# Monday Afternoon, November 7, 2022

## MEMS and NEMS Technical Group
## Room 302 - Session MN+2D-MoA

### Emerging Materials and Structures for MEMS/NEMS Devices

**Moderators: Azadeh Ansari**, Georgia Institute of Technology, **Yanan Wang**, University of Nebraska - Lincoln

1:40pm **MN+2D-MoA-1 Phononic Crystals based on Two-Dimensional Materials***, Yanan Wang,* University of Nebraska - Lincoln **INVITED**

Thanks to the ultimate thinness, excellent elastic properties, and unparalleled advantages in device integration, two-dimensional (2D) materials have emerged as compelling candidates for enabling high frequency nano-/microelectromechanical systems (NEMS/MEMS). This talk will discuss the further exploration of 2D materials in phononic devices, such as quasi-1D phononic waveguides and tunable phononic crystal lattices, emphasizing their potential applications in quantum information processing and quantum sensing systems.

2:20pm **MN+2D-MoA-3 Scaling Acoustics into mm-Wave: Higher-Order Lamb Mode Devices in Piezoelectric Thin Films***, Ruochen Lu, J. Kramer, S. Cho, O. Barrera,* The University of Texas at Austin **INVITED**

The evolving wireless communication moves to higher frequency bands with broader bandwidth for faster data rate. New types of front-end elements are required to perform the signal processing at the new bands. Acoustic devices are among the processing candidates, thanks to their compact footprints and low loss. However, It has been a long-standing challenge to scale piezoelectric resonators beyond 6 GHz without significantly losing quality factor ($Q$) and electromechanical coupling ($k^2$).

Until now, three approaches have been investigated, including reduced wavelength, higher-order modes, and multi-layer periodically poled piezoelectric films (P3F) structures. The first method requires small feature sizes, e.g., the electrode pitch width of laterally vibrating devices or the thickness of film bulk acoustic wave resonators (FBARs). The direct scaling inevitably leads to fabrication challenges and more importantly, severely reduced $Q$ from the electrical resistance and acoustic damping. The second approach utilizes the additional thickness component in higher-order Lamb modes to relax the lateral feature size requirement. However, sub-400 nm piezoelectric thin films are needed if operated at the first-order thickness mode, e.g., first-order antisymmetric (A1) mode, inducing limited $Q$ below 500 from the surface damages during the implementation. Alternatively, one can operate at higher frequencies using increased thickness mode order acoustic modes, e.g., second-order antisymmetric (A2) mode. Nevertheless, further increasing the mode order in the thickness direction without modifying the transducer configuration leads to reduced $k^2$, as the generated charge tends to cancel out, limiting the applications.

Recently, we proposed the P3F platforms using thin-film lithium niobate ($LiNbO_3$) to address the challenge. By stacking transferred thin-film $LiNbO_3$ with alternating orientations in the thickness direction, we can achieve remarkable frequency scaling without losing $k^2$ or relying on thinner films. Complementarily oriented bi-layer acoustic resonator (COBAR) following thickness-shear modes have been demonstrated. We will report COBARs leveraging the thickness-extensional (TE) modes at 15.8 GHz using sixth-order antisymmetric (A6) mode COBAR with a high loaded $Q$ of 720. The measured loaded $Q$ and $f{\cdot}Q$ product ($1.14{\times}10^{13}$) are among the highest for piezoelectric acoustic resonators beyond 6 GHz.

3:00pm **MN+2D-MoA-5 AlScN Piezoelectric Metamaterials for Next Generation RF Systems***, C. Cassella, **Dan Zhao**,* Northeastern University **INVITED**

In the last two decades, microacoustic resonators (µARs) have played a key role in integrated 1G-to-4G radios, providing the technological means to achieve compact radio frequency (RF) filters with low loss and moderate fractional bandwidths (BW<4%). More specifically, Aluminum Nitride (AlN) based filters have populated the front-end of most commercial mobile transceivers due to the good dielectric, piezoelectric and thermal properties exhibited by AlN thin-films and because their fabrication process is compatible with the one used for any Complementary Metal Oxide Semiconductor (CMOS) integrated circuits (ICs). Nevertheless, the rapid growth of 5G and the abrupt technologicalleap expected with the development of sixth-generation (6G) communication systems are expected to severely complicate the design of future radio front-ends by demanding Super-High-Frequency (SHF) filtering components with much larger fractional bandwidths than achievable today. Even more, the recent invention of on-chip nonreciprocal components, like the circulators and isolators recently built in slightly different CMOS technologies, has provided concrete means to double the spectral efficiency of current radios by enabling the adoption of full-duplex communication schemes. Nevertheless, for such schemes to be really usable in both military and commercial wireless systems, self-interference cancellation networks including wideband, low-loss and large group delay lines are needed. Yet, the current on-chip delay lines that are also manufacturable through CMOS processes, which rely on the piezoelectric excitation of Surface Acoustic Waves (SAWs) or Lamb Waves in piezoelectric thin films, have their bandwidth and insertion-loss severely limited by the relatively low electromechanical coupling coefficient exhibited by their input and output transducers. As a results, these components are hardly usable to form the delay lines forming any desired self-interference cancelation networks. In order to overcome these challenges, only recently, new classes of microacoustic resonators and delay lines exploiting the high piezoelectric coefficient of Aluminum Scandium Nitride (AlScN) thin films and the exotic dispersive features of acoustic metamaterials have been emerging. These devices rely on forests of locally resonant piezoelectric rods to generate unique modal distributions, as well as unconventional wave propagation features that cannot be found in conventional SAW and Lamb wave counterparts. In this talk, the design, fabrication and performance of the first microacoustic metamaterials based resonators and delay lines will be showcased.

