Quantum Science and Technology Mini-Symposium
Room 123 - Session QS1+EM+MN+PS-MoA

Materials + Devices for Quantum Systems

Moderators: Somil Rathi, Arizona State University, **Jaesung Lee**, University of Central Florida

1:30pm **QS1+EM+MN+PS-MoA-1 Elastic Layered Quantum Materials***, **Jiun-Haw Chu,*** University of Washington **INVITED**

Recently elastic strain has emerged as a powerful tool for probing and controlling quantum materials. By changing chemical bond lengths, elastic strain can modulate electronic structure up to very high energy scale. Additionally, as a second rank tensor, strain enables access to various instabilities associated with different symmetry channels. In this talk, I will discuss several examples of the application of strain to unconventional electronic orderings in van der Waals layered materials, including zigzag antiferromagnetism, charge density waves and excitonic insulators.

2:00pm **QS1+EM+MN+PS-MoA-3 Controllable Extended Defect States in Topological Insulators and Weyl Semimetals***, **Eklavya Thareja**, J. Gayles,* University of South Florida*; I. Vekhter,* Louisiana State University

Over the past decade study of topological materials has emerged as one of the most active areas in condensed matter physics, owing to a wide range of their proposed applications ranging from quantum computing to spintronics. What sets them apart from the materials currently used to build information technology is their robustness to disorder. However, in addition to the immunity of their electronic states against disorder, one needs ways to control the properties of these electronic states in these materials. We show that extended defects such as line defects and planar defects host localized states in Topological Insulators and Weyl Semimetals, which are two common topological materials. These localized states can be manipulated by controlling the scattering at the defects, for example, by using an external magnetic field. This leads to controllable spin accumulation and non-dissipative currents near the defects, due spin-momentum locking. These results bring us closer to functional applications.

2:15pm **QS1+EM+MN+PS-MoA-4 Topological Interfacial State in One-Dimensional h-BN Phononic Waveguide***, Y. Wang, **Sanchaya Pandit,*** University of Nebraska - Lincoln

Artificial topological structures have gained considerable research attention in the fields of photonics, electronics, mechanics, acoustics, and many others, as they promise robust propagation without loss along the edges and interfaces. In this work, we explored the topological states in one-dimensional (1D) phononic waveguides empowered by hexagonal boron nitride (h-BN), a hallmark two-dimensional (2D) material with robust mechanical properties that can support phonon propagation in high frequency regime. First, degenerate trivial and nontrivial topological structures were designed based on the Su-Schrieffer-Heeger (SSH) model. The dispersion engineering was then performed to match the passbands and bandgaps for these two topological structures through optimizing the geometric parameters of the unit cells. An interfacial state emerged when connecting these two sets of unit cells together and forming the 1D waveguide. The topological nature of this interfacial state, immune to structural and material parameter perturbation, was verified with the variation of strain and thickness in the waveguide. The phononic topological state studied here can be further coupled with defect-related quantum emitters in h-BN, opening the door for next-generation hybrid optomechanical circuits.

2:30pm **QS1+EM+MN+PS-MoA-5 Scanning Nano-Optical Imaging of Quantum Materials***, **Guangxin Ni,*** Florida State University

Scanning near-field Nano-Optical imaging is an invaluable resource for exploring new physics of novel quantum materials. Surface plasmon polaritons and other forms of hybrid light-matter polaritons provide new opportunities for advancing this line of inquiry. In particular, nano-polaritonic images obtained with modern scanning nano-infrared tools grant us access into regions of the dispersion relations of various excitations beyond what is attainable with conventional optics. I will discuss this emerging direction of research with two examples from 2D layered quantum materials.

2:45pm **QS1+EM+MN+PS-MoA-6 Engineering of Erbium-Implanted Lithium Niobate Films for Integrated Quantum Applications***, **Souryaya Dutta,*** College of Nanotechnology, Science, and Engineering (CNSE), University at Albany*; A. Kaloyeros, S. Gallis,* College of Nanotechnology, Science, and Engineering (CNSE), University at Albany (UAlbany)

Rare-earth-doped materials have garnered significant attention as material platforms in emerging quantum information and integrated photonic technologies. Concurrently, advances in its nanofabrication processes have unleashed thin film lithium niobate (LN), $LiNbO_3$, as a leading force of research in these technologies, encompassing many outstanding properties in a single material. Leveraging the scalability of ion implantation to integrate rare-earth erbium (Er^{3+}), which emits at 1532 nm, into thin film lithium niobate can enable a plethora of exciting photonic and quantum technologies operating in the telecom C-band. Many of these technologies also rely on coupling via polarization-sensitive photonic structures such as waveguides and optical nanocavities, necessitating fundamental material studies.

Toward this goal, we have conducted an extensive study on the role of implantation and post-implantation processing in minimizing implantation-induced defectivity in *x*-cut thin film LN. By leveraging this, we have demonstrated an ensemble optical linewidth of ~140 GHz of the Er emission at 77 K. Our demonstration showcases the effectiveness of our ion implantation engineering in producing cutting-edge Er emission linewidth in thin film LN at higher temperatures compared to values reported for diffusion-doped bulk materials at liquid helium temperatures (~3 K). Furthermore, we show that the Er photoluminescence (PL) is highly polarized perpendicular to the *x*-cut LN *c*-axis through a systematic and combinational PL and high-resolution transmission electron microscopy (HRTEM) study. These results indicate that using Er rare-earth emitters in thin film LN, along with their polarization characteristics and related ion implantation engineering, presents a promising opportunity to produce highly luminescent Er-doped LN integrated photonic devices for nanophotonic and quantum applications at telecom wavelengths.

3:00pm **QS1+EM+MN+PS-MoA-7 MBE Grown InAs/GaAs Quantum Dot Platforms with Spatial and Spectral Control for Quantum Devices***, **Nazifa Tasnim Arony,*** University of Delaware*; L. McCabe,* University of Delaware-Now at Yale University*; J. Rajagopal, L. Mai, L. Murray, P. Ramesh, T. Long, M. Doty, J. Zide,* University of Delaware

Epitaxially grown semiconductor quantum dots (QDs) have been well studied in the past few decades and have shown great promise as single photon emitters, and as a basis for potential qubits. These features of quantum dots grown on a semiconductor matrix make it a desirable platform/building block for quantum devices which has a wide-range of applications in quantum information, quantum sensing and quantum computing. For a complete epitaxially grown quantum device, spatial, spectral and structural homogeneity, optical tunability, and scalability are the key requirements. Recent work from our group has shown a method for site controlled QD growth where InAs QDs are grown on site-templated GaAs substrates with arrays of nano-pits.[1] However, achieving spectral homogeneity and good optical quality to ensure scalability is still a big challenge due to the size distribution of the QDs during growth, and impurities introduced in the regrowth surface from the fabrication processes respectively. This work addresses these challenges and explores three different objectives, first one being the domain of quantum dot columns (QDCs) as a buffer layer for the top QD-arrays of interest while burying defects/impurities underneath the QDCs. Additionally, initial experiments on spectral control of InAs/GaAs QDs by an in-situ method called ‘cap and flush’ are discussed, and the concept of quantum dot molecules (QDMs) is introduced for optical tunability in site-templated scalable device platforms.

