricating complex graphene structures in micro/nano scale [2, 3] make graphene a great candidate for temperature sensor applications due to its excellent electrical properties, outstanding mechanical strength, and high thermal conductivity.

In this study, micro-fabricated single-layer graphenes on a SiO2/Si, a SiN membrane, a suspended architecture, and a spatially nano-modulated Si substrate are presented for their use as temperature sensors. These graphene temperature sensors act as resistance temperature detectors, showing a quadratic dependence of resistance on the temperature. The observed resistance change of the graphene temperature sensors are explained by the temperature dependent electron mobility relationship (~ T^4) and electron-phonon scattering. The transient response analysis of the graphene temperature sensors on different substrates shows that the graphene sensor on the SiN membrane exhibits the highest sensitivity due to low thermal mass, whereas the sensor on SiO2/Si reveals the lowest one. In addition, the graphene on the SiN membrane reveals the fastest response, as well as better mechanical stability in comparison with the suspended graphene sensor. Therefore, we can expect that the graphene temperature sensors with an extremely low thermal mass will be used in various applications requiring high sensitive and fast operation.

References

[1] P. Sun, M. Zhu, K. Wang, M. Zhong, J. Wei, D. Wu, and H. Zhu, *ACS Applied Materials & Interfaces* 5, 9563 (2013).

[2] M. K. Bless, A. W. Barnard, P. A. Rose, S. P. Roberts, K. L. McGill, P. Y. Huang, A. R. Ruyack, J. W. Kevek, B. Kobrin,

D. A. Muller, and P. L. McEuen, *Nature* 524, 204 (2015).

[3] Z. Sun, T. Feng, and T. P. Russell, *Langmuir* 29, 13407 (2013).

8:20am **MN+2D-WeM2 Characterizing the Resonant Behavior and Quality Factors of 3C-SiC Diaphragms Using Frequency Analysis and the Ring-Down Technique**, ***Yongkun Sui****, H. Chong, K. Shara, C.A. Zorman,* Case Western Reserve University

Silicon carbide (SiC) has become a mainstream material for microelectromechanical systems (MEMS) due to its unique combination of outstanding electrical, mechanical and chemical properties, making it the preferred choice for applications in harsh environments where Si is not well suited. SiC is an attractive material for MEMS that utilize mechanical transduction due to its high Young’s modulus, mechanical strength and chemical inertness. The cubic polytype of SiC (3C-SiC) is particularly attractive for resonant sensing applications because SiC diaphragms can readily be fabricated from thin films by Si bulk micromachining.

This abstract reports the findings of a study to characterize the resonant behavior of MEMS-based single crystalline 3C-SiC diaphragms. The 1 x 1 mm2 diaphragms consisted of 3C-SiC films that were heteroepitaxially grown on Si by APCVD and created by conventional bulk micromachining. The diaphragms were excited into resonance under vacuum using a piezoelectric PZT crystal and their vibratory behavior was assessed using a custom-built optical interferometer.

Over 20 resonant peaks were observed from a 250 nm-thick diaphragm for frequencies up to ~2 MHz. Quality factors were initially determined by analyzing the full-width-at-half-maximum of particular resonant peaks from the frequency spectrum. Although the fundamental mode exhibited a quality factor of ~3000, at least 3 other modes had high Q's of >20,000, with the highest being over 119,000. For those high quality factor resonance modes, the vibration energy took ~1 s to fully dissipate. As such, the frequency response had to be measured in a relatively slow manner otherwise the residual energy would propagate, resulting in a broadened peak. The ring-down test, which specifically characterizes the vibration energy dissipation rate, was used to measure the high quality factors. The highest Q at (2,3) mode was found to be 195,981 using ring-down test compared to 119,200 from the FWHM method. The resonance modes of the SiC diaphragm showed a non-linear Duffing behavior when the drive voltage exceeded 200 mV. The resonance peaks exhibited jump discontinuities and one of the half-power points ceased to be experimentally visible. In the nonlinear regime, quality factors measured by ring-down test differ only 1% from those in the linear region measured by both the FWHM and ring-down techniques.

