Multifunctional and Hybrid Microsystems
Room 318 - Session MC-TuM

Multifunctional and Hybrid Microsystems: MEMS and Bio Applications

Moderators: Prof. Dr. Jesse Berezovsky, Case Western Reserve University, **Prof. Dr. Jaesung Lee**, University of Central Florida

8:00am **MC-TuM-1 Ultralow-Dissipation Diamagnetically Levitated Graphite Rotors for Gyroscopic Inertial Sensing**, ***Samira Yasmin****, Pooja Roy,* University of Central Florida*; Yunong Wang, Philip Feng,* University of Florida*; Jaesung Lee,* University of Central Florida

Rotational degrees of freedom are nearly unconstrained, making levitated rotors compelling candidates for next-generation inertial sensors. By eliminating mechanical anchors entirely, this approach suppresses the dominant loss pathways—support loss and friction—that limit the performance of conventional gyroscopes. Here we report on a diamagnetically levitated pyrolytic graphite rotor platform operating under high vacuum, characterized through ringdown measurements, and analyzed toward practical gyroscopic readout.

The rotor is laser-machined from highly oriented pyrolytic graphite, which exhibits strong negative magnetic susceptibilities ($\chi_x = \chi_y = -85\times10^{-6}$, $\chi_z = -450\times10^{-6}$) enabling passive, stable levitation above a concentric permanent-magnet assembly integrated beneath a custom PCB. The annular rotor geometry (inner radius 2.175 mm, outer radius 4.175 mm, mass ~95 mg) concentrates rotational inertia at large radius.

Rotational actuation and sensing are implemented via a closed-loop system combining a 633 nm laser interferometer, FPGA-based digital timing, and a high-voltage (200 V) electrostatic pulse drive. The optical contrast between the graphite rotor arms and the PCB surface generates a periodic photodetector signal, from which the FPGA extracts instantaneous rotation speed and generates phase-synchronized drive pulses. Under vacuum conditions of 80−100 μTorr, where gas damping is substantially reduced, the rotor is driven to 410 RPM, after which free ringdown is recorded. The rotational speed decay follows $\Omega(t) = \Omega_0 e^{-\gamma t}$, yielding an extracted damping constant of $\gamma = 1.9\times10^{-4}$/s.

The measured γ and I_z directly set the thermomechanical noise floor, expressed as an angular random walk (ARW). At 410 RPM and room temperature, the thermal-noise-limited ARW is estimated at 2.28×10^{-4} °/√h, with a projected improvement to 9.1×10^{-5} °/√h at 1100 RPM. To connect this platform to practical gyroscopic operation, we derive an analytical scale factor linking optically measured out-of-plane rim displacement to input angular rate through the coupled tilt dynamics of the spinning rotor. Under the nearly symmetric rotor approximation in the weak-damping limit, the estimated scale factor is $S = 3.02\times10^{-5}$ m/(rad/s), implying that a 1 nm displacement resolution at the rotor rim translates to an angular-rate resolution of ~40 μrad/s upon full gyroscope readout implementation.

These results establish a quantitative performance framework for diamagnetically levitated graphite rotors, highlighting vacuum environment, spin-axis inertia, and tilt stiffness as the primary design levers for advancing sensitivity in compact, anchor-free rotational inertial sensors.

8:15am **MC-TuM-2 Influence of Fluid Dynamics on a Halide-Suppressor Electrolyte for Copper Electrodeposition in High Aspect Ratio Through Silicon Vias**, ***Jessica McDow****, Matthew Jordan,* Sandia National Laboratories

Through silicon vias (TSVs) are essential for three-dimensional microelectronic integration, enabling enhanced electrical and thermal connectivity. Copper electrochemical deposition (ECD) with halide-suppressor chemistries has achieved void-free, bottom-up filling of high aspect ratio TSVs[1]. However, the interplay between hydrodynamics, ion transport, and suppressor adsorption kinetics within these recessed features remains incompletely understood.

This work combines experimental electrochemical depositions and computational fluid dynamics (CFD) modeling to understand the critical role of fluid flow in governing copper deposition profiles within TSVs of a 70 μm diameter and 625 μm depth. Cyclic voltammetry (CV) on rotating disk electrodes reveals that increased rotation rates enhance suppressor replenishment, shifting the re-inhibition potential and diminishing hysteresis associated with the s-shaped negative differential resistance (S-NDR) behavior. Electrochemical deposition experiments demonstrate that rotation rate modulates deposition uniformity: low rotation rates lead to void formation due to insufficient suppressor transport, while excessively high rotation rates cause premature plating termination near the via opening due to enhanced suppressor adsorption.

CFD simulations confirm that convective flow penetrates only the upper ~100 μm of the via, establishing a hydrodynamic boundary layer where suppressor concentration approaches bulk levels, sustaining suppression and limiting deposition at the via mouth. Below this region, transport is diffusion-dominated, enabling concentration gradients that promote bottom-up filling. By strategically modulating rotation rates—starting at 400 rpm, increasing to 1000 rpm, then returning to 400 rpm—void-free filling is achieved with a 33% reduction in plating time from 18 to 12 hours.