[1] J. Vac. Sci. Technol. B 38, 022803 (2020).

3:15pm **QS1+EM+MN+PS-MoA-8 High Bandwidth Al-Based Single Electron Transistors for Silicon Quantum Dot Charge Sensing***, **Runze Li,*** University of Maryland, College Park*; P. Namboodiri, J. Pomeroy,* NIST-Gaithersburg

We have reduced the resistance of all-metal-based single electron transistors (SETs) for a 10 to 15 times higher operation current. This will provide more bandwidth and less noise to the SETs for eventual use as quantum dot charge sensors. People want to use the gate layer integrated all-metal-based SETs as charge sensors for quantum computing, but the long-remaining problem was the instability of readout due to the charge offset drift. Our group has developed stable aluminum-based SETs using plasma oxidation techniques, solving the instability problem. However, the devices we made are limited by the output current, typically <10 pA level when working in the single electron regime. The limitation on the current is due to the AlOx tunnel junctions' high resistance. Our goal is to bring up the output current up to ~100 pA level. We have been working on reducing the resistance of the AlOx thin film by reducing the plasma oxidation time and increasing the thin film area. We have seen a 10 to 15 times reduction in the resistance by varying plasma parameters. And we have also seen an obvious decrease in the resistance when increasing the tunnel junction area. We are continuing to develop data to study the quantitative relationship between the oxidation time/area and resistance. We are expecting to report the results of the reduced resistance in this talk.

MEMS and NEMS
Room 125 - Session MN1-TuM
RF and Magnetic MEMS

Moderators: Robert Davis, Brigham Young University, **Vikrant Gokhale**, Naval Research Laboratory

8:30am **MN1-TuM-3 Acoustoelectric Devices on Thin-Film Piezoelectric on Substrate Platform: Harnessing the Potential of Phonon-Electron Coupling***, Reza Abdolvand,* University of Central Florida **INVITED**

MEMS devices based on the thin-film piezoelectric on substrate (TPoS) platform, such as resonators, have demonstrated exceptional characteristics including low loss, high power handling, and low noise, enabling the creation of high-performance filters, clocks, and sensors. The TPoS platform also facilitates strong energy coupling between acoustic phonons and electrons, which can be harnessed for key radio frequency (RF) components in the micro-acoustic domain. This talk will review the advancements in utilizing the TPoS platform to achieve amplification, non-reciprocal transmission, and phonon mixing in a compact and energy-efficient manner. These innovations can simplify and miniaturize RF frontend modules, transitioning from passive RF filters to active amplifiers, isolators, and mixers, potentially reducing or eliminating the need for their electronic and magnetic counterparts. Despite the phonon-electron coupling, known as the “acoustoelectric effect,” being understood for over sixty years, only recent advancements in thin-film processing technology have enabled the development of scalable and manufacturable platforms with strong phonon-electron coupling. Heterostructures like thin-film lithium niobate on silicon, tailored to support specific acoustic waves with high electromechanical coupling and optimized electronic properties, offer a promising platform for scalable fabrication of miniaturized and energy-efficient “acoustoelectric” devices.

9:00am **MN1-TuM-5 Enhanced Performance of Thin-Film Lithium Niobate RF Acoustic Devices through Novel Material Process***, T. Busani, **Arjun Aryal,*** University of New Mexico*; S. Tiwari, D. Branch, A. Siddiqui,* Sandia National Laboratories, USA

Advancements in RF acoustic devices for telecommunications are significantly enhanced by the novel application of thin-film lithium niobate (LiNbO3), favored for its high electromechanical coupling. A persistent challenge in utilizing this material has been its compatibility with Si process manufacturing which results in poor quality device manufacturing. Moreover, the various spurious resonances present in those devices degrades the resonator efficient in storing energy, thus degrading quality factor Q and the electromechanical coupling coefficient k_t^2. This can be overcome typically by device design or by material processing, such as controlling the side walls roughness and their verticality. In this work we demonstrate how, comparing different edge treatments, i.e. different etching processes, we can both suppress spurious modes and increase the coupling coefficient at the main mode.

Unlike conventional methods, our innovative approach involves adjusting the surface roughness of the resonator's edges. In this study, resonators with specifically engineered roughened edges exhibited significant reduction and elimination of spurious resonances below 500 MHz frequency. This effect is more pronounced for a surface roughness of approximately 110 nm. Further explorations in this work demonstrate that varying the degree of roughness allows for controlled suppression behavior not only in the lower frequency range, but also potentially across broader frequency spectra. This method opens new opportunities for optimizing the performance of lithium niobate RF devices. Future investigations will focus on quantifying the effects of both higher and lower roughness levels to develop a comprehensive understanding of their impact on device performance across all operating frequencies.

Figure 1. (b) compares the resonant behavior between two resonators of same architecture with two different edged roughness. Several spurious modes, respectively at 50 MHz, 150 MHz, and 365 MHz are completely removed by the edge treatment process, while the peaks at 175 MHz and 250 MHz are greatly suppressed. The observed phenomenon is attributed to the ability of the roughened edges to scatter short-wavelength spurious modes, preventing the establishment of strong resonances.

9:15am **MN1-TuM-6 Garnet Based Integrated GHz Thin Film Inductors With High Quality Factor and High Inductance Density***, **Rafael Puig**, D. Hedlund, P. Kulik,* University of Central Florida

Demand for lighter and smaller devices is increasing, and thus the interest in thin film inductors (TFI) is rising. Inductors are key components in electronics and are used for e.g. power delivery and filters. Especially TFIs that can be heterogeneously integrated with e.g. existing silicon processing steps for integrated circuits. Furthermore, the inductor should be easy to fabricate. TFI need magnetic layer(s) and to magnetically bias the devices to be effective.

The magnetic material in a TFI should have a large permeability (μ) in the operating frequency (f_0). This can be achieved through the relationship $\mu \approx 4\pi M_s/H_a$, where M_s is the saturation magnetization and H_a is the magnetic anisotropy field. Kittel’s formula [1] of ferromagnetic resonance (FMR)

$$f_{FMR}=\gamma(4\pi M_s H_a)^{1/2}$$

where γ is the gyromagnetic gives rise to Snoek’s limit [2], where to achieve high μ, M_s/H_a should be large, whereas to achieve high FMR frequency $M_s H_a$ should be large. Frequencies near and above f_{FMR} yields that μ is mainly imaginary, i.e. a high magnetic loss tangent tan(δ), in this regime the inductor starts working resistively. In addition, the material should have low FMR linewidths, as this is related to dissipation processes, such as eddy currents in the material, which are mostly reduced with electrical insulation. This can be mitigated by using magnetic materials that are electrically insulated, such as ferrites in inductors.