8:40am **MN+2D-WeM3 Ion Radiation Effects in Silicon Carbide (SiC) Crystal Probed by Multimode Diaphragm Resonators**, ***Hailong Chen****, V. Pashaei,* Case Western Reserve University*, W. Liao, C.N. Arutt,* Vanderbilt University*, H. Jia,* Case Western Reserve University*, M.W. McCurdy,* Vanderbilt University*, C.A. Zorman,* Case Western Reserve University*, R.A. Reed, R.D. Schrimpf, M.L. Alles,* Vanderbilt University*, P.X.-L. Feng,* Case Western Reserve University

Radiations effects from energetic particles (ions) and electromagnetic waves (photons) on electronics (*e.g.*, MOSFETs and ICs) have been widely investigated for applications in radiative harsh environments including space and nuclear reactors [1]. Radiation effects in mechanical domain, however, remain largely unexplored due to challenges in capturing and detection [2]. Meanwhile, most of preliminary studies on radiation effects in mechanical domain have been limited to Si structures and devices [3-4], while those on more intriguing radiation-durable materials such as SiC have not been investigated yet.

Here we report on experimental investigation and analysis of energetic ion radiation effects on silicon carbide (SiC) crystal, by exploiting a novel scheme of 4 vertically stacked resonant micromechanical SiC diaphragms. The SiC diaphragms are fabricated using a standard photolithographic and wet etching process to form resulting diaphragms (1 mm × 1 mm × 2.1 µm). An S-series Pelletron system is employed to irradiation oxygen ions into the SiC diaphragms (14.3MeV, 8h radiation, corresponding to a total fluence of $5.6 \times 10^{13}/cm^2$). Before and after radiation, multimode resonances are characterized in vacuum by using an ultrasensitive optical interferometry system. We have observed as large as ~9% frequency shifts (the largest value to date) in the multimode resonances of the 3rd diaphragm (counting from top in the stack) where most ions are expected to stop, as well as obvious quality (*Q*) factor degradation, which result from ionizing and displacement radiation damage. The 1st and 2nd diaphragms, which ions have mostly penetrated, exhibit moderate multimode frequency downshift of ~2% owing to displacement damage, while the 4th diaphragm shows the least frequency shift ~0.1%. The diaphragm stack exhibits outstanding capability for probing radiation damages in MEMS, not only able to capture the radiation events obviously but also help analyze different amount and types of damages induced in each stacking layer. Combining the data with a mixed elasticity model (that takes into account both flexural rigidity and pre-tension effects), we find: (i) the diaphragms operate in the *transition* regime (between ‘*plate*’ and ‘*membrane*’ but closer to the latter). (ii) after radiation behavior moves further towards the ‘*plate*’ regime, suggesting reduction in *built-in tension* and possible reduction in Young’s modulus as well.

[1] J.R. Schwank, *et al.*, IEEE Trans. Nucl. Sci. **55**, 2008.

[2] H. Shea, *et al.*, J. Micro/Nanolith. MEMS MOEMS. **8**, 2009.

[3] B. Bhandaru, *et al*., IEEE Trans. Nucl. Sci. **62,** 2015.

[4] H. Gong, *et al*., IEEE Trans. Nucl. Sci. **64**, 2017.

9:00am **MN+2D-WeM4 High-Aspect Ratio, Multi-Electrode, Carbon Nanotube Array**, ***Berg Dodson****, G. Chen, R.R. Vanfleet, R.F. Davis,* Brigham Young University

We demonstrate a carbon nanotube based, high aspect ratio (~1 mm tall and 20 um diameter posts) multi-electrode array with individually addressable electrodes. The mechanical robustness and electrical conductivity of the carbon nanotubes make them a good candidate for the multi-electrode array. The electrode is made out of CNT posts which were grown on a patterned conductive substrate and kept vertically aligned with supporting hedges. The supporting hedges were subsequently removed to leave an isolated CNT post array. The fabrication method makes the structure compatible with a variety of surface coatings, including carbon, metals, and ceramics. Good electrical connection is made to individual elements of the array despite the insulating alumina barrier that is used between the substrate and CNT forests.

