MEMS and NEMS Technical Group
Room C120-122 - Session MN1-WeM

MEMS Processes, Materials, and Fabrication

Moderators: Benjamín Alemán, University of Oregon, **Jaesung Lee**, University of Central Florida

8:00am **MN1-WeM-1 Additive Manufacturing for 3D Metal Microsystems***, **Robert Roberts,*** The University of Texas at El Paso **INVITED**

Recent developments in precision additive manufacturing technology offer a new dimension in microfabrication design and fabrication. In this talk, the use of additive manufacturing for the realization of three-dimensional metal microsystems is explored via micro laser sintering (MLS). MLS is able to directly fabricate metal features from precursor metal powder with lateral resolutions of 15µm and layer heights of 5µm, making it well suited for the applications of MEMS, BioMEMS, and microsystems packaging.

An overview of the micro laser sintering fabrication process will be detailed, along with developments in new materials for MLS use. Multiple microsystems fabricated via this technology will then be highlighted including microelectrode arrays, high-temperature microfluidic reactors, and electrostatic relays.The use of metal additive manufacturing for the fabrication of metal microsystems packaging is presented. These system-in-packages (SiP) feature embedded microfluidic thermal management structures towards heterogeneous integration microsystems applications with high-power electronics. The additively manufactured devices were able to decrease the thermal resistance to 1.57ºC/W, compared to 5.25ºC/W for a conventional packages design.

8:40am **MN1-WeM-3 Epitaxial Materials and Devices for High Performance RF Acoustics***, **Vikrant Gokhale**, B. Downey, D. Katzer, M. Hardy, J. Roussos, S. Mack, J. Champlain, A. Lang,* US Naval Research Laboratory*; P. Dhagat, A. Jander,* Oregon State University*; E. Jin,* US naval Research Laboratory*; N. Nepal, V. Wheeler, D. Meyer,* US Naval Research Laboratory **INVITED**

Thin film piezoelectric materials are crucial for creating acoustic micromechanical systems (MEMS) for RF signal processing applications. Conventionally, the metal-piezoelectric-metal transducer materials have been deposited via sputtering, which generally lead to well-textured polycrystalline films. Recent advances in the epitaxial growth of Group III-Nitride (III-N) piezoelectrics, and transition metal nitrides (TMNs) electrodes have enabled all-epitaxial RF acoustic devices with crystalline, lattice-matched and acoustic impedance-matched layers. Such heterostructures are capable of direct integration with GaN RF electronics. In this talk, we shall discuss new opportunities provided by epitaxial RF acoustics, as well as constraints on materials selection, heterostructure growth, and fabrication processes.

Epitaxial RF acoustic devices developed at NRL include surface acoustic wave (SAW) devices, and epitaxial high overtone bulk acoustic wave resonators (epi-HBARs) with a III-N/SiC and III-N/TMN/SiC heterostructure, respectively. Epitaxial SAW devices are used as resonators and delay line filters for low-loss RF signal processing while epi-HBARs are multi-mode phonon cavities with a comb-like RF spectrum capable of extending beyond 40 GHz (Ka band) with extremely low intrinsic loss, which results in record ($f \times Q$) values and long cavity phonon lifetimes [1, 2]. Cryogenic experiments verify that epi-HBARs approach the fundamental limits of intrinsic anharmonic phonon loss [3] and may be well suited for applications such as RF oscillators and in quantum acoustodynamic systems. The near lattice-matched epitaxy of these heterostructures on 4H-SiC results in void-free films with high crystallinity, well-controlled phase and orientation, low defect density, and low surface/interface roughness [1, 4].

1. *Epitaxial bulk acoustic wave resonators as highly coherent multi-phonon sources for quantum acoustodynamics.* Nature Communications, 2020. **11**(1): p. 2314.
2. *X – Ka Band Epitaxial ScAlN/AlN/NbN/SiC High-Overtone Bulk Acoustic Resonators.* IEEE Electron Device Letters, 2023: p. 1-1.
3. *Temperature evolution of frequency and anharmonic phonon loss for multi-mode epitaxial HBARs.* Applied Physics Letters, 2020. **117**(12): p. 124003.
4. *Control of phase purity in high scandium fraction heteroepitaxial ScAlN grown by molecular beam epitaxy.* Applied Physics Express, 2020. **13**(6): p. 065509.