These findings highlight the complex balance between convective and diffusive transport in controlling suppressor dynamics and copper deposition within TSVs. Understanding and harnessing fluid dynamic effects are crucial for optimizing scalable, high-throughput TSV filling processes in advanced 3D integration technologies.

[1] Schmitt, R. P.; Menk, L. A.; Baca, E.; Bower, J. E.; Romero, J. A.; Jordan, M. B.; Jackson, N.; Hollowell, A. E. Void-Free Copper Electrodeposition in High Aspect Ratio, Full Wafer Thickness Through-Silicon Vias with Endpoint Detection. *J. Electrochem. Soc.* **2021**, *167* (16), 162517. https://doi.org/10.1149/1945-7111/abd56e.

SNL is managed and operated by NTESS under DOE NNSA contract DE-NA0003525

SAND2026-21050A

8:30am **MC-TuM-3 Redefining Dynamic Limits of MEMS Resonators via Nonlinear Dynamics**, ***Hanna Cho****,* The Ohio State University **INVITED**

As resonant MEMS approach fundamental material and performance limits, new design paradigms are required to enable the next generation of sensing and timing technologies. Nonlinear dynamics are increasingly recognized as a pathway to overcome the constraints of conventional linear operation. Among these, internal resonance (InRes), in which two or more vibrational modes are nonlinearly coupled through integer frequency ratios, provides opportunities for dynamic range extension, frequency stabilization, and controlled intermodal energy transfer. Unlike traditional MEMS devices operating within narrow linear regimes, InRes enables energy exchange between coupled modes, allowing stable resonance to be maintained under large excitation levels and environmental perturbations. In this talk, I will present recent advances in understanding and engineering InRes in MEMS resonators through combined theoretical modeling and experimental validation. In particular, I will demonstrate how InRes can passively suppress frequency drift by anchoring the primary mode response to an InRes condition, effectively mitigating amplitude-to-frequency conversion induced by nonlinear effects. These insights have direct implications for the development of timing references with long-term frequency stability, as well as for the design of high-performance inertial sensors with larger scale factors. The results illustrate the emerging potential of nonlinear resonance as a transformative design paradigm for next-generation MEMS technologies.

9:00am **MC-TuM-5 Multifunctional AlN-Based MEMS Resonator Platforms for Advanced RF Filtering and Sensing Applications**, ***Mingyo Park****,* Pennsylvania State University **INVITED**

Next-generation wireless systems (5G and emerging 6G) are driving demand for RF nano/micro-electromechanical (N/MEMS) acoustic resonators that operate across the 3–30 GHz band. Future RF front-ends require compact, high-performance devices that deliver low insertion loss, wide bandwidth, multi-band compatibility, and robust high-power operation — requirements captured by the resonator figure of merit, FoM = $Q \times kt^2$. Pushing acoustic resonators toward higher frequencies, however, demands aggressive reduction of piezoelectric film and electrode thicknesses, introducing compounding mechanical and electrical losses that ultimately limit performance.

This talk will discuss recent progress in thin-film piezoelectric MEMS resonators built on ultra-thin epitaxial AlN and AlScN. AlScN has emerged as a particularly attractive piezoelectric due to its enhanced electromechanical coupling relative to conventional AlN. By pairing high-quality epitaxial films with optimized resonator geometries, film bulk acoustic resonators (FBARs) operating near 19 GHz [1] have demonstrated strong potential for compact filtering solutions in next-generation RF front-ends, while surfacing the central challenges of mm-wave acoustic design: electrode loss and material quality at extreme thinness.

Beyond passive filtering, piezoelectric MEMS resonators can also be engineered to support nonlinear electromechanical functionality through mechanical frequency comb generation [2]. When driven beyond a critical threshold, single or coupled resonators exhibit strong nonlinear modal interactions that produce equally spaced spectral lines in the mechanical domain. These phononic frequency combs can evolve from a few discrete sidebands into broad, tunable spectral clusters as device geometry, modal coupling, and drive conditions are varied. The resulting nonlinear dynamics offer a route to on-chip multi-frequency signal generation without the complexity of external circuitry.

Taken together, high-frequency acoustic filtering and nonlinear comb generation point toward a broader class of reconfigurable RF microsystems built on the AlN/AlScN piezoelectric material family. Such devices could enable compact filters, low-power frequency sources, spectral processors, and multi-frequency sensing architectures for future wireless and sensing networks. The talk will close by reflecting on how materials engineering, resonator design, and nonlinear dynamics can be combined to expand the functionality of piezoelectric MEMS well beyond conventional RF filtering.

[1] M. Park, et al., EDL.,2024 [2] M. Park, et al., JMEMS.,2019.