The first published magnetic TFI dates back more than 50 years [3] and demonstrated a quality factor (Q) of 18 at an $f_0$of 10 MHz. Major advancements in thin-film inductors were made 10 years later when Soohoo [4] presented a thorough analysis on the requirements of the magnetic material and how high-performing TFI could be produced. It is rare to find thin film inductors operating in the GHz range with high Q, even though major advancements has been made in recent years [5–11].

In this work, we used Ansys Maxwell to model and design a $Y_3Fe_5O_{12}$ (YIG)-integrated TFI that has a f_0 in the GHz range, Q of 8, and an inductance density of 4300 nH/mm^2 when approaching magnetic saturation. We applied the magnetic field both in-plane and out-of-plane. The thin film stack used composed of 500 µm thick gadolinium gallium garnet substrate coated with a 10 µm thick YIG layer with M_s of 140 kA/m (1750 G), to which we placed a spiral inductor composed of 1 µm thick Cu wires with 270 µm spacing. This design was a compromise for rapid prototyping. We used YIG because it shows highμ [12] in the GHz range, with very few losses associated with dissipative processes. Future work will involve fabricating several designs to improve performance and incorporating with MEMS.

9:30am **MN1-TuM-7 Fabrication of Strip Line Micro Inductors Using Nickel-Iron Oxide Nanocomposite for Power-Supply on Chip Applications***, **Sai Pranesh Amirisetti**, D. P. Arnold,* University of Florida, Gainesville

The demand for miniaturized, more power efficient electronics has spurred the need for power supply solutions using novel magnetic materials that offer high permeability, operate at high frequencies, and minimize losses [1]. This study introduces a microfabrication technique for strip line inductors using nickel-iron oxide nanocomposite cores with an area of 0.07 mm^2, offering a significant advancement over traditional air-core or other magnetic-core microinductors.

Electro-infiltration, a process where a magnetic composite is formed by electroplating a metal through a deposited nanoparticle layer, yields a nickel-iron oxide nanocomposite with high relative permeability (~20) up to 300 MHz and low loss tangent [2,3]. The fabrication process, as shown in figure 1, involves deposition of the magnetic nanocomposite over patterned molds on a silicon substrate, followed by planarization, insulation layer deposition, seed layer deposition for copper electroplating, and finally a second deposition of the magnetic nanocomposite layer.

While there are relatively large device-to-device variations in this early-stage fabrication process, the experimental findings demonstrate that these nickel-iron oxide nanocomposite microinductors exhibit inductance between 0.5-1 nH and with a max quality factor between 4-6 at 100 MHz Furthermore, the compatibility of the fabrication process with semiconductor manufacturing techniques enables seamless integration for power system on chip (PwrSoC) applications.

This research contributes to the advancement of micro inductor technology for PwrSoC applications, shedding light on the potential of nickel-iron oxide magnetic nanocomposites as promising materials for high-performance on-chip power supply solutions.

References:

[1] Mathúna, Cian Ó., et al. "Review of integrated magnetics for power supply on chip (PwrSoC)." IEEE Transactions on Power Electronics 27.11 (2012): 4799-4816.

[2] Smith, Connor S., et al. "Electro-infiltrated nickel/iron-oxide and permalloy/iron-oxide nanocomposites for integrated power inductors." *Journal of Magnetism and Magnetic Materials* 493 (2020): 165718.

[3] Mills, Sara C., et al. "Method for the fabrication of thick multilayered nickel/iron oxide nanoparticle magnetic nanocomposites." *Journal of Magnetism and Magnetic Materials* 542 (2022): 168578.

9:45am **MN1-TuM-8 Rapid Fabrication of Tunable Resonators on Garnet based Magnetic Thin-Films***, **Nicholas Gagnon**, M. Franz, M. Gamez, D. Hedlund, R. Abdolvand, P. Kulik,* University of Central Florida

Current MEMS-based resonators are limited in frequency tunability by providing a narrow operational frequency range or requiring complex architectures. These challenges impose practical limitations for tunable devices operating over desired large frequency ranges (>5%). For the first time, an Al/YIG/GGG (aluminum, yttrium iron garnet, and gadolinium gallium garnet) tunable resonator was fabricated using rapid laser lithography. This tunable resonator requires zero static power and leverages a permanent magnet to provide a magnetic field bias (H_{ex}). YIG is a promising material for tunability due to high permeability (μ), low losses and low Gilbert damping [1–6]. The ferromagnetic resonance frequency, the shift in frequency due to a H_{ex}, can be calculated using Kittel's equation (eq. 1) [7],

$$f_{FMR}=\gamma(4\pi M_s H_a)^{1/2},\text{(eq. 1)}$$

where M_s,H_a,γ is the saturation magnetization, magnetic anisotropy field and gyromagnetic ratio respectively. The H_{ex} applied by the permanent magnet shifts the operational frequency of the device, hence providing tunability. Using finite element method (FEM) simulations, we have designed a device that can operate between 0.5 and 2 GHz with a quality factor (Q) of 200. Q is calculated using eq. 2,

$$Q=f_{res}/(\Delta f_{3db}),\text{ (eq. 2)}$$

where f_{res} is the resonance frequency and Δf_{3db} is the 3-dB bandwidth. The results of the FEM simulations can be seen in Figure 1(A) together with the model in Figure 1(C). Compared to conventional lithography our method can prototype devices in *seconds* on any garnet material stack. The resonator presented here was manufactured in <10s and shows tunability of 33%. Figure 1(C) shows the tunability, and the resonator can be seen in Figure 1(D). The Q factor of the fabricated resonator operating near 1 GHz is 130. For a rapid prototyping method, that eliminates conventional lithography, a Q factor that is more than 50 % of expected from simulations is promising.

Future efforts will delve into investigating means to improve our fabrication method, i.e. smaller feature sizes as it is applicable to a wide range of devices. Additionally, we are focusing on concentrating H_{ex} using flux-based techniques providing additional tunability. The thin-film resonator presented here shows great potential to compete with commercially available sphere based YIG-resonators, with much smaller size and ease of manufacturing.

MEMS and NEMS
Room 125 - Session MN2-TuM

Heterogeneous Integration and Packaging

Moderators: Robert Davis, Brigham Young University, **Vikrant Gokhale**, Naval Research Laboratory

11:00am **MN2-TuM-13 Advanced Packaging Driven Heterogeneous Integration***, **Robert Patti**,* NHanced Semiconductors Inc **INVITED**

Introduction

Semiconductors are an amazing success story. Since their introduction in 1959 they have found their way into every segment of our lives – transportation, entertainment, medicine, communication, weaponry, etc.At each step the chips became smaller, faster, cheaper, and more powerful, in a progression known as Moore's Law.

