Thursday Morning, September 25, 2025

2D Materials
Room 208 W - Session 2D+AQS+EM+MI+MN+NS+QS+SS+TF-ThM

2D Materials: Optoelectronics and Moire Excitons

Moderators: Shengxi Huang, Rice University, **Daniel Yimam**, Oak Ridge Natinal Laboratory

8:00am **2D+AQS+EM+MI+MN+NS+QS+SS+TF-ThM-1 Probing the Ultrafast Charge Dynamics and Exciton Emission from Single Atomic Defects in 2D Semiconductors by Lightwave-Driven STM***, Laric Bobzien, Lysander Huberich, Jonas Allerbeck, Eve Ammerman, Nils Krane, Andres Ortega-Guerrero, Carlo Pignedoli, Oliver Gröning,* Empa, Swiss Federal Laboratories for Materials Science and Technology, Switzerland*; Joshua A. Robinson,* The Pennsylvania State University*;* ***Bruno Schuler,*** Empa, Swiss Federal Laboratories for Materials Science and Technology, Switzerland **INVITED**

Two-dimensional (2D) semiconductors provide an exciting platform to engineer atomic quantum systems in a robust, yet tunable solid-state system. This talk explores the intriguing physics of single point defects in transition metal dichalcogenide (TMD) monolayers, investigated through atomically resolved scanning probe microscopy.

We have determined the layer-dependent charge transfer lifetimes of selenium vacancies in WSe_2 on graphene substrates, spanning picosecond to nanosecond timescales [1]. By leveraging our recently developed lightwave-driven scanning tunneling microscope (THz-STM) [2,3], we could probe the ultrafast charge dynamics on the atomic scale. Time-domain sampling with a THz pump-THz probe scheme enabled capturing atomic-scale snapshots of transient Coulomb blockade, a hallmark of charge transport mediated by quantized defect states [4].

Moreover, the extended charge state lifetimes provided by hBN decoupling layers facilitated the local, electrical stimulation of excitonic emission from pristine MoS_2 and individual charged defects via STM luminescence (STML).

By combining the structural and electronic properties accessible by conventional scanning probe microscopy with the optical fingerprint from STML and the excited-state dynamics revealed through pump-probe THz-STM, we gain a comprehensive microscopic understanding of localized quantum states in low-dimensional materials.

References:

[1]L. Bobzien et al. Phys. Rev. Lett. (accepted, arxiv: 2407.04508)
[2]J. Allerbeck et al. ACS Photonics 10, 3888 (2023)
[3]L. Bobzien et al. APL Mater. 12, 051110 (2024)
[4]J. Allerbeck et al. arXiv:2412.13718 (2024)
[5]L. Huberich et al. (in preparation)

8:30am **2D+AQS+EM+MI+MN+NS+QS+SS+TF-ThM-3 Many-Body Effects on Excitons, Trions, and Defect-Bound States in 2D Materials***,* ***Kai Xiao,*** *Taegwan Park, Alexander Puretzky,* Oak Ridge National Laboratory, USA*; Xufan Li,* Honda Research Institute*; Kyungnam Kang,* Oak Ridge National Laboratory, USA*; Austin Houston,* University of Tennessee, Knoxville*; Christopher Rouleau, David Geohegan,* Oak Ridge National Laboratory, USA

Two-dimensional (2D) materials, particularly transition metal dichalcogenides (TMDs) exhibit strong many-body interactions due to reduced dielectric screening and spatial confinement. These interactions, involving electrons, holes, excitons, phonons, and plasmons, give rise to emergent phenomena distinct from their bulk counterparts. In this talk, I will present our recent investigations into the many-body effects on the optical properties and ultrafast excitonic dynamics of monolayer and bilayer TMDs. Specifically, we synthesized isotopically pure monolayer MoS_2 and highly defective WS_2 via nonequilibrium chemical vapor deposition, enabling a controlled study of isotope effects, defects, and background doping on excitonic behavior. Using ultrafast laser spectroscopy and temperature-dependent optical spectroscopy, we observed pronounced many-body interactions, including exciton-phonon and exciton-electron coupling, which significantly influence exciton energy, dynamics, and light-matter interactions in both monolayer and bilayer TMDs. These strong interactions give rise to novel quantum states and make 2D materials promising platforms for next-generation optoelectronics, quantum information technologies, and fundamental condensed matter physics.

Synthesis science was supported by the U.S. Dept. of Energy, Office of Science, Materials Science and Engineering Division. This work was performed at the Center for Nanophase Materials Sciences, which is a DOE Office of Science User Facility.

8:45am **2D+AQS+EM+MI+MN+NS+QS+SS+TF-ThM-4 Proximity-Induced "Magic" Raman Bands in TERS Spectra of MoS2 / WS2 @ 1L H-BN-Capped Gold***,* ***Andrey Krayev,*** HORIBA Scientific*; Pavel Valencia Acuna,* PNNL*; Ju-Hyun Jung,* Pohang University of Science and Technology (POSTECH), Republic of Korea*; Cheol-Joo Kim,* POSTECH, Republic of Korea*; Andrew Mannix,* Stanford University*; Eleonora Isotta,* Max Planck Institute for Sustainable Materials, Germany*; Chih-Feng Wang,* PNNL

Recently it was proposed to use the monolayer h-BN – capped gold substrates as an ideal platform for the gap mode TERS and TEPL imaging, that on the one hand, should preserve strong gap mode enhancement of Raman signal due to small thickness (0.3 nm) of the dielectric h-BN layer, and on the other hand preserve strong TEPL response due to de-coupling of 2D semiconductors from the metallic substrate. TERS data collected on mono- and a few-layer-thick crystals of MoS_2 and WS_2 on 1L-h-BN-capped gold show both the TERS and TEPL response, confirming the validity of the proposed approach.

In addition to the enhancement of both the PL and Raman signal, in the course of assessment of TERS/TEPL response of mono- and a few-layer-thick crystals of MoS_2 and WS_2 deposited on 1L h-BN-capped gold we observed in TERS spectra, completely unexpectedly, appearance of Raman bands at about 796 cm^{-1} and 76 cm^{-1} which are not normally observed in regular Raman spectra of h-BN or WS_2/MoS_2. We can safely state that these "magic" bands belong to h-BN as they appear at the same spectral position in TERS spectra of both the monolayer MoS_2 and WS_2 deposited on the monolayer h-BN capped gold, moreover, the 796 cm^{-1} band often was the strongest band observed in TERS spectra, even stronger than A' mode from WS_2 or MoS_2. Presence of the transition metal dichalcogenide (TMD) monolayer is mandatory for the appearance of these "magic" bands as they are absent outside of the monolayer TMDs in these samples. Literature search showed that similar (but not identical) phenomenon was observed earlier in h-BN encapsulated WSe_2,$MoSe_2$, and WS_2. There have been several significant differences between our data and the earlier reported one: in our case we have not been able to observe the "magic bands" in $MoSe_2$ and WSe_2 @ 1L h-BN@Au, while WS_2 monolayers deposited on the same substrate as WSe_2, showed expected response. More importantly, the excitation laser wavelength dependence in our case was completely different from what was reported earlier: in WS_2-based samples we observed strong "magic" bands with excitation at 830 nm, 785nm, 594nm, but not 633nm, the wavelength closest to the A exciton in this material. This excitation profile is remarkably reminiscent of the excitation profile of the monolayer WS_2 in intimate contact with silver where we observed strong dip of the intensity of main A' mode in TERS spectra at 633nm excitation wavelength.