11:00am **MN+2D-WeM10 Interferometric Motion Detection in Atomic Layer 2D Nanoelectromechanical Systems (NEMS)**, ***Zenghui Wang***, University of Electronic Science and Technology of China, China, *P.X.-L. Feng*, Case Western Reserve University

Atomic layer crystals have emerged as a new class of two-dimensional (2D) materials, exhibiting great promises for both fundamental research and technological applications. Their outstanding mechanical properties make these materials ideal for constructing novel 2D nanoelectromechanical systems (NEMS), providing opportunities for coupling their material properties across multiple information-transduction domains, at scales down to individual atomic layers. One particularly interesting prototype of 2D NEMS is 2D nanomechanical resonators. While various electrical, mechanical, and optical motional signal transduction schemes have been employed for 2D NEMS resonators, laser optical interferometry [1][2] clearly stands out as one of the most important and widely used techniques. To date, it is the only technique capable to measure the completely undriven thermomechanical motions in these 2D nanostructures.

Toward pushing the ultimate limits, it is highly desirable to quantitatively understand the detection efficiency and its dependence on the device parameters and interferometric conditions. Here, we present a systematic study [3] of the intrinsic motion responsivity in 2D NEMS using a Fresnel-law-based model, analyzing the dependences of motion responsivity upon parameters in device structure, probing wavelength, and type of 2D material. We find that the best responsivity is achieved as the vacuum gap varies (with crystal thickness) around integer multiples of half of the probing wavelength. The optimized device thickness depends on both the type of crystal and probing wavelength. Specifically, when using 633nm He-Ne laser, the ~300nm-SiO_2-on-Si substrate commonly used in 2D research offers close-to-optimal motion responsivity for several 2D crystals over a wide range of thickness, provided that the oxide is fully removed underneath the 2D layer. We further show that different type of 2D layered materials exhibit different patterns in the same parameter space due to their different band structure and dielectric constants.

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[1] Wang, Z., Lee, J., & Feng, P. X.-L. Spatial Mapping of Multimode Brownian Motions in High Frequency Silicon Carbide (SiC) Microdisk Resonators. *Nature Commun.* **5**, 5158 (2014).

[2] Hiebert ,W. K., Vick, D., Sauer, V., & Freeman, M. R. Optical interferometric displacement calibration and thermomechanical noise detection in bulk focused ion beam-fabricated nanoelectromechanical systems. *J. Micromech. Microeng.* **20**, 115038 (2010).

[3] Wang, Z. & Feng, P. X.-L. Interferometric Motion Detection in Atomic Layer 2D Nanostructures: Visualizing Signal Transduction Efficiency and Optimization Pathways. *Sci. Rep.* **6**, 28923 (2016).

11:20am **MN+2D-WeM11 NEMS on Flexible Substrates for Strain Engineering in Sensing Applications**, ***Swapnil More***, Indian Institute of Science, India

Although nanoelectromechanical systems (NEMS) utilizing 2D material are potent instruments for ultra-sensitive mass spectroscopy, the onset of nonlinearities severely reduces their dynamic range. However, strain tuning of dynamic range is possible if the strain is introduced by methods other than electrostatic gating. Here, we present a method for the fabrication of nanoelectromechanical resonators (NEMRs) from 2D materials on flexible substrate, which allows straining devices through substrate bending, which is independent of electrostatic excitation of the of the resonator. This device platform can be a basis for studying dynamic range of NEMRs as a function of strain in the resonating membrane, along with studying new novel concepts for sensors involving strain engineering. With the advent of new 2d materials having exotic strain dependent properties, strain engineering opens whole new set of opportunities for the sensing technologies employing NEMS, other than strain tunable dynamic range.

11:40am **MN+2D-WeM12 Parametric Amplification in MoS2 Drum Resonator**, ***Parmeshwar Prasad****, *N. Arora, A.K. Naik*, Indian Institute of Science, India