Today, Moore's Law is slowing and the industry's path forward is less well defined.This paper introduces a new concept, Foundry 2.0™, that offers fresh solutions for the future.

Current Challenges

Scaling

Shrinking the transistors no longer produces inevitable gains. Each new node is more difficult and expensive to achieve and some elements, notably capacitors, actually perform more poorly at smaller sizes. Meanwhile, wiring is approaching its physical limits, consuming a larger share of the power and signal time and generating problematic capacitance.

Size and Yield

One solution to the scaling problem is to cram more functionality onto each chip. The resulting system-on-chip (SoC) dies are powerful but physically larger, which translates directly to poorer yield. In addition, all functionality is necessarily built in the same processes, which imposes compromises.

Cost vs. Innovation

The cost and complexity of today's leading-edge chips dictates that they be manufactured in vast quantities to achieve economies of scale. Customization is out of the question and innovation is greatly constrained.

Foundry 2.0™ Solutions

Foundry 2.0™ is a manufacturing model that takes dies and chiplets from high-volume foundries and applies advanced packaging (AP) and other back-end-of-line (BEoL) processes to create specialized devices at lower volumes. Foundry 2.0 does not attempt to replace the existing industry, but to transform it. It does not compete with the high-volume leading-edge foundries; it works with them to penetrate the smaller markets where customization is prized.

As a neutral party, the Foundry 2.0 manufacturer can source its dies from any major foundry. Best-of-class components can be selected regardless of node, substrate, manufacturing process, or source, and then combined in 3D stacks or 2.5D assemblies that precisely fill the needs of specific markets.

By avoiding the high cost of building transistors Foundry 2.0 can economically produce smaller lots. Its high-mix low-volume model addresses markets that high-volume fabs simply cannot afford to accommodate. Foundry 2.0 makes innovation profitable again.

11:30am **MN2-TuM-15 Advances in Reliability Monitoring and Failure Analysis in Three-Dimensional Microsystems***, **Matthew B. Jordan**, M. Bahr, L. Basso, A. Mounce, A. Ferris, J. McDow, J. Christiansen, J. Walraven, W. Mook,* Sandia National Laboratories*; J. Lee,* University of Central Florida*; A. Jarzembski, W. Hodges, J. Carroll, B. Young, G. Pickrell, L. Yates, J. Neely,* Sandia National Laboratories

Three-dimensional, heterogeneous integration of microsystems has introduced new failure mechanisms while making it more difficult to screen and diagnose those failures. High-consequence applications require accurate reliability estimates; thus, we have developed *in-situ* reliability monitors for continuous surveillance. Furthermore, when components fail, we need to locate and characterize the failure mechanisms. To that end, we have adapted and developed novel failure analysis techniques for use in 3D microsystems.

In this manuscript we present two reliability monitors designed to provide granular detail on the state of health of a 3D microsystem. The first generalizes daisy-chain analysis methods based on network flow. The individual 3D interconnects are treated as vertices in a network where when they are cut it alters the maximum flow through the network. In this way, data on the failure rate of individual interconnects can be accurately determined with a smaller set of tests than a standard daisy chain where the network is severed after a single failure. The second reliability monitor is an *in-situ* strain gauge based on the Si piezoresistive effect allowing for localized measurement of the fatigue of 3D microsystems.

Secondly, we will discuss some methods used to localize and characterize failures in 3D microsystems. As we cannot access the surface of the components as we would in a planar system, we must rely on subsurface probing methods. The first of these methods is frequency domain thermoreflectance (FDTR), which utilizes a pump/probe laser system to characterize the thermal interfaces of a 3D microsystem. We find with FDTR that after sufficient sample preparation, small changes in microbumps can be resolved based on their thermal transport properties. Secondly, EM field analysis as nitrogen-vacancy in diamond based magnetic field measurements and scanning electric field measurements have been utilized to determine short-circuit and open circuit defects. Lastly, electrical frequency has been used to characterize components as they age (power spectrum analysis).

Guaranteeing the reliability of 3D microsystems is crucial for high-consequence systems. Monitoring system reliability and effectively localizing and analyzing failures are essential for providing this guarantee.

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MEMS and NEMS
Room 125 - Session MN1-TuA
Bio and Environmental MEMS

Moderators: Matthew Jordan, Sandia National Laboratories, **Yanan Wang**, University of Nebraska-Lincoln

2:15pm **MN1-TuA-1 Gaede-Langmuir Award Talk: Ingestible Technologies for Disease Assessment and Treatment in the Gastrointestinal Tract*, Reza Ghodssi*[1]*,* University of Maryland, College Park **INVITED**

MEMS and Microsystems have shown the potential to improve healthcare through advanced monitoring and treatment approaches among other applications. Microsystems, like wearable electronics, that interface with the body have been thoroughly explored in academic research and commercially. A rising field of research is the development of ingestible technologies to address gastrointestinal (GI) and related diseases. The GI tract is the only internal organ that can be non-invasively accessed, so it provides a gateway to analyze bodily processes and reach specific organ systems for treatment. Moreover, digestive diseases affect more than 40 million people in the US alone. My group's research focuses on the development of ingestible tools for diagnostics and treatment of gastrointestinal and systemic diseases. Embedded electronics and sensors enable analysis of critical biomarkers, like hydrogen sulfide (H_2S) and tissue impedance, while actuators allow sampling and drug delivery at precise locations in tissue for diagnostics and highly effective on-command treatment. In this talk, I will discuss current progress toward integrated capsule systems capable of biomarker sensing, localized actuated drug injection and intestinal sampling for further analysis.

2:45pm **MN1-TuA-3 Packaging Development with an Integrated Wireless System for an Electrochemical Cardiac Biosensor*, Jorge Manrique Castro,*** The University of Texas at El Paso*; B. Walker, F. Kashem, S. Rajaraman,* University of Central Florida

Cardiovascular disease is one of the main causes of mortalities globally. It is of high importance to identify early conditions given by the analysis of biomarkers in blood such as troponin, D-Dimers and brain natriuretic peptide **[1]**. In order to capture information emanating from these biomarkers, BioMEMS technologies have emerged as solution for the development, and packaging of biosensors aimed for accurate diagnosis and prognosis of cardiac diseases **[2]**. Among them, wearable cardiac biosensors **[3]**, and point-of-care platforms **[4]** have been proposed.

Data collection, processing, and telemetry is a challenge due to limitations in power source, consumption, and range of operation accompanied by issues in biocompatibility, size, and hermeticity. There is also a lack of exploration in processing techniques for biocompatible materials to minimize wound infection; point-of-care immunosensors optimization to improve patient compliance; and continuous monitoring for making informed decisions in real-time to overcome any life threatening situation in the short and long term.