We will argue that intricate interaction between the tip-substrate gap plasmon, TMD excitons and most probably, normally mid-IR-active phonons in h-BN is responsible for the appearance of observed "magic" bands.

9:00am **2D+AQS+EM+MI+MN+NS+QS+SS+TF-ThM-5 Correlated Excitons in TMDC Moiré Superlattice***,* ***Sufei Shi,*** Carnegie Mellon University **INVITED**

In a strongly correlated electronic system, Coulomb interactions among electrons dominate over kinetic energy. Recently, two-dimensional (2D) moiré superlattices of van der Waals materials have emerged as a promising platform to study correlated physics and exotic quantum phases in 2D. In transition metal dichalcogenides (TMDCs) based moiré superlattices, the combination of large effective mass and strong moiré coupling renders the easier formation of flat bands and stronger electronic correlation, compared with graphene moiré superlattices. Meanwhile, the strong Coulomb interaction in 2D also leads to tightly bound excitons with large binding energy in TMDCs. In this talk, we will discuss how to use optical spectroscopy to investigate excitonic physics and strongly correlated phenomena in TMDC moiré superlattice, along with correlated exciton states arising from strong interactions.

9:30am **2D+AQS+EM+MI+MN+NS+QS+SS+TF-ThM-7 Sub-Stoichiometric Phases in 2D $MoTe_2$***,* ***Onyedikachi Alanwoko****, Nirosha Rajapakse, Matthias Batzill,* University of South Florida

Atom vacancy formation in crystalline materials is energetically expensive. To lower the energy cost for non-stoichiometry, point defects can condense into energetically more favorable extended defects. Studies on Mo-dichalcogenides have shown that excess Mo is condensed into closed, triangular Mirror Twin Boundary (MTB) loops. These MTBs can form in high densities where the triangular loops connect and form a cross-hatched network of MTBs. Here we show through Scanning Tunneling Microscopy (STM) that periodically ordered MTB networks can obtain a homologous series of sub-stoichiometric $MoTe_{2-x}$ phases. We systematically investigate the preparation conditions (which include a variation of the growth temperature, Te-desorption by post-growth annealing, and vapor-deposited Mo), enabling the controlled synthesis of these new phases. The different phases require different synthesis procedures, and once formed, these phases appear thermally stable in vacuum. The ability to control and create these different phases of $MoTe_2$ and other two-dimensional (2D) materials is a promising way of realizing new electronic and chemical properties of 2D materials. Particularly promising is the observation that we can react $MoTe_2$ with dissimilar transition metals to create new doped or alloyed 2D materials with potentially desirable properties.

9:45am **2D+AQS+EM+MI+MN+NS+QS+SS+TF-ThM-8 Quantum Confining Excitons with Electrostatic Moiré Superlattice***, **Liuxin Gu**, Lifu Zhang, Sam Felsenfeld,* University of Maryland, College Park*; Rundong Ma,* University of Maryland College Park*; Suji Park, Houk Jang,* Brookhaven National Laboratory*; Takashi Taniguchi, Kenji Watanabe,* National Institute for Materials Science, Japan*; You Zhou,* University of Maryland, College Park

Quantum confining excitons has been a persistent challenge in the pursuit of strong exciton interactions and quantum light generation. Unlike electrons, which can be readily controlled via electric fields, imposing strong nanoscale potentials on excitons to enable quantum confinement has proven challenging. In this study, we utilize piezoelectric force microscopy to image the domain structures of twisted hexagonal boron nitride (hBN), revealing evidence of strong in-plane electric fields at the domain boundaries. By placing a monolayer $MoSe_2$ only one to two nanometers away from the twisted hBN interface, we observe energy splitting of neutral excitons and Fermi polarons by several millielectronvolts at the moiré domain boundaries. By directly correlating local structural and optical properties, we attribute such observations to excitons confined in a nanoscale one-dimensional electrostatic potential created by the strong in-plane electric fields at the moirédomain boundaries. Intriguingly, this 1D quantum confinement results in pronounced polarization anisotropy in the excitons' reflection and emission, persistent to temperatures as high as ~80 Kelvins. These findings open new avenues for exploring and controlling strongly interacting excitons for classical and quantum optoelectronics.

11:00am **2D+AQS+EM+MI+MN+NS+QS+SS+TF-ThM-13 Microwave Imaging of Excitonic States and Fractional Chern Insulators in 2D Transition Metal Dichalcogenides***, **Zhurun Ji**,* SLAC National Accelerator Laboratory/ MIT **INVITED**

Nanoscale electrodynamics offers a unique perspective on states with bulk-edge correspondence or spatially dependent excitations. I will introduce our latest advancements in optically coupled microwave impedance microscopy, a technique that enhances our capability to explore electrodynamics at the nanometer scale. I will discuss our recent studies utilizing this technology to extract spectroscopic information on exciton excitations within transition metal dichalcogenide systems. Additionally, I will share our recent findings on probing topological and correlated electronic states, specifically the fractional Chern insulator states in twisted TMD bilayers.

11:30am **2D+AQS+EM+MI+MN+NS+QS+SS+TF-ThM-15 Control and Properties of Single Dislocations in Van Der Waals Nanowires***, **Peter Sutter**, Eli Sutter,* University of Nebraska - Lincoln

Line defects (dislocations) not only govern the mechanical properties of crystalline solids but they can also produce distinct electronic, thermal, and topological effects. Identifying and accessing this functionality requires control over the placement and geometry of single dislocations embedded in a small host volume to maximize emerging effects. We have identified a synthetic route that enables the rational placement and tuning of dislocation in van der Waals nanowires, where the 2D/layered crystal structure limits the possible defect configurations and the nanowire architecture puts single dislocations in close proximity to the entire host volume.[1] While homogeneous layered nanowires carry individual screw dislocations, the synthesis of radial (core-shell) nanowire heterostructures transforms the defect into a mixed (helical) dislocation whose edge-to-screw ratio is continuously tunable via the core–shell lattice mismatch.

Such deterministic control over defects now enables the probing of functionality arising with single dislocations. For example, germanium sulfide van der Waals nanowires carrying single screw dislocations incorporate Eshelby twist and thus adopt a chiral twisted structure,[2] which for the first time allowed the identification of chirality effects in the photonic properties of a single nanostructure.[3] Using cathodoluminescence spectroscopy, whispering gallery modes could be excited and probed to directly compare the photonics of chiral and achiral segments in single nanowires. The data show systematic shifts in energy, which with the help of simulations are assigned to chiral whispering gallery modes in wires hosting a single dislocation.