Transition metal dichalcogenide (TMDC) materials offer an alternative to carbon based materials, due to their unique mechanical, electrical and optical properties [1] . Molybdenum disulphide (MoS_2) is one such material which is being explored for NEMS applications. It has ultra-low mass density of 3.3 fg/μm^2 and high Young's modulus 0.3 TPa . Furthermore, its semi-conducting property allow its mechanical motion to be transduced electrically. NEMS devices based on 2D materials perform exceptionally well in terms of quality factor at low temperatures. Quality factors (Q) as high as 10^5 have been observed at cryogenic temperatures[2]. However, at room temperatures quality factors are typically pegged at 100. Low quality factor of these resonators make them difficult to transduce the motion of these resonators and thus hinder applications as potential ultra-sensitive detectors. In this paper, we amplify the motion of these resonators by parametric amplification. We report enhancement of mechanical response in MoS2 drum resonator using parametric amplification and achieve ~ 10dB gain. We also show quality factor enhancement in the resonator with parametric amplification at 397 K. The signal enhancement is similar to the recently reported NEMS devices [2], However, the amplification is significantly lower as compared to the reported MEMS devices [3]. We investigate the effect of Duffing (cubic) non-linearity in the current work and show that it plays significant role in the maximum achievable gain from NEMS devices using parametric amplification. The experiments are performed using direct capacitive measurement technique on near insulating ~ 1GΩ device. This shows the ability to perform electrical capacitive actuation and detection technique in very high resistance NEMS devices.

References:

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[1] Morell, N. et al, Nano Lett. 2016, 16 (8), 5102–5108.

[2] Changyao Chen et al, Nat. Nano (2009) 861 - 867

[2] Mathew John P. et al, Nat. Nano.(2016) 747-751

[3] Karabalin R. B. et al, App. Phys. Lett. (2010) 97

12:00pm **MN+2D-WeM13 Anisotropic Thermal Conductivity of Suspended Black Phosphorous Probed by Opto-thermomechanical Resonance Spectromicroscopy**, ***Arnob Islam****, *P.X.-L. Feng*, Case Western Reserve University

Two-dimensional (2D) black phosphorus (P) exfoliated from its layered bulk crystals has attracted great attention due to its unique in-plane anisotropic properties along armchair (AC) and zigzag (ZZ) directions [1-2]. Probing the anisotropic properties in the black P is important for both exploring fundamental science and engineering device performance . Here, we employ 2D nanoelectromechanical systems (NEMS) platform to study anisotropic thermal conductivity (k) of black P.

In this study, for the first time, we use thermomechanical motion with localized laser heating (Fig. 1a) (*optothermomechanical spectromicroscopy)* in combination with finite element modeling (FEM) to precisely determine anisotropic k_{AC} and k_{ZZ} of black P. We fabricate a black P circular drumhead resonator (thickness of t=~80nm and diameter of d=~9μm) using a dry-transfer method [3]. Before resonance measurement, polarized reflectance measurement is performed to determine the crystal orientation of the black P flake (Fig. 1b) [4]. We then employ a 633nm laser (laser power of P=1.6mW, spot size of 1μm) to photothermally heat up the device and interferometrically detect Brownian motion. We obtain the fundamental mode frequency at f_{res}=~9MHz when the laser is located on the center of the device. We move the laser spot location along AC/ZZ on the resonator, and track f_{res} along the path. We find that measured f_{res} values are higher when laser spot is moving in AC direction ($f_{res,AC}$) than that in ZZ direction ($f_{res,ZZ}$)(Fig. 1c) at same distance from the center. This can be attributed to anisotropic k_{AC} and k_{ZZ}, which dictates different temperature distribution on the device as the laser is moving along AC/ZZ, providing uneven biaxial thermal expansion thus frequency shift.

We employ FEM simulation to model the coupling between thermal transport from optothermal heating and resonance characteristics of the black P drumhead resonator. By fitting the modeling to the experimental results, we are able to determine anisotropic thermal conductivities along AC/ZZ orientations (k_{AC}=15Wm^{-1}K^{-1} and k_{ZZ}=55Wm^{-1}K^{-1}) (Fig. 1c and 1d), which are consistent with k_{AC} and k_{ZZ} obtained by other methods [2].

References:

[1] X. Ling, *et al.*,*Proc. of the Nat. Acad. of Sci.*, 112(15), pp.4523-4530 (2015).

[2] B. Smith, *et al.*,*Adv. Mat.* 29, 1603756 (2017).

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

[4] A. Islam *et al., Manuscript in Preparation* (2017).

* **MEMS/NEMS Best Paper Award Finalist**

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