Here, we present the development of a cardiac microsystem for electrochemical sensing with wireless data extraction. Two workflows are presented: Packaging and system integration. Material processing for packaging was performed with multimodal and CO_2 lasers on fused silica. This material was selected due to its great biocompatibility, chemical and mechanical robustness, and its transparency to optical and RF signals **[5]**. **Fig. 1** details results from the laser micromachining process with different parametrization. After engraving a microcavity on fused silica quartz, laser confocal characterization was carried out to measure the 3D profile and surface roughness (**Fig. 2**). On the other hand, system integration started at the macrolevel with Arduino-based board (Elegoo Uno R3), bluetooth module (HC-05), and impedance converter board (EVAL-AD5933EBZ) as presented in **Fig. 3**. Miniaturization of the impedance board was implemented by extracting the AD5933 chip from the board (**Fig. 4**). It was connected and programmed using I^2C communication protocol and customized script **[6]**. To test impedance measurements, 1 kΩ resistor was used as device under test. Real, imaginary and magnitude impedance were collected and sent wirelessly to a remote laptop (**Fig. 5**).

Ongoing work exploring different techniques for etching glass are being studied. Miniaturization of the Arduino board and bluetooth module into a single microcontroller unit is in progress to reduce footprint. A flex circuit with an interdigitated electrode is conceived to be encapsulated within the fused silica cavity.

3:00pm **MN1-TuA-4 Self-Powered, Eco-Friendly, and Edible UV Sensors for Food Packaging Applications*, Pouya Borjian,*** *M. Chimerad, P. Pathak, H. Cho,* University of Central Florida

We present a novel self-powered ultraviolet (UV) sensor based on non-toxic and edible materials. UV radiation can play an important role in food spoilage. Prolonged exposure to UV can lead to the degradation of different nutrients such as vitamins in the food. Proper control and monitoring UV exposure levels are crucial to minimizing food spoilage and maintaining food quality throughout production and distribution. Although there are some sensors available in the food industry for detecting UV radiation, many of them are fabricated using toxic or harmful materials. Additionally, most of these sensors require external power sources to perform. In this work, a flexible UV sensor was developed based on a non-toxic and edible ethyl cellulose (EC) substrate coated with gold interdigitated electrodes using sputtering. The interdigitated electrodes were incorporated with an algae-based electrolyte and safe-to-eat zinc oxide (ZnO) nanoparticles as a UV-absorbent material. The formation of ZnO nanoparticles was characterized using scanning electron microscopy (SEM). Moreover, the optical response of the EC coated with the ZnO layer showed an absorbance edge around 370 nm compared to a bare EC film. The photocurrent response of the sensor was tested at various bias voltage and zero bias. At zero bias, the fabricated UV sensor displayed repeatable and steady photocurrent responses. In conclusion, a self-powered UV sensor was successfully demonstrated utilizing sustainable materials certified for food-grade applications.

3:15pm **MN1-TuA-5 Inkjet Printing of $AgNO_3$ inks With Solvent-Selective Morphologies on Liquid Crystal Polymer Substrates**, *L. Murthy, **Christian Zorman**, A. Hess-Dunning,* Case Western Reserve University

Inkjet printing offers unique prototyping and customization advantages for microfabricated biosensors, in particular sensors printed on flexible substrates. Electrochemical biosensors exhibit analyte sensitivities that increase with total exposed sensor area; therefore, rough or porous electrode structures with high specific surface areas are desirable for maximizing analyte sensitivity. In this work, we explored the properties of inkjet printed silver structures from plasma-reduced silver nitrate inks on liquid crystal polymer (LCP) substrates. LCP is an attractive substrate material for biosensing applications due to its biocompatibility, low moisture absorption and mechanical flexibility. Unfortunately, high quality printing of microscale structures on LCP can be challenging. We evaluated the pattern fidelity, conductivity, and surface morphology of silver nitrate in monoethylene glycol (mono-EG) and triethylene glycol (tri-EG) ink solvents in terms of their use in electrochemical sensors for measuring hydrogen peroxide concentration.

Inks were prepared by dissolving silver nitrate in a mono-EG/water or tri-EG/water solution. LCP substrates were prepared by cleaning the substrate surface with appropriate solvents and then exposing the substrates to a low power oxygen plasma. Structures were printed on the LCP substrates using a Dimatix inkjet printer. The substrates were then exposed to a low-pressure argon plasma to reduce the dissociated silver cations and form elemental silver.

We found that the ink solvent had a strong influence on all measured parameters. While the mono-EG ink demonstrated good print fidelity on LCP, the tri-EG ink displayed either excessively hydrophobic or excessively hydrophilic behavior, leading to poor print fidelity. Silver structures printed from the tri-EG inks displayed a sheet resistivity three order of magnitude higher than structures printed using mono-EG inks. Scanning electron microscope images indicated that silver structures from the mono-EG inks were dense and flat, while those from tri-EG inks had a rough surface morphology. As no single ink could meet the requirements for the hydrogen peroxide sensor, we developed a bilayer approach in which the interconnect and base contact pads were printed from the mono-EG ink and a sensing electrode consisted of a tri-EG/mono-EG bilayer. Compared to the smooth Ag from mono-EG inks alone, the addition of the rough Ag coating from the tri-EG improved the electrochemical sensitivity to hydrogen peroxide by a factor of 3.6. The bilayer approach allowed for leveraging the advantageous characteristics of both ink types for improving sensor characteristics.

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[1] **Gaede-Langmuir Award Winner**

MEMS and NEMS
Room 125 - Session MN2-TuA
MEMS Sensing and Computation

Moderators: Matthew Jordan, Sandia National Laboratories, **Yanan Wang**, University of Nebraska-Lincoln

4:15pm **MN2-TuA-9 Facile Fabrication of CuO/ZnO Heterojunctions from Sputtered Films UV Sensing**, *P. Pathak, **Mohammadreza Chimehrad**, P. Borjian, H. Cho,* University of Central Florida

UV sensors are highly demanded for environmental monitoring, healthcare, and manufacturing, where understanding UV radiation's impacts is essential. Despite the prevalence of silicon-based photodetectors, their reliance on external power and broad absorption spectra are significant drawbacks. Addressing these challenges, we present a novel low-cost wet chemical method for constructing CuO/ZnO heterojunctions from sputtered thin films. This technique simplifies the traditional complex fabrication processes by using a one-step oxidation of DC-sputtered zinc and copper films on ITO-coated glass slides, resulting in the formation of p-type CuO nanowires and n-type ZnO nanoparticles that create a self-powered p-n junction. The morphological and chemical properties of the fabricated heterojunctions were meticulously analyzed using Scanning Electron Microscopy (SEM), X-ray Diffraction (XRD), and X-ray Photoelectron Spectroscopy (XPS). These analyses confirmed the successful creation of heterojunctions, which are critical for the desired sensor functionality. The optical properties were evaluated through UV-visible spectroscopy, demonstrating a strong absorption in the UV range, which is essential for UV sensing applications. Photonic responses based on current-voltage (I-V) relationships under a 365 nm laser were examined. The fabricated sensing device exhibited excellent photovoltaic behavior with a significant increase in current under illumination compared to dark conditions, showcasing an ideal p-n junction behavior with impressive responsivity (0.108 A/W) and photosensitivity (114). These characteristics indicate an efficient separation of photo-generated charge carriers at the junction which facilitates a strong and stable photoresponse without the necessity for an external power source. This work not only pioneers a simplified approach to heterojunction fabrication but also positions the resultant UV sensors as a good candidate for sustainable, low-power applications. The development presents significant advancements over traditional multi-step and high-temperature processes, offering a promising avenue for the scalable, low-temperature production of efficient UV sensors out of sputtered films