The ability to design nanomaterials containing individual dislocations with controlled geometry paves the way for identifying a broad range of functional properties of dislocations, with the potential to herald a paradigm shift from the traditional strategy of suppressing dislocations to embracing and harnessing them as core elements of new technologies.

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2. P. Sutter, S. Wimer, and E. Sutter, *Nature* 570, 354 (2019); DOI: 10.1038/s41586-019-1147-x
3. P. Sutter, L. Khosravi-Khorashad, C.V. Ciobanu, and E. Sutter, *Materials Horizons* 10, 3830 (2023); DOI: 10.1039/D3MH00693J

11:45am **2D+AQS+EM+MI+MN+NS+QS+SS+TF-ThM-16 Electrical Manipulation of Valley Polarized Charged Excitons in 2d Transition Metal Dichalcogenides***, **Kuan Eng Johnson Goh**,* Agency for Science Technology and Research (A*STAR), 2 Fusionopolis Way, Innovis #08-03, Singapore 138634, Singapore

The control of excitons in 2-dimensional (2D) Transition Metal Dichalcogenide (TMD) semiconductors is a key enabler for their use in optoelectronic, valleytronic and quantum applications. Reproducible electrical control of excitons remains elusive as excitons are intrinsically charge neutral quasiparticles. Here, we demonstrate that charge defects present in 2D TMDs like single-layer H-phase WS_2 [1,2], could be advantageous for electrical control through the coherent coupling of the exciton or biexciton with intrinsic charges in the single-layer WS_2, thus enabling a simple and robust method for electrical manipulation of the degree of valley polarization from <10% to >60% [3]. Such robust electrical tunability of the spectral resonance of the charged states indicates resonant control of valley polarization by exploiting the intricate interplay between the charged and neutral exciton/biexciton states, representing a key advance towards using the valley degree of freedom as an alternate information carrier.[4].

References

[1] Bussolotti, F., et al., ACS Nano 15 (2021) 2686

[2] Bussolotti, F., et al., ACS Nano 18 (2024) 8706

[3] Das, S., et al., ACS Nano 18 (2024) 30805

[4] Goh, K. E. J., et al., Advanced Quantum Technologies 3 (2020) 1900123

12:00pm **2D+AQS+EM+MI+MN+NS+QS+SS+TF-ThM-17 Thickness Dependent Band Gap and Electrical Anisotropy of 2DSnSe***, Marshall Frye, Jonathan Chin, Joshua Wahl, Jeremy Knight,* Georgia Institute of Technology*; Walter Smith,* Purdue University*; Dilara Sen, Samuel Kovach,* Kenyon University*; Frank Peiris,* Kenyon College*; Charles Paillard,* University of Arkansas*; Thomas Beechem,* Purdue University*; Anna Osterholm, **Lauren Garten**,* Georgia Institute of Technology

2D SnSe presents unique opportunities for optoelectronics, and scalable microelectronics, but it is first critical to understand how the electrical and optical response change upon downscaling. Tailoring the band gap and electrical anisotropy of 2D monochalcogenides, like SnSe, has previously been shown but the mechanisms that drive the changes in band gap are still not understood. This study revealshow changes in bond length and structure drive the thickness dependences of band gap, carrier mobility and lifetime of SnSe thin films.Molecular beam epitaxy is used to deposit (2h00) oriented SnSe thin films with thicknesses ranging from 4 nm to 80 nm. The direct band gap increases from 1.4 eV at 80 nm to 1.9 eV at 4 nm, underscoring the potential of SnSe as a tunable and direct band gap material for thin film optoelectronics. Raman spectroscopy showsdifferent simultaneously changes in the crystal structure and bonding occurring parallel versus perpendicular to the 2D plane with decreasing film thickness. TEM further supports the hypothesis that the increase in the band gap with reduced thickness is due to changes in crystal structure resulting in a contraction of the out-of-plane SnSe covalent bonds, while the in-plane bond length increases. In addition to the reduction in band gap, tracking the time dependent photoluminescence shows an increase in carrier lifetime with decreasing film thickness, while Hall measurements show a change in the carrier mobility with decreasing thickness. Overall, this work provides the critical missing insight needed to design these optically and electronically relevant2D materials for scalability.

MEMS and NEMS
Room 205 ABCD W - Session MN1-ThA
RF and Magnetic MEMS

Moderators: Robert Davis, Brigham Young University, **Sushma Kotru**, University of Alabama

2:15pm **MN1-ThA-1 Control of Magnetoelastic Properties for Magnetoelectric Magnetic Field Sensors***, **Margo Staruch,*** US Naval Research Laboratory **INVITED**

The increasing demand for low SWaP-c magnetic field sensors has led to heightened interest in magnetoelectric MEMS and NEMS resonators. The direct coupling of the piezoelectric and magnetic phases allows for highly sensitive readoff of AC magnetic fields via an induced voltage. Dynamic sensing modalities, achieved by driving the piezoelectric phase at a resonance, have also been demonstrated to significantly decrease the noise floor and improve sensitivity. Much of the recent focus has been on maximizing the sensitivity of the resonant frequency to a field either through magnetoelastic effects or the ΔE effect. At NRL, efforts have been focused on fabricating clamped-clamped beam resonators with heterostructured AlN and magnetostrictive layers that operate at the fundamental bending mode. In this presentation, methods to improve the figures of merit including the piezomagnetic coefficient and the change in frequency with magnetic field (df/dH) through selection and control of the deposition of the magnetic phase will be explored. The impacts of boundary conditions and film stresses on the resonance behavior and the selection of the resonance modes will be established. Considerations of the development of shape anisotropy due to the high aspect ratio of the beams and resultant angular dependence of the sensitivity will emphasize the use of these resonating beams as vector magnetometers. Lastly, recent results on the limit of detection and noise floor of the sensors will be presented. Based on these results, design parameters for future packaged MEMS field sensors will be discussed.

2:45pm **MN1-ThA-3 Low-Loss Wideband Nonreciprocal Magnetoacoustic RF Isolators Enabled by Non-Collinear Dipolar-Coupled Ferromagnetic Stack***, **Bin Luo,*** Department of Electrical and Computer Engineering, Northeastern University*; Andreas Winkler, Hagen Schmidt,* SAWLab Saxony, Leibniz IFW Dresden, Germany*; Vipul Sharma, Mingzhong Wu,* Department of Physics, Northeastern University*; Benyamin Davaji, Nian-Xiang Sun,* Department of Electrical and Computer Engineering, Northeastern University