4:00pm **MN+2D-MoA-8 Fabrication, Actuation and Control of 3D-Printed Microscale Robots***, Azadeh Ansari,* The Georgia Institute of Technology **INVITED**

This talk covers the fabrication methods of micro scale robots using two photon lithography nanoscale 3D printing of various micro robot designs for biomedical applications. The polymer-based 3D printed robots are integrated with piezoelectric actuators, or magnetic thin films/cubes. Tiny polymer legs/bristles and contacts are designed for precise robot motion control. Furthermore, the microbots are equipped with various mechanical add-ons such as micro-tips/needles for penetration into soft tissues, micromanipulators, micro-drillers, and PH sensitive drug delivery units.

4:40pm **MN+2D-MoA-10 Fabrication of Resistor-based Zinc Devices using Selective Chemical Deoxidation of Screen Printed Zinc Inks by Inkjet Printing***, A. Radwan*[1]*,* Case Western Reserve University*; Y. Sui,* University of Colorado at Boulder*; **Christian Zorman**,* Case Western Reserve University

Zinc (Zn) is a common metal that harmlessly decomposes in the environment and thus is considered a leading metal for use in environmentally-friendly electronics. Zn readily oxidizes under ambient conditions forming a thin, electrically-insulating zinc-oxide (ZnO) layer on the surface of Zn particles. Fortunately, conductive Zn structures can be formed by etching the ZnO layer using aqueous solutions of acetic acid dispensed by drop casting. Although drop-casting is simple to implement, dispensing extremely small volumes is difficult . As such, drop casting is limited to producing structures with high conductivity (i.e., electrodes) but is not suitable to produce structures with tunable resistivity.Although designed to dispense inks, inkjet printers are precision liquid dispensing systems capable of depositing picoliter droplets at designated locations. Therefore, it is feasible to use an inkjet printer as an acetic acidic dispenser to form Zn structures by selective etching of Zn-based inks. Unlike drop casting, this reactive inkjet printing (RIJ) process enables the resistivity of Zn structures to be tuned by controlling the amount of acetic acid dispensed. Moreover, inkjet printing offers precision lateral control of the dispensing process which could enable the fabrication of both conductive and resistive structures in the same Zn layer.

In this paper, a selective RIJ method to dispense an etching agent on screen printed Zn structures with a high degree of volumetric and spatial control is described. This RIJ process is used in conjunction with screen printing to precisely control the amount of acetic acid deposited on the surface of printed Zn structures. The number of print passes and drop spacing are utilized to precisely regulate the exposure of the Zn structures to acetic acid thus enabling unparalleled control of the etching process. The screen printing and RIJ processes are performed at room temperature, making them compatible with temperature sensitive substrates including many that are attractive for flexible, implantable and biodegradable electronics. The substrate only needs to be inert to acetic acid. This study specifically focuses on the formation of Zn structures with tunable resistivity and

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explores the relationships between key printing parameters and electrical resistivity of the resulting Zn structures. As process demonstrators, microheaters and RC filters are fabricated and characterized.

5:00pm **MN+2D-MoA-11 Mechanically Tunable One-Dimensional Photonic Crystals Fabricated by Two-Photon Polymerization***, **Victoria P. Stinson**[1], N. Shuchi, M. McLamb, G. Boreman, T. Hofmann,* University of North Carolina at Charlotte

Photonic crystals have attracted interest in optical applications, due to their highly reflective photonic bandgaps [1-3]. These photonic bandgaps are formed by creating a dielectric periodicity. Depending on the complexity of this periodicity the photonic crystal can be described as being one-, two-, or three-dimensional. In the one-dimensional case, this periodicity is created in a single direction. One-dimensional photonic crystals fabricated by two photon polymerization have demonstrated high-contrast photonic bandgaps in the infrared spectral range [2]. This is achieved by alternating layers of high- and low-density. In order to allow additional spectral filtering of the photonic bandgap, defects have also been implemented into these designs, allowing narrow band transmissions to exist within the otherwise reflective photonic bandgap [3]. While the spectral position of these features can be easily designed for a desired range, there are currently few methods for manipulating these features post-fabrication. Introducing mechanically sensitive flexures as low-density layers into these one-dimensional photonic crystals could fill this gap. Opto-mechanical devices fabricated by two-photon polymerization is an emerging field which has applications in areas such as MEMS and microrobotics [4]. The ability to control the spectral response via an external mechanical stimuli opens the door for more complex and adaptable sensing and filtering bandgap devices. The use of two-photon polymerization in the development of these devices allows for three-dimensional design freedom with efficient fabrication times. In this study we report on the use of sub-wavelength mechanical flexures in the low-density layers of one-dimensional photonic crystals fabricated by two-photon polymerization. Upon compression the change in thickness of these low-density layers will result in an overall spectral shift of the photonic bandgap. The degree of spectral shifting, as well as an analysis of the mechanical properties of one-dimensional photonic crystals with flexures are presented and discussed.

[1] H. Shen, Z. Wang, Y. Wu, B. Yang, RSC Adv. **6**, 4505-4520 (2016).

[2] Y. Li, D. Fullager, S. Park, D. Childers, R. Fesperman, G. Boreman, T. Hofmann, Opt. Lett. **43**, 4711-4714 (2018).

[3] V.P. Stinson, S. Park, M. McLamb, G. Boreman, T. Hofmann, Optics **2**, 284-291 (2021).

[4] Z. Lao, N. Xia, S. Wang, T. Xu, L. Zhang, Micromachines **12**, 465 (2021).

[1] **MEMS/NEMS Best Research Work Award**

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