4:30pm **MN2-TuA-10 Design and Development of a Wearable to Monitor UV Exposure**, ***Sushma Kotru**, S. Kothapally,* The University of Alabama

With more than 5 million diagnoses per year, skin cancer outpaces the instances of diagnosis for breast, lung, colon and prostate cancer combined. It is estimated that one in five Americans will have skin cancer at some point in their life and 90% of the most widely diagnosed skin cancers are from exposure to the sun. Excessive exposure to sunlight can result in sunburn, which over a period of time, under repeated sun exposures, is responsible for cell and DNA damage, increasing the risk of developing skin cancer. The extent and nature of the damage depends on the type and dosage of UV exposure and differs for individuals based on many factors including their skin type. Thus, having a way to monitor UV exposure and getting feedback on sun protection using a wearable would be beneficial.

Our group has developed a wearable using a UV sensor based on ferroelectric thin films which responds to UVA and UVB radiations. The sensor is fabricated on Si for scalability and future commercialization. In this talk fabrication and testing of the thin film-based UV sensors, approaches used to enhance the UV response of these sensors, integration of UV sensor with other electronic components to create a wearable for monitoring UV index in real-time, and development of a phone app will be presented.A review of similar wearables currently being researched or commercialized will be presented. Further, results and insights from market analysis and customer discovery from participation in NSF's I-Corps program will be shared.

4:45pm **MN2-TuA-11 Diamagnetically Levitating Graphite Plate Resonators**, *Y. Wang, S. Yousuf,* University of Florida*; J. Lee,* University of Central Florida*; P. Feng,* University of Florida*; **Alexander Gage**,* University of Central Florida

Diamagnetically levitated and trapped systems hold great promise for developing high-performance anchor-less resonant devices with excellent stability. This scheme generates sufficiently large levitation force via diamagnetism, effectively counteracting gravity and facilitating levitation at room temperature without external power. Also, they are mechanically isolated from the external environments, enabling outstanding stability and minimal energy dissipation.

In this work, we combine theoretical analysis with experimental investigations to explore the complete levitation and rigid body resonances of diamagnetically levitating millimeter-scale graphite plates. Leveraging the strong diamagnetic susceptibility of graphite, we employ a square graphite plate (length of L=2.5mm, thickness of t=0.5mm, and mass of m=7mg), which exhibits stable levitation above permanent magnets without requiring active control. The resonance motions of the levitating graphite device are excited by electrostatic or dielectric gradient forces and detected by using an ultrasensitive optical interferometry system. We observed two distinct rigid body resonance motions at frequencies of f_1=37.7Hz and f_2=49.1Hz with quality (Q) factors of Q_1=48 and Q_2=37 in atmospheric pressure at room temperature. Notably, we find that the Q factors are primarily compromised by air damping.

Our initial study represents a significant step toward developing stabilized levitating systems at room temperature with a large mass. Furthermore, the findings presented here shall contribute to building high-performance resonant sensors.

5:00pm **MN2-TuA-12 A Novel MEMS Reservoir Computing Approach for Classifying Human Acceleration Activity Signal**, *F. Alsaleem, **Mohammad Okour**, M. Megdadi, A. Al Zubi, M. Fayad,* University of Nebraska - Lincoln

Neuromorphic computing, drawing inspiration from the human brain, harnesses specialized hardware and software to mimic intricate information processing. A pivotal component within this domain is the Micro-Electro-Mechanical Systems (MEMS). This paper marks a pioneering effort by introducing a groundbreaking MEMS reservoir computing model that departs from conventional virtual node concepts. This novel approach couples multiple MEMS systems to create dynamic and high-dimensional responses. The primary objective of our study is to distinguish between walking and running signals based on acceleration measurements. Our research advances the boundaries of reservoir computing and MEMS applications and marks an important milestone in signal processing analysis and classification. In this paper, we achieved a remarkable classification accuracy of 96%, demonstrating the practical potential of this technology across various applications in wearable technology and beyond.

MEMS and NEMS
Room Central Hall - Session MN-ThP
MEMS and NEMS Poster Session

MN-ThP-1 Fundamental-mode Surface Acoustic Wave Magnetoacoustic Nonreciprocal Low-loss RF Isolator for Efficient Control of NV− Centers*, **Bin Luo,*** Northeastern University, US*; A. WINKLER, H. SCHMIDT,* SAWLab Saxony, Germany*; B. DAVAJI, N. Sun,* Northeastern University, US

Owing to long coherence time, high fidelity and easy optical initiation and readout of quantum states tuned by magnetic excitations over a broad temperature range, NV^- centers are intriguing solid-state platforms for quantum computing, communication, information processing and sensitive non-invasive nanoscale magnetic sensors [1-5]. Traditional control of NV^- centers were realized by microwave striplines or antennas, which consume high power on the order of 1~10 W but yields low magnetic field even at a short distance of 1 mm [6-8]. The surface acoustic wave (SAW) delay line driven spin wave enabled by magnon-phonon interactions exhibits superior properties of high-power efficiency, low noise and small footprint, leading to efficient voltage control of NV^- center. Recent demonstration of NV^- center excited states control by 5th-order-SAW-driven spin wave in a 20 nm Ni film shows comparable Rabi frequencies with 1300 times less power than microwave excitation [9]. However, the low magnitude of high-order SAW and the high damping of Ni film degrades the efficiency and coherence time of NV^- center control and hinders the realization of efficient control of NV^- center ground states exhibiting longer lifetime.

Recently, magnetoacoustic non-reciprocal RF devices exhibit substantial nonreciprocity with remarkable power efficiency and CMOS compatibility, making them ideally suited for low-power and one-directional quantum transducer. Non-reciprocal magnetoacoustic devices consist of a magnetic stack situated between two interdigital transducers (IDTs) on a piezoelectric substrate. By applying RF voltage on IDTs, the induced SAW propagates and interacts with SW in the magnetic stack. The strong magnon-phonon coupling leads to hybrid magnetoacoustic waves that exhibit a much higher backward loss rate than the forward one or vice versa. Ongoing research strives to enhance non-reciprocity strength and bandwidth while maintaining high transmission between device ports [10]. Despite successful demonstrations of magnitude or phase non-reciprocity in various magnetic stacks such as antiferromagnetically coupled $FeGaB/Al_2O_3/FeGaB$ stack [11-12], the insertion loss is still high (>50 dB) owing to the low transmission of SAW high-order mode. Here we demonstrated a low-loss magnetoacoustic non-reciprocal device driven by SAW fundamental mode at 2.87 GHz. The 10-dB low insertion loss and strong non-reciprocity of 23.5 dB/mm make the device potential for coherent and efficient control of NV^- center ground states and the realization of non-reciprocal quantum transducer for one-directional quantum information transfer.