Nonreciprocal RF isolators and circulators have enabled full duplex radio systems and protection of power amplifiers from back-reflections in high power microwave transmitters, greatly boosting the spectral efficiency and coordination in mesh or relay networks for modern wireless communication systems like 5G, IoT, and future 6G [2]. However, conventional RF isolators and circulators are bulky, expensive with high power consumption owing to CMOS-incompatible ferrites with high growth temperature in oxidizing environment and the need of permanent magnet/electromagnets for operation via Faraday rotation [2]. Recently, non-reciprocal magnetoacoustic RF devices exhibit substantial nonreciprocity with remarkable power efficiency and CMOS compatibility [1] [3-7]. They consist of a magnetic stack within the SAW path between two interdigital transducers (IDTs) on a piezoelectric substrate. By applying RF voltage on IDTs, the induced SAW propagates and interacts with spin waves in a magnetic stack. The magnon-phonon interactions lead to hybrid magnetoacoustic waves that exhibit a much higher backward loss rate than the forward one or vice versa [2]. Despite progress using various magnetic heterostructures, such as FeGaB/Al_2O_3/FeGaB [3, 4] and synthetic antiferromagnetic CoFeB/Ru/CoFeB stacks [6, 7], prior demonstrations often suffer from high insertion loss (>40 dB) due to the inefficiency of higher-order SAW harmonics. Additionally, devices with giant nonreciprocity often exhibit narrow bandwidths, and vice versa. Here we demonstrate a low-loss wideband non-reciprocal magnetoacoustic RF isolator based on a non-collinear dipolar-coupled ferromagnetic FeGaB/SiO_2/FeGaB stack driven by SAW fundamental mode at 2.87 GHz on 128° Y-X cut $LiNbO_3$ substrate (**Figure 1**). By intentionally misaligning uniaxial anisotropies in the two ferromagnetic layers (10° and 70° to k_{SAW}) using in-situ angled magnetic field depositions, multiple wideband non-reciprocity has been first realized from 2.48 to 3.15 GHz with reduced insertion loss (**Figure 2**). The maximum nonreciprocity reaches ~40 dB (200 dB/mm) near modulated SAW peaks, where standing waves enhance acoustic resonance. The device demonstrates a low insertion loss of ~13 dB off-resonance and ~25 dB on-resonance at 2.87 GHz, with ~10 dB nonreciprocity (33.3 dB/mm) (**Figure 3**). The ultra-compact, low-loss, wide-band non-reciprocal, integrated magnetoacoustic isolator shows great potential for low power compact full-duplex radio/radar commmunication systems [2], efficient and coherent excitation of ground state NV^- centers [8] and nonreciprocal quantum information transfer in future magnon–phonon transducers [9].

3:00pm **MN1-ThA-4 High-Q Diamagnetically Levitated Mechanical Resonators for Magnetic Field Sensing***, **Pooja Roy,** Samira Yasmin,* University of Central Florida*; Yunong Wang, Philip Feng,* University of Florida*; Jaesung Lee,* University of Central Florida

Diamagnetically levitated and trapped systems hold great promise in the development of high-performance, anchor-less resonant devices with excellent stability. This scheme generates sufficient levitation force via diamagnetism, enabling three-dimensional (3D) trapping at room temperature without external power input (Supplementary Fig. 1).

In this work, we combine theoretical analysis with experimental investigation to explore the complete levitation behavior and rigid body resonances of diamagnetically levitated graphite/dielectric composite plates, ranging in size from millimeters to centimeters and in mass up to 680mg. These systems exhibit stable, clamping-free levitation with low energy dissipation and high quality (Q) factors, making them promising candidates for high-precision sensing applications.

The fabricated composite plates, in which graphite particles are embedded in a dielectric material (nonconducting epoxy), are diamagnetically levitated over permanent magnets (Supplementary Fig. 2). Their resonant performance is measured by using a laser interferometry system (Supplementary Fig. 3), where resonance motions of the plates are excited by simultaneously applying both AC and DC signals to the permanent magnets. A representative device with a mass of 34mg (Device 1) exhibits multiple resonant modes, including a primary resonance at f=19.7Hz with Q=7 in air. Operating the devices in vacuum, significantly improves the Q factor to Q=1400 at 10mTorr and Q=33,000 at 0.6mTorr (Supplementary Fig. 4). A larger 680mg device (Device 2) shows a resonance at f=20.35Hz with Q=17,000 at 24µTorr.

To evaluate frequency stability and resonant sensing performance, we implement Device 2 into a phase-locked loop (PLL), achieving an Allan deviation of σ_A=~$2.5*10^{-8}$ at averaging time of t=10ms (Supplementary Fig. 5). Upon applying a ~2mT magnetic field, we find clear resonance frequency shift; the device shows magnetic field sensing responsivity of 0.45Hz/T, with a sensitivity of 0.15mT/$Hz^{1/2}$.

This extensive experimental characterization manifests high-Q resonant levitated microsystems with significant mass and enhanced sensitivity, laying the foundation for advanced levitation technologies and the development of next-generation resonant sensors.

MEMS and NEMS
Room 205 ABCD W - Session MN2-ThA
Bio and Flexible/Wearable Devices

Moderators: Matthew Jordan, Sandia National Laboratory, **Margo Staruch**, Naval Research Laboratory

3:15pm **MN2-ThA-5 Fabrication of Wearable Carbon Microelectrode Arrays for Bioimpedance***, **Robert Davis,** Nick Allen, Sharisse Poff, Shiuh-hua Wood Chiang, Brian Jensen, Richard Vanfleet,* Brigham Young University

Reusable, dry microelectrodes for bioimpedance measurements can enable wearable health monitoring devices. Here we demonstrate the fabrication of carbon composite microelectrode arrays designed specifically for wrist-based bioimpedance. Carbon electrodes are chemically inert and can form 3D structures for positive skin engagement. The electrodes were fabricated using carbon nanotube-templated microfabrication, in which patterned carbon nanotube forests were infiltrated with a nanocrystalline carbon matrix material to create a solid structure. The electrode material was tested for strength and wear resistance by three-point bending. The fabricated electrode arrays were mechanically and electrically adhered to pads on a flexible printed circuit (FPC) using an anisotropic conductive adhesive film, which was cured with pressure and heat. A controllable alignment and attachment technique was developed to simultaneously attach all electrodes in the array to the FPC. Human subject bioimpedance data verified that the electrodes were effective in measuring bioimpedance from 100 kHz to 200 MHz.

3:30pm **MN2-ThA-6 3D Ultrablack Microstructures for Wearable Optical Spectroscopy**, ***Bridgett Kemper***, *Woodson Parker,* Brigham Young University*; Tyler Westover,* Octavian Solutions*; Richard Vanfleet, Robert Davis,* Brigham Young University

Miniaturized spectrometers could enable the application of spectroscopy in wearable devices such as fitness/health monitors. Here we will present the fabrication of miniaturized spectrometers with integrated carbon nanotube parallel-hole collimators for use in diffuse light spectroscopy. The microscale collimators are precise optical elements balancing low reflectance with low transmission through the high aspect-ratio carbon nanotube hedges that isolate the holes. The collimators are grown on a transparent fused silica substrate allowing the fragile collimators to remain on the transparent substrate for integration into optical systems.