9:30am **MC-TuM-7 Electrochemical Sensing of Hormonal Serotonin Levels in Crayfish***, **Sydney Overton**, Kanishka Balamurugan, Jens Herberholz, Reza Ghodssi,* University of Maryland College Park

The neurotransmitter serotonin (5-hydroxytryptamine, 5-HT) has been implicated as a key biomarker that regulates a range of neurobehavioral functions, including playing a prominent role in modulating social behavior across species. Here, we refined a surface-modification method to enable detection of endogenous (i.e., naturally occurring), nanomolar concentrations of 5-HTfrom crayfish hemolymph (i.e., blood) collected from communally housed (COMs) animals and those isolated for one (1-day ISOs) or seven days (7-day ISOs). The three-electrode sensor for measuring 5-HT is comprised of a carbon-fiber microelectrode (CFME) working electrode, Pt counter electrode, and Ag/AgCl reference electrode. Previous *in vivo* measurements utilized a CFME electrochemically etched (EC) then dip-coated into a carbon nanotube (CNT)-Nafion dispersion (EC/CNT-Nafion). However, to match the electrochemical sensor's detection sensitivity, crayfish were injected with 5-HT. Here, we optimized the surface modification to improve signal-to-noise and sensitivity for *in vitro* 5-HT detection by dip-coating then electrochemically etching (CNT-Nafion/EC). Doing so improved the signal-to-noise ratio 2.8x and maintained the limit of detection from previous fabrication (60nM), enabling successful measurements of endogenous 5-HT *in vitro.*

To investigate how social isolation affects serotonergic mechanisms, we measured hormonal 5-HT in hemolymph from isolated and communally housed crayfish utilizing our CNT-Nafion/EC CFME.Voltammetry results show a clear oxidation peak at 0.29 V, demonstrating detection of un-spiked, hormonal 5-HT. Our findings indicate that 5-HT levels change in response to social isolation, and these changes are species-dependent. 7-day ISOs *Procambarus* (*P. clarkii)* crayfish exhibited a major increase in 5-HT compared to COMs, whereas *Faxonius* (*F. Spp*) crayfish hormonal concentrations of 5-HT peaked in 1-day ISOs. 7-day ISOs *P. clarkii* crayfish contained an average of 581.2nM 5-HT in their hemolymph, a 307.6% increase from COMs, and1-day ISOs did not have significantly higher concentrations compared to COMs. By comparison, *F. spp* 5-HT concentrations in 1-day ISOs were 867.5nM, a 540.1% increase in hormonal 5-HT concentrations compared to COMs, and 7-day ISOs 5-HT concentrations matched COMs.

The *in vitro* results demonstrate the sensor's utility for studying 5-HT dynamics and exhibit results strongly suggesting an underlying effect of social isolation on hormonal 5-HT. Moreover, our findings provide an exciting avenue for future studies, including those providing higher temporal fidelity on 5-HT changes that modulate neural activities and corresponding behaviors.

9:45am **MC-TuM-8 Development of Dissolvable Cantilevers for Localized Oral Drug Delivery***, **Yung Priscilla Lai**, Joshua Levy, Reza Ghodssi,* University of Maryland

Therapeutics to treat inflammatory bowel disease can cause severe systemic side effects. Localized drug delivery in the gastrointestinal (GI) tract can lower these side effects and increase drug efficacy. Our team has developed an ingestible device that can deliver drugs on-demand in the intestines with multiple cantilever actuators (Fig. S1a). The strained cantilever beams act as springs that can drive the penetration of drug-loaded microneedles into inflamed areas. The current polymer cantilevers made of polyether ether ketone (PEEK) films remain rigid but are not dissolvable, leading to risks of retention and unforeseen consequences as they remain in the body after drug delivery. Dissolvable and biocompatible cantilevers provide a safer alternative for targeted drug delivery in the GI tract.

The difficulty in using dissolvable polymer films as cantilevers arises from their low mechanical strength and stress relaxation under strain, undermining their ability to deploy drugs into the GI mucosa. We can improve these properties by changing the film's degree of crosslinking while maintaining film dissolution. Several crosslinked films were investigated: 1) polyvinyl alcohol (PVA), 2) PVA with citric acid (PVA-Citric) baked at 120°C for 4 hours, 3) freeze-thaw crosslinked PVA with 1M NaCl (PVA-NaCl), and 4) PEEK as a control. Polymer films were cut to size with a CO_2 laser cutter as the cantilever's length dictates its delivery range, ensuring the drug can reach inflamed areas further above the device surface (Fig. S2a). The films were then characterized for their blocking force (Fig. S1b and Fig. S2a), dissolution (Fig. S1c), and stress relaxation (Fig. S1d).

We measured the blocking force at the cantilever tip to evaluate whether polymer films could deliver drug-loaded microneedles without tissue damage. Crosslinking parameters that can provide higher blocking force at large cantilever displacements were identified. (Fig. S2a, PVA-NaCl and PVA-Citric vs. PEEK). Moreover, higher citric acid content appeared to increase film swelling for cantilever dissolution (Fig. S2b, PVA-Citric 80:20). Further materials optimization will enable lower PVA stress relaxation (Fig. S1d and Fig. S2c) while maintaining high blocking force and film dissolution.

Author Index

Bold page numbers indicate presenter