MN-ThP-2 3D Carbon Nanotube Collimators Grown on a Transparent Substrate for Diffuse Spectroscopy*, **Bridget Kemper,** W. Parker,* Brigham Young University*; T. Westover,* Tula Health*; R. Vanfleet, R. Davis,* Brigham Young University

Miniaturized spectrometers could enable the application of spectroscopy in wearable devices such as fitness/health monitors. In prior work, miniaturized spectrometers with carbon nanotube parallel-hole collimators were fabricated for use in diffuse light spectroscopy. The miniaturized collimators were formed using carbon nanotube templated microfabrication (CNT-M). CNT-M collimators were grown on an opaque silicon substrate and removed for use. For the CNT-M structure to be robust enough for transfer, it requires significant carbon infiltration. However, this infiltration step results in increased sidewall reflection, impairing the collimation of light. Here we present the use of a transparent fused silica growth substrate. This allows the collimators to remain on the transparent substrate in spectroscopy applications, circumventing the need for infiltration and substrate removal steps. Omitting the carbon infiltration reduced sidewall reflection and improved collimation performance.

MN-ThP-3 Pressure Controlled Brazing to Form Microscale Metal Fluidic Interfaces*, **David Hayes,** J. Grow, H. Davis, B. Jensen, N. Crane, R. Vanfleet, R. Davis,* Brigham Young University

2D and 3D metal microchannels have been fabricated using diffusion bonding and metal additive manufacturing for applications including micro heat exchangers and microcolumns for gas chromatography. However, creating precise and robust fluidic interfaces remains challenging for these microchannel applications. Brazing is a potential method for forming microscale fluidic interfaces but introduces the risk of clogging the fluidic channel with the molten filler metal. Here, we present brazing methods for interfacing stainless steel capillary to microfluidic parts. We used a powder-based method of pressure control which allowed the filler metal to form a precise hermetic seal at the fluidic interface without clogging the channel. We demonstrate this method by hermetically interfacing two 100 µm inner diameter stainless steel capillaries without clogging. Along with pressure and flow testing results, scanning electron cross-sections (see example in the supplemental figure) show the morphology of the brazed interface.

MN-ThP-4 Concurrent Mitigation of Packaging Stress and Support Loss in Microacoustic Resonators*, **Maliha Sultana,** T. Hasan, J. Vivas Gomez, K. Chan, H. Mansoorzare, R. Abdolvand,* University of Central Florida

In this work, the effectiveness of compact isolation frames in mitigating the stress-induced frequency shifts and concurrently boosting the quality factor (*Q*) of piezoelectric MEMS resonators is studied. Piezoelectric MEMS resonators are a promising candidate for replacing quartz and capacitive resonators. However, having multiple anchor points makes them susceptible to failure due to packaging induced stress. Here, by introducing tailored trenches around said resonators and experimentally comparing their performance with baseline devices, it is shown that the stress-induced frequency shifts are reduced by up to ~94%. Moreover, compared to baseline, the isolation frame boosts the Q of the devices by up to 2.9x, while minimally impacting the device footprint.

Commercially available capacitive MEMS resonators have weak electromechanical coupling which results in higher loss and limits their application in low power scenarios. To overcome this issue, a viable solution is piezoelectrically exciting/detecting the vibration of a single crystal MEMS resonator, as shown in thin-film piezoelectric-on-silicon platform with promising results. However, commercializing this platform is challenging due to packaging and unwanted stresses (e.g., from die attachment material) that translate into the resonant body, causing frequency drifts. This is exacerbated by having two or more anchoring points to substrate that suspend the resonant body. To mitigate this impact, auxiliary trenches with specific geometry are designed (using COMSOL) adjacent to the resonant body to ensure compact footprint. Thickness-lamé mode resonators with low thermoelastic damping are designed and fabricated using a stack of 1um AlN on 21um Si with a frequency around 145MHz.

To evaluate, the resonator die is affixed to a PCB using an epoxy die attachment suspended over another PCB and supported with screws. Stress is applied by tightening screws to bend upper PCB while frequency response of the resonator is recorded by micro-probes connected to network analyzer. Experimental results show, the bending can cause a maximum frequency shift of 18KHz in baseline, which is reduced to around 1KHz (18x reduction) in a device with isolation frame. The curvature of the devices measured using Keyence 3-D Optical Profiler follows the same trend; devices with isolation frame show less bending which implies less impact from stress. Finally, the effectiveness of the isolation frame in reducing the anchor loss is evident by the higher measured *Q*s compared to baseline. Detailed experimental setup and results demonstrating the effectiveness of isolation frame is available in the provided supplementary document.

2D Materials
Room 122 - Session 2D+EM+MN+TF-FrM
2D NEMS and Strain Engineering

Moderator: Matthias Batzill, University of South Florida

8:45am **2D+EM+MN+TF-FrM-3 Longitudinal Sound Speed Determination in 2D Semiconducting Crystal of GaS by Broadband Time-Domain Brillouin Scattering***, **Watheq Al-Basheer,*** King Fahd University of Petroleum & Minerals, Saudi Arabia*; C. Viernes, R. Zheng, S. Netzke, K. Pichugin, G. Sciaini,* University of Waterloo, Canada

Due to their unique structure and exceptional physicochemical characteristics, 2D semiconducting materials like GaS have recently attracted significant interest, making them viable options for numerous photonic industries and applications. In this study, time-domain broadband Brillouin scattering measurements were performed on a single, flake-like gallium sulfide (GaS) crystal to determine the out-of-plane longitudinal sound speed, evaluated at (3140 ± 20) m/s. As a member of the group-III monochalcogenide semiconductors, GaS has recently attracted significant attention owing to its remarkable semiconducting properties.Moreover, its high absorption coefficient and efficient carrier mobility have made it a perfect candidate in many photonic and optoelectronic applications and industries, such as fast UV photodetectors,hydrogen evolution catalysis, field-effect transistors,energy storage, gas sensing, and nonlinear optics. The reported results demonstrate the effectiveness of this non-destructive, all-optical technique for investigating the elastic properties of fragile 2D layered materials and provide the value of the out-of-plane compressive elastic constant,

Keywords

Time-domain Brillouin scattering, coherent acoustic phonons, broadband transient spectroscopy,

elastic constant, sound speed, 2D semiconductors, GaS, layered materials.