3:45pm **MN2-ThA-7 A Tetrapolar Bioimpedance Sensor with Electropolymerized PEDOT:PSS Electrodes for Improved Stability in the Gastrointestinal Tract**, ***Mateo Lim***, *Justin Stine, Reza Ghodssi,* University of Maryland College Park

Inflammatory bowel diseases, such as Ulcerative Colitis and Crohn's disease, cause degradation of the mucosal barrier throughout the gastrointestinal (GI) tract. This leads to afflicted regions of intestinal tissue having higher permeability, increasing the uptake of undesired bacteria and exacerbating inflammation. Bioimpedance is a direct monitoring method that has been identified to relate tissue conductivity with alterations in permeability. Through integration of a bioimpedance sensor on the surface of an ingestible capsule, we can wirelessly measure impedance throughout the GI tract (Fig. S1a). However, adapting these sensors to maintain performance in the GI environment is challenging. Here, we present the fabrication of a tetrapolar impedance sensor with poly 3,4-ethylenedioxthiophene (EDOT) and polystyrenesulfonate (PSS) dopant (PEDOT:PSS) electropolymerized onto gold (Au) electrodes for minimal fouling in simulated GI fluids (Fig. S1b). The PEDOT:PSS film decreases electrode interfacial impedance while enhancing the charge transfer capability (CTC).

The Au electrodes are patterned onto a polyimide substrate with photolithography, electron-beam evaporation, and liftoff. The sensor is coated with a biocompatible Parylene-C layer to insulate the electrical traces, and the electrodes and contact pads are subsequently exposed using reactive ion etching (Fig. S2a). The electrodes are coated with a PEDOT:PSS film via chronopotentiometry (CP) using a BioLogic VSP potentiostat (current density: 5μA/mm^2) for 180s in a solution of 10mM EDOT and 2M PSS (Fig. S2b). The CTC of bare Au and PEDOT:PSS electrodes were characterized using cyclic voltammetry (CV) in phosphate buffered saline (PBS), resulting in a 375-fold increase in current response for the PEDOT:PSS sensor (Fig. S3a). Sensor reliability and drift were verified using simulated gastric fluid (SGF, pH 1) and simulated intestinal fluid (SIF, pH 6.8) to represent the traversal through the GI tract. Electrochemical impedance spectroscopy (EIS) measurements from 100Hz to 100kHz were recorded at 5-minute intervals over 90 minutes with the EVAL-AD5940BIOZ development kit while the sensor was immersed in the GI fluids. Overall, the impedance measurement remained invariant with frequency; hence, 10kHz was selected for analysis. The average impedance over time was observed to increase at 7.6%/hr and 0.04%/hr for SGF (Fig. S3b) and SIF (Fig. S3c), respectively. These results demonstrate minimal sensor degradation over prolonged exposure to GI fluids, marking an important step towards realizing non-invasive bioimpedance sensing in the GI tract.

4:00pm **MN2-ThA-8 Development of Ingestible Capsule Technologies for Sensing Gut Serotonin Toward Understanding the Gut-Brain Axis**, ***Sydney Overton***, *Michael Straker, Reza Ghodssi,* University of Maryland, College Park

Serotonin (5-HT) is a biomarker of the gut-brain axis (GBA), regulating neurological and gastrointestinal (GI) functions such as mood and GI motility. Notably, 95% of 5–HT is produced in the GI tract and secreted below the epithelium. Furthermore, 5-HT is implicated in GI and neurological diseases, motivating interest in understanding 5-HT dynamics for diagnostics, treatments, and unveiling the underlying pathways of the GBA. However, research insights have been limited by the absence of appropriate tools for quantifying 5-HT in the gut. Here we present a system engineering approach to address this critical technology gap using ingestible capsules. We report the miniaturization of an electrochemical biosensor and integration with a meso-scale electromechanical actuator to create a module for real-time quantification of subepithelial-5-HT (Fig. S1).

Our novel biosensor for penetrating the GI epithelium and measuring underlying 5-HT features a surface-modified carbon fiber microelectrode (CFME) working electrode and a quasi-reference/counter electrode (QRCE). Fabricated using additive manufacturing and microfabrication, the QRCE incorporates four 3D-printed microneedles (MN) with 60μm sharpness and is functionalized via electron-beam deposition. Directly assembling the biosensor in a micromotor-driven cam and follower (CnF) mechanism simplifies assembly, resulting in a more compact module. Future integration with custom printed circuit board (PCB) electronics would enable precise control of actuation and electrochemical measurements, while biocompatible packaging ensures safe traversal through the GI tract.

We modeled the integrated biosensor-CnF using dynamic simulation to estimate actuation time and displacement of the follower, demonstrating a total displacement of 1.0mm at a cam angle of 45.8°. Next, we demonstrated the repeated actuation of the CnF, where the biosensor was displaced outside the capsule 823±28μm in 0.3s, dwells for 5s for an electrochemical measurement, then returns inside the capsule shell (Fig. S2e). Subsequently, we measured the CnF's actuation force to be 3.85±0.1mN, which is 10x greater than the 0.3mN insertion force of the biosensor previously characterized (Fig. S3a-b). To validate the biosensor, cyclic voltammetry (CV) was conducted in Agar GI tissue phantoms spiked with 10μM 5-HT. The resultant peak oxidation current of 0.1μA at 0.4V compared to a PBS control confirmed the electrochemical detection of 5-HT (Fig. S3c). By integrating MEMS biosensing and meso-scale actuators into a compact module, we have demonstrated the first step towards an ingestible capsule capable of detecting micromolar concentrations of 5-HT.

MEMS and NEMS
Room Ballroom BC - Session MN-ThP
MEMS and NEMS Poster Session

MN-ThP-1 Statistical Analysis of 3D Printability and Mechanical Performance in Reinforced Polymer Composites*, Vladimir Milosavljevic,* School of Physics, Clinical & Optometric Sciences, Technological University Dublin, Ireland*; Alison J. Clarke, Denis P. Dowling,* I-Form Centre, School of Mechanical & Materials Engineering, University College Dublin, Belfield, D04 C1P1 Dublin, Ireland

The study explores the challenges and opportunities in 3D printing continuous fiber-reinforced polymers, with a focus on Polylactic Acid-Stainless Steel Fiber (PLA-SSF) composites. Statistical analysis of the printed parts highlighted deviations from design specifications, especially in acute angles and tight radii, emphasizing the need for optimized printing parameters and tooling paths. Fiber migration and excess polymer deposition were identified as key factors influencing geometric distortions, particularly at smaller radii and more acute angles. The study also developed a curvature bending stiffness (CBS) testing methodology to assess the mechanical performance of PLA-SSF composites, comparing them with neat PLA, nylon with short carbon fibers (Onyx), and nylon with continuous carbon fibers (Onyx-cCF). Results showed that PLA-SSF composites exhibited the highest CBS, with stiffness increasing linearly as radii decreased from 20 mm to 3 mm. PLA and PLA-SSF samples failed by tensile fracture, while Onyx samples deformed without fracturing. By employing statistical techniques, the study achieved a robust analysis of the printability and mechanical performance. The non-parametric Kruskal-Wallis test allows for the comparison of medians across multiple groups, such as different materials or different geometries, providing a reliable way to assess differences in mechanical performance without relying on normal distribution assumptions. Moreover, regression analysis is valuable for modeling relationships between printing parameters and outcomes such as dimensional accuracy or mechanical performance. This technique helps optimize printing parameters to achieve better results. Further, the Wilcoxon Signed-Rank Test, a nonparametric method, is useful for comparing as-printed dimensions with designed dimensions, especially when data does not follow a normal distribution. It provides a robust way to assess deviations from design specifications. The findings highlight the geometric limitations of 3D printing continuous fiber-reinforced polymers and suggest that adjusting printing speeds and tooling paths can mitigate distortions. This work provides critical insights into optimizing the printability and mechanical performance of reinforced polymer composites for advanced manufacturing applications. Moreover, the findings not only provide insights into improving the geometric accuracy and mechanical properties of 3D-printed composites but also suggest potential applications in structural health monitoring and sensor technologies. This work contributes to advancing the understanding of reinforced polymer composites for high-performance manufacturing applications.