9:20am **MN1-WeM-5 Slanted Wire Diffraction Gratings Fabricated by Two-Photon Polymerization for Micro-Mechanical Applications***, **V. Paige Stinson**, U. Subash, M. Poutous, T. Hofmann,* University of North Carolina at Charlotte

The use of diffraction gratings in communication and sensing technology is expansive, ranging from their use in integrated optics and spectral analysis to quantum electronics [1]. Their effectiveness in these applications depend on the manipulation of reflected and transmitted efficiencies by the principles of interference and diffraction. Slanted wire gratings are a particularly useful grating geometry as they can be operated at normal incidence. The transmitted diffraction efficiencies of slanted wire gratings are sensitive to changes in slant angle [1]. In this study, this slant angle sensitivity is used to design a mechanically tunable diffractive grating. Motivated by the successful fabrication of infrared optics as well as micro-mechanical structures by two-photon polymerization, a resin compatible for fabrication by this approach (IP-Dip) is selected for modeling [2,3]. A rigorous coupled wave approach is used to determine a geometry which optimizes sensitivity to changes in slant angle. A geometry is selected such that the diffraction efficiency is transferred between the 0^{th} and $+1^{st}$ orders. The efficiency transferred modulates between 0% and 75% for changes in slant angle between 45° to 35°. Realistically, this change in slant angle can be achieved by applying compression to the grating. The mechanical capabilities of the grating are investigated using finite-element method simulations. A prototype slanted wire grating is fabricated by two-photon polymerization and the quality is characterized using scanning electron microscopy. The results of the numerical modeling are presented and potential micro-mechanical applications for their use as transmissive pressure sensors and tunable beam splitters are discussed.

[1] T.K. Gaylord, M. Moharam, *Proceedings of the IEEE*, **73**, 894-937 (1985).

[2] V.P. Stinson, N. Shuchi, M. McLamb, G.D. Boreman, T. Hofmann, *Micromachines*, **13**, 2248 (2022).

[3] V.P. Stinson, N. Shuchi, D. Louisos, M. McLamb, G.D. Boreman, T. Hofmann, *Optics*, **4**, 300-309 (2023).

9:40am **MN1-WeM-6 Very High Frequency Stability of Single-Crystal Silicon Thermal-Piezoresistive Resonators with Phase-Locked Loop***, C. Watkins,* University of Florida, Gainesville*; **Jaesung Lee,*** University of Texas at El Paso*; J. McCandless,* Cornell University*; H. Hall,* Air Force Research Laboratory*; P. Feng,* University of Florida, Gainesville

The Si piezoresistive MEMS heat engine first reported in 2011 [1] marked the start of research to examine the effects of self-sustained thermal-piezoresistive resonators (TPR) in applications such as sensing [2] and signal amplification [3]. TPRs are among a new class of actively transduced devices that offer performance benefits, specifically low motional resistance [4]. Besides, TPRs have the advantage of reduced thermal control needs thanks to the thermal-piezoresistive effect inherent to their operation and thus they could offer very high frequency stability. This paper reports a single-crystalline silicon (Si) TPR achieving very high frequency stability with phase-locked loop (PLL) measurement. A pair of resonators operating in a balanced-bridge configuration is presented, with one device being driven at resonance and the other used to systematically null the undesirable background response. The resonance frequency of the single Si TPR is collected over 40 hours in closed-loop tracking by PLL and yields an Allan deviation of $\sigma_A \approx 2.66$ppb for averaging time of $\tau \approx 4.95$ seconds - the lowest ever reported among all Si TPRs studied to date. This result is significant because it suggests that such Si TPRs can potentially achieve frequency stabilities comparable to, or better than, existing state-of-the-art resonators used in oscillator circuits, with significantly reduced thermal control requirements (ovenization) and subsequent power demands. In this work we examine the potential impact of utilizing the Si TPR to generate an ultra-stable frequency source. We hypothesize that the intrinsic internal feedback offers enhanced quality (Q) factor which could contribute to a higher frequency stability. Additionally, an external DC power feedback loop could improve Si TPR stability by removing the linear long-term background frequency drift that is present in all of our PLL measurements.

[1] P. G. Steeneken, *et al.*, *Nat. Phys.***7**, 354-359, (2011).

[2] A. Zope, *et al., Front. Mech. Eng*. **8**, 898668, (2022).

[3] A. Ramezany, *et al., Nano. Lett.* **18**, 2551-2556, (2018).

[4] A. Rahafrooz, *et al., Trans. Elec. Dev.* **59**, 3587-3593, (2012).

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