9:00am **2D+EM+MN+TF-FrM-4 Laser-Induced Strain Tuning in Monolayer Graphene Nanomechanical Resonators***, **Muhammad Ashar Naveed**, S. Pandit, Y. Wang,* University of Nebraska - Lincoln

Graphene, as the paradigm-shifting two-dimensional (2D) material, has demonstrated great potential in micro-/nano-electromechanical systems (MEMS/NEMS) due to its extraordinary mechanical properties, ultimate device thicknesses, and unparalleled flexibility in integration. On the other hand, the atomic thickness and the transfer process employed in device fabrication pose challenges to achieving uniform strain over the entire device. In this work, we utilize Raman spectroscopy and investigate the strain distribution in drumhead resonators based on the mechanically exfoliated graphene monolayers suspended over patterned oxidized silicon (SiO_2/Si) substrates. Moreover, the effects of laser-induced heating and consequential strain tuning have been systematically explored by combining Raman spectroscopy and mechanical resonance measurements. This study sheds light on the strain engineering of monolayer graphene nanomechanical resonators, and the methodology developed is readily applied to other 2D materials and heterostructures.

9:15am **2D+EM+MN+TF-FrM-5 Developing 2D Snse for Piezoelectric Applications***, J. Chin, M. Frye, B. Gardner,* Georgia Institute of Technology*; D. Liu,* Penn State University*; M. Hilse,* Pennsylvania State University*; I. Graham,* Georgia Institute of Technology*; J. Shallenberger, K. Wang, M. Wang, Y. Shin, N. Nayir, A. can Duin, S. Law,* Pennsylvania State University*; **Lauren Garten,*** Georgia Institute of Technology

Unique functionalities can arise when 2D materials are scaled down near the monolayer limit. Tin selenide (SnSe) is one such 2D material which is centrosymmetric in bulk but becomes non-centrosymmetric when reduced to the monolayer limit, enabling piezoelectricity, and potentially, ferroelectricity. Developing 2D piezoelectric and ferroelectric materials is critical for the scaling of efficient sensors and electronics, such as ferroelectric field effect transistors. However, unlike other 2D materials, the strong interlayer bonding makes exfoliating a monolayer of SnSe challenging. Therefore, direct film growth is necessary to control the layer thickness and promote lateral growth large enough for device testing. This talk will focus on the development of processing routes to control the morphology and layering of SnSe thin films grown by molecular beam epitaxy (MBE) for piezoelectric devices. The bulk *Pnma* phase of SnSe is stabilized over a broad range of Sn:Se flux ratios from 250 – 300 °C on (100) MgO and (0001) Al_2O_3 substrates. Changing the flux ratio did not affect the SnSe film stoichiometry; increasing the flux ratio only changes the predominant crystallographic orientation. ReaxFF molecular dynamics (MD) show that the limited stoichiometric change is due to the formation of Se clusters that weakly interact with the surface of the SnSe particles. Changing the temperature, flux ratios, and flux timing had a significant impact on the morphology and orientation of the SnSe thin films. Machine learning was used to infer the critical processing parameters that are needed for creating an oriented, wafer-scale thin film. Overall, this study identifies the conditions for the growth of monolayer SnSe thin films necessary for the development of 2D piezoelectric devices.

9:30am **2D+EM+MN+TF-FrM-6 Two-Dimensional (2D) $FePS_3$ Nanoelectromechanical Resonators with Local-Gate Electrostatic Tuning***, **Yunong Wang**, S. Yousuf, X. Zhang, P. Feng,* University of Florida

Nanoelectromechanical systems (NEMS) based on 2D magnetic materials are promising candidates for exploring ultrasensitive detection and magnetostrictive phenomena due to their high mechanical stiffness, high strength, and low mass. The resonance frequency of the suspended membrane resonator can be probed optically and manipulated mechanically via electrostatically induced strain. This makes electrostatic frequency tuning of the 2D magnetic NEMS resonator a promising way for exploring the novel magneto-mechanical coupling mechanism. Towards building magneto-mechanical coupling NEMS devices, we fabricated circular drumhead $FePS_3$ NEMS resonators with different cavity-diameter sizes (3um to 7um). In this work, we report on experimental demonstrations of high-performance antiferromagnet $FePS_3$ drumhead resonators with the highest frequency tuning range up to 31.62%. We further perform analytical modeling to gain insight and quantitative understanding of the frequency scaling law for $FePS_3$ drumhead resonators. Combining our experimental results and analytical modeling of the resonances, we resolved the elastic behavior of $FePS_3$, including the transition from 'membrane-like' regime to 'plate-like' regime, with built-in tension (γ) ranging from 0.1 to 2N/m. This study not only offers methods for characterizing the mechanical properties of ultrathin membranes of magnetic 2D materials but also provides important guidelines for designing high-performance magnetic NEMS resonator devices and opens possibilities for building drumhead resonator devices to exploit strain- and dynamics-engineered applications based on ultrathin magnetic 2D crystals.

9:45am **2D+EM+MN+TF-FrM-7 Tunable Phononic Frequency Combs in Atomically Thin Resonators***, **S M Enamul Hoque Yousuf**, T. Kaisar,* University of Florida*; J. Lee,* University of Central Florida*; S. Shaw,* Florida Institute of Technology*; P. Feng,* University of Florida

Phononic frequency comb (PnFC), the analogue of optical frequency comb in the radio frequency (RF) regime, has attracted significant research interest due to its potential applications in sensing and computing. In this abstract, we report on PnFCs generation via an atomically thin molybdenum disulfide (MoS_2) nanoelectromechanical resonator. We first measure the nonlinear mode coupling coefficient (λ) due to 1:1 internal resonance from the first-principles approach. To describe the energy exchange between the coupled modes, we employ two resonator equations with a single dispersive coupling term to model the response. The coupled mode equations are solved using the method of averaging to derive a closed form expression for the nonlinear mode coupling coefficient.To calibrate the vibration amplitude of both modes in the displacement domain, we measure the undriven thermomechanical noise.The nonlinear shift of the resonance frequency of mode 1 (f_1) that results from the dispersive coupling to mode 2 is measured as we drive mode 2 near its natural frequency (f_2). We estimate the mode coupling coefficient using our derived model.Additionally, we investigate the impact of Duffing nonlinearity on the energy cycling of the modes.

We utilize the 1:1 internal resonance to couple energy between two modes. The resonator response can be tuned from stable periodic response to quasi-periodic response by controlling external perturbation signals, such as DC gate voltage, RF drive voltage and frequency. The resonator exhibits three unique comb regions with well-defined comb structure. We observe that the periodic and quasiperiodic branches exist for a particular drive voltage and frequency, based on distinct initial conditions. Our demonstration leads the way to achieving tunable PnFCs in nanoscale devices to study nonlinear modal interactions and build ultrasensitive sensors and computing devices.

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