MN-ThP-2 Performance of Copper Filled Through Glass Vias for Radio Frequency Applications*, Jessica McDow,* *Scott Grutzik, Matthew Jordan,* Sandia National Laboratories

The material properties of glass such as low dielectric constant and loss, low roughness, adjustable coefficient of thermal expansion (CTE), and low electrical conductivity at high frequencies make it a desired material for high function radio frequency (RF) device interposers.[1] Through glass vias (TGV) are a key technology for incorporating 3D integration techniques into RF devices as a way of improving device performance, increasing I/O per unit volume, simplifying design and assembly, and allowing for a more compact system. Vias are typically filled with copper (Cu) to form an electrical connection from one surface to another. Although TGVs are a promising technology, they are subject to thermo-mechanical reliability challenges due to the interaction between glass and Cu during thermal cycling. The thermal mismatch between copper (CTE_{Cu}= 16.7e^{-6}/°C) and glass (CTE_{glass}= 3.4-9.0e^{-6}/°C) can cause reliability issues, such as glass fractures, Cu protrusion, and Cu via sliding and delamination which are difficult failure mechanisms to predict.

In this work, Corning SG3.4 glass was bonded to an Si carrier with vias fabricated of diameters 30 um, 50 um, and 75 um in both square and hexagonal arrays with three different pitches being investigated 120 um, 160 um, 200 um. These samples were tested in various methods to study the mechanical and thermomechanical stability of Cu filled TGVs. For thermomechanical stability, the vias were filled with Cu through an electrochemical depTosition (ECD) process with a 30 nm platinum seed layer. The variation in TGV geometry was studied to determine the yield strength of glass for the different TGV geometries and densities. This was used to develop optimal design and process parameters for future TGV applications in RF devices. The Cu filled TGV samples were heated in a reflow oven which allows for controlled ramp rates and dwell times while keeping the substrates in an inert environment. Observed fractures and Cu protrusion was recorded to determine yield strength. Mechanical stability was studied through various flexure method tests to understand how the glass performed with the various via densities. This work demonstrates novel design and process parameters for reliability of through glass vias for future generation RF devices. Different via geometries and densities were analyzed to determine the yield strength of a glass interposer, relieving stress and reliability issues within RF devices.

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[1]K. Pan *et al.*, *2021 IEEE 71st Electronic Components and Technology Conference (ECTC)*, pp. 1660-1666, doi: 10.1109/ECTC32696.2021.00263.

MN-ThP-3 3D Microfluidic Integrated Electronic Packaging for Enhanced Thermal Management via Two Photon Polymerization*, Angel Yglecias,* University of Texas at El Paso

Thermal management currently stands in the way of optimizing chip performance for the increasingly powerful and compact microsystems needed for heterogenous integration. Utilizing 3D printing, this work addresses these current thermal management limitations by actively cooling a device die mounted directly onto a microfluidic channel, to provide a package level cooling solution. Historically thermal management has been addressed at the board level through heat sinks and lead frames, where the package simply provides a passive thermal conduction conduit between the lead frame and PCB below. Designs to incorporate active cooling onto PCBs have shown promise but require larger systems real estate and are not in direct contact with the die, limiting performance. Alternatively, die level cooling designs use standard microfabrication techniques to etch channels directly onto the backside of semiconductor dies to yield high performance, but at the cost of increasingly the complexity of the cleanroom fabrication steps. The proposed design is a printed microfluidic pin-fin cooling package printed using two photon polymerization (2PP). 2PP uses a laser to selectively cure a photopolymer resin or photoresist, allowing direct writing of polymer microstructures with features down to 200 nanometers. Through 3D printing, not only do structural design options become vast, but optimization of microfluidic effects, thermal resistance, and heterogeneous integration can be performed. We have previously demonstrated metal microfluidic packages using direct metal laser sintering, but this work explores the capabilities and resulting performance of 3D microfluidic packaging utilizing 2PP manufacturing techniques. Where previous work utilized designs with no variable features in the Z-direction, the 2PP packaging work implements spiral topologies to enhance fluidic interactions with the die. Scanning electron microscopy and fluidic cooling performance are explored to characterize the 2PP manufactured microfluidic packages for comparison to the state of the art.

MN-ThP-4 Nanomechanical Response of Magnetic 2D Materials Across Phase Transitions*, Timofei Savilov,* *Makars Šiškins, Konstantin Novoselov,* NUS Institute for Functional Intelligent Materials, Singapore

Recently identified as extremely promising candidates for next-generation nanoelectromechanical systems (NEMS), magnetic 2D materials are particularly well suited to applications where magnetic ordering and mechanical motion are tightly coupled, such as sensors and spintronics. The high area-to-volume ratio of suspended 2D resonators makes them highly sensitive to magnetic phase transitions through strain change detected by mechanical properties such as resonance frequency and dissipation.

We explore the coupling of magnetic ordering to nanomechanical response as a function of external conditions, including temperature and magnetic field. Theoretical modeling is done using Landau phase transition theory to analyze the magnetic behavior. The theory used focuses on the dynamic regime and does not rely on assumptions of small deflections, which makes it suitable for more general applications under extreme conditions. The model is also tested against experimental data obtained on $CrBr_3$ and $FePS_3$ nanodrums.

This work provides the basis for further development of improved NEMS sensors and actuators that use phase transitions to enhance performance.

MEMS and NEMS
Room 205 ABCD W - Session MN1-FrM
Integration and Multiphysics

Moderators: Philip Feng, University of Florida, **Jaesung Lee**, University of Central Florida

8:15am **MN1-FrM-1 MEMS-Enabled Photonic Integrated Circuits*, Marcel Pruessner*,** *Todd Stievater, Nathan Tyndall, Steven Lipkowitz, Jacob Bouchard, Kyle Walsh,* US Naval Research Laboratory **INVITED**

Photonic integrated circuits (PICs) are maturing and are rapidly finding application beyond telecommunications, including for sensing and quantum photonics. Many of these applications require PICs that operate at non-telecom wavelengths (e.g. in the visible wavelength spectrum) as well as PICs with new functionality enabled by micro-electro-mechanical systems (MEMS). In collaboration with AIM Photonics, we have developed a foundry PIC platform optimized for visible wavelengths focusing on reducing propagation loss and designing efficient PIC components[1]. At the same time, we have also investigated novel functionality in PICs enabled by MEMS. This presentation will focus on “MEMS-enabled photonic integrated circuits,” their fabrication and incorporation in PIC foundries, and novel functionality enabled by combining PICs with MEMS. A variety of MEMS-enabled PIC devices will be discussed including MEMS-tunable phase shifters[2] and optical cavities[3], optical forces in cavity optomechanical systems[4], mode conversion using MEMS perturbation[5] and phase matching[6], and broadband waveguide thermal emitters[7] enabled by MEMS bulk micromachining techniques[8].

[1] https://doi.org/10.1117/12.3012847 and https://doi.org/10.1364/OE.504195

[2] https://doi.org/10.1364/OE.24.013917 and https://doi.org/10.1364/OSAC.419410

[3] https://doi.org/10.1063/1.2883874 and https://doi.org/10.1364/OL.44.003346

[4] https://doi.org/10.1364/OE.19.021904 and https://doi.org/10.1103/PhysRevLett.108.223904

and https://doi.org/10.1021/acsphotonics.8b00452

[5] https://doi.org/10.1364/OE.488624

[6] https://doi.org/10.1364/OL.474806

[7] https://doi.org/10.1038/s41467-024-48772-6

[8] https://doi.org/10.1063/5.0252536

8:45am **MN1-FrM-3 Slot Mode Optomechanical System for Mass Sensing*, Cheeru Thrideep,*** University of Alberta, Canada*; Miroslav Belov,* NRC, Canada*; Wayne Hiebert,* University of Alberta and The National Institute for Nanotechnology, Canada

Optomechanical systems have demonstrated their significance in sensing applications. We study a slot mode optomechanical system where in a THz optical mode from a Photonic Crystal (PhC) cavity is coupled to a MHz mechanical mode of the cantilever to construct an effective mass sensitive device specifically operating at low-frequency region.

In slot-mode optomechanical devices, the coupling of photonic and phononic beams is utilized to enhance the optomechanical coupling strength beyond what is achievable in single nanobeam crystals. We consider the integration of Silicon PhC with cantilevers on either side which essentially behave as a slot mode optomechanical system. A modified inline coupling technique in reflection mode is used to couple light into the cavity by manipulating losses at the mirrors. To achieve this, the coupling end of the waveguide is provided with only 1 to 5 holes to access different coupling regimes. We utilized COMSOL to model our slot-mode optomechanical system, considering both photonic and phononic bandgap. The PhC- cantilever system was fabricated, and the chip underwent testing through a pump and probe system to evaluate the device’s mass sensitivity. We were able to realize a mass sensitivity of 51zg despite the encountered temperature fluctuation noise. This aligns with the notion that our shorter cantilever demonstrated an improved G of 0.12 GHz/nm, as compared to the value achieved by our research group for a longer cantilever coupled to a racetrack resonator.

9:00am **MN1-FrM-4 Integration of Metal Microsystems for Gas Sensing*, David Hayes*,** *Henry Davis, Jeremy Cook, Jordan Grow, James Harkness, Isa Kohls, Richard Vanfleet, Brian Jensen, Nathan Crane, Robert Davis,* Brigham Young University

Microfluidic devices are a versatile and powerful class of analytical and production tools with applications spanning medical diagnostics, drug development, food safety, and chemical production among others. A subset of microfluidic devices are microscale gas chromatography columns, which offer high speed chemical separations and system miniaturization. Hermetic sealing of micro chromatography channels and interfaces are challenges that have inspired a wide range of solutions. We will describe our developments in interfacing to both 3D printed metal microcolumns and machined metal microfluidic structures using pressure-controlled microbrazing.

9:15am **MN1-FrM-5 Nanomechanical Resonances of Graphene Membranes Integrated on $LiNbO_3$-on-Insulator Chips*, Nawara Tanzee Minim*,** *S M Enamul Hoque Yousuf, Yunong Wang, Philip Feng,* University of Florida

We present the integration and dynamic characterization of graphene membrane suspended over engineered dual-depth trench structures on a lithium niobate ($LiNbO_3$) -on-insulator (LNOI) substrate for probing out-of-plane flexural resonances. The substrate comprises a 600 nm $LiNbO_3$ film atop 4.7 μm thermally grown SiO_2 and a bulk silicon handle wafer, enabling piezoelectric compatibility and optical transparency. The device features rectangular trenches (12 μm × 70 μm, 300 nm deep) patterned via lithography and etching, with centrally embedded circular cavities (12 μm diameter, 1.5 μm deep) fabricates with focused ion beam (FIB) milling after carbon coating to introduce localized geometric perturbation. The structure is actuated using a broadband piezoelectric shaker coupled to the chip, inducing flexural motion across the suspended regions, and resonance modes are detected using laser interferometry. This architecture enables the comparative analysis of flexural eigenmodes in shallow vs. deep trench regions, highlighting the effect of local stiffness gradients, boundary conditions, and air damping. The use of $LiNbO_3$ as the underlying substrate introduces unique opportunities for acousto-optic and electro-mechanical coupling due to its strong piezoelectric and nonlinear optical properties. By leveraging the anisotropic elastic constants of $LiNbO_3$ and the high mechanical compliance of graphene, this platform facilitates the study of mode hybridization (coupling between localized modes of the deep circular trench and delocalized modes of the surrounding shallow trench, mediated by the continuous graphene membrane) and strain-tunable resonances through in-plan actuation of piezoelectric response in nanoscale membranes. Furthermore, the dual-depth trench geometry introduces spatially varying boundary stiffness, enabling mode localization and geometric control over frequency splitting. These architectures are compatible with SAW devices and $LiNbO_3$ photonic circuits, offering a pathway to integrated NEMS-photonic systems for sensing, transduction, and filtering applications.

MEMS and NEMS
Room 205 ABCD W - Session MN2-FrM
2D and NEMS

Moderators: Marcel Pruessner, Navel Research Laboratory, **Yanan Wang**, University of Nebraska-Lincoln

10:30am **MN2-FrM-10 Optomechanical Resonant Pixels with Metasurface and Phonon Engineering for Uncooled Infrared (IR) Detection*, Philip Feng*,** University of Florida **INVITED**

In this invited talk, we will present experimental demonstration and theoretical analysis of ultrathin trampoline-shaped nano-optomechanical resonators with strong potential for uncooled ultrasensitive infrared (IR) detection. We analyze and design trampoline resonators with high opto-thermal-mechanical transduction responsivities, strong thermal isolation, and multiple high-Q nanomechanical resonances that are suitable for low-noise optical transduction. We explore optimized designs by analyzing and understanding the multiple engineering tradeoffs involving both properties of the constitutive materials and parameters of geometric design and fabrication processes.We demonstrate resonant pixels enabled by various ultrathin trampoline designs, made of both silicon nitride (SiN) and atomically thin 2D materials. 05

11:00am **MN2-FrM-12 Controlled Thinning of Semiconductor Membranes Using Low-Fluence Laser Pulses at MHz Frequencies***, **Shahadat Hossain**, Renato Camata,* University of Alabama at Birmingham

Free-standing ultrathin membranes of two-dimensional (2D) materials exhibit distinct mechanical, electronic, and optical properties compared to their bulk counterparts, making them promising for novel nanoscale devices. Controlled thinning of these membranes is an effective approach for customizing them to nanoelectromechanical systems (NEMS). In this study, we show that low-fluence laser pulses at MHz frequencies allow precise thinning of molybdenum disulfide (MoS_2) membranes.

MoS_2 flakes exfoliated from bulk crystals are freely suspended over 5-µm diameter circular wells of 285-nm depth, etched on silicon wafers. The thinning process is monitored using Fabry-Perot interferometry (633-nm laser), which allows measurement of the resonance frequency and Q-factor of the membranes. The fluence of the MHz frequency-modulated thinning laser (405 nm) ranged from 10 µJ/cm^2 to 30 µJ/cm^2, which is significantly lower than that of single-pulse laser irradiation techniques typically used in 2D material thinning.

We employ existing models from thin plate elasticity theory and tension-dominated membrane theory to predict the resonance frequencies of plate-like and membrane-like resonators. This provides insight into the frequency scaling of 2D membranes as a function of the number of atomic layers. We validate the models by experimental resonance frequency measurements. This combined experimental-theoretical approach enables accurate layer differentiation and Q-factor extraction, permitting basic studies of the nanomechanical properties of our resonators. Our experimental system integrates charge-coupled device imaging with resonance frequency analysis, allowing layer quantification. In a typical experiment, the resonance frequency of a plate-like resonator initially measures 47 MHz but suddenly drops to 25 MHz. The resonance frequency then increases monotonically with time until it reaches 51 MHz as the Q-factor varies from 5.5 to 71. The abrupt frequency drop corresponds to a sudden change in the number of layers from 130 to six. The six-layer membrane is then gradually thinned until eventually reaching monolayer thickness after multiple hours of irradiation. These findings reveal a variation in mechanical stiffness consistent with a shift between plate and membrane regimes. In the plate regime, the abrupt resonance change is likely driven by laser-induced superheating, whereas in the membrane regime, material removal via sublimation results in a gradual frequency evolution. This MHz variant of laser thinning allows precise control over MoS_2 layer thickness down to the monolayer limit and may contribute to advancing NEMS fabrication in next-generation devices.

11:15am **MN2-FrM-13 Electrical Tunability of AlN Nanoelectromechanical Resonators***, **Sariha Azad**, Tahmid Kaisar, Timothy Caplice,* University of Florida*; Philip X.-L. Feng,* University of Florida, Gainesville

Electrical tunability in piezoelectric resonators is essential for applications requiring reconfigurable frequency control, including radio-frequency (RF) communications, sensing, and analog computing. Among available piezoelectric materials, aluminum nitride (AlN) stands out due to its CMOS compatibility, low dielectric loss, and high acoustic velocity, making it a strong candidate for integration into tunable MEMS platforms. Prior work has demonstrated voltage-induced frequency modulation in AlN resonators through piezoelectric field coupling, and strain-mediated deformation. Contour-mode AlN resonators with DC-bias-induced stress have shown frequency tuning ranges of 10–50 kHz under 20–80 V, with performance constrained by anchor loss and *Q* degradation[1] Laterally vibrating AlN resonators have demonstrated similar shifts, with tuning rates of 100–300 ppm achieved using field-induced strain, though these effects become increasingly nonlinear at higher voltages[2]. In AlN, the modest electromechanical coupling limits tuning efficiency, with practical frequency shifts typically below 100 ppm under DC biases approaching the dielectric breakdown threshold, ranging from 40 to 120 V for 100–150 nm thick films depending on quality and deposition conditions. In this work, we show a comparative study of out-of-plane flexural mode AlN resonators. Two device architectures have been fabricated, the first type is a buckled membrane, comprising a compressive-stress 120 nm-thick AlN layer on top of a tensile low- or high-stress SiN base (50–100 nm). The second type is a non-buckled membrane, formed without SiN to create a flat, mechanically neutral structure. Both types incorporate a symmetric Pt/AlN/Pt stack with 25–75 nm-thick electrodes. The resonators have been characterized with applied DC polarization voltage swept between 0 and 5 V to analyze the voltage responsivity of resonance frequency. The experimental results show that buckled AlN membrane NEMS resonators exhibit negative voltage responsivities ranging from −3.58 to −6.33 kHz/V over resonance frequencies of 5–9.4 MHz. On the other hand, the non-buckled membranes demonstrate a positive voltage responsivity of 2.83 kHz/V over the resonant frequency at 1.78 MHz. Across both device types, frequency shifts of ~20 kHz have been achieved under low tuning voltages (up to +/-5V), without reaching nonlinearity.

[1]G. Piazza et.al. “Piezoelectric Aluminum Nitride Vibrating Contour-Mode MEMS Resonators,” *J. Microelectromechanical Syst.*, vol. 15, no. 6, pp. 1406–1418, Dec. 2006

[2]R. Tabrizian and F. Ayazi, “Laterally-excited silicon bulk acoustic resonators with sidewall AlN,” pp. 1520–1523, Jun. 2011

11:30am **MN2-FrM-14 Probing Velocity Limits of Resonant SiC Electromechanical Cantilevers***, **Aswathi Madhu**, Philip Feng,* University of Florida, Gainesville

In inertial sensing applications harnessing resonant micro/nanoelectromechanical systems (MEMS/NEMS), maximizing velocity while ensuring structural integrity poses important challenges in design, fabrication, and characterization of the resonant transducers. This study aims to explore the limits of velocity of such devices built on a SiC thin film platform to exploit the excellent elastic properties of SiC including its high fracture limit. We report on analytical modelling and computer simulations, combined with experimental investigation of the velocity limits of singly-clamped SiC NEMS cantilevers lithographically patterned on a 500 nm-thick 3C-SiC film on top of 500 nm SiO_2 insulating layer on Si substrate. The specific goal is to determine the highest achievable velocity by enhancing displacement amplitude without exceeding the material’s fracture limit.

In this study, first theoretical analysis is done to explore the trade-off between maximum displacement amplitude and resonant frequency, and the results are validated using finite element simulations in COMSOL Multiphysics^{TM}. The fundamental resonant frequencies of SiC cantilevers, with dimensions 8 µm × 200 nm × 500 nm, are 3.25 MHz for in-plane and 6.32 MHz for out-of-plane motion. The preliminary results from initial measurements show a linear dependency between peak amplitude and applied actuation gate voltage, indicating the potential for scalable performance. These results provide insight into the dynamic range limitations MEMS structures operating near their mechanical limits.

To further study the material-dependent performance, the results are also compared with experimental data from 4H-SiC cantilevers fabricated using bulk micromachining and focused ion beam (FIB) milling. The comparison shows how the yield stress and fracture limit of 3C-SiC and 4H-SiC affect the estimation of the maximum achievable velocity. This work offers valuable guidance for designing future high-performance SiC inertial devices that balance velocity and structural robustness.

Author Index

Bold page numbers indicate presenter

Author Index