MEMS and NEMS Technical Group
Room Ballroom A - Session MN-TuP
MEMS and NEMS Poster Session

MN-TuP-1 Nanoelectromechanical Resonators Based on Mechanically Anisotropic 2D Material, ***Bo Xu***[1], *F. Xiao, J. Zhu, Y. Liang, C. Jiao, J. Li, Q. Deng, S. Wu, T. Wen, S. Pei, J. Xia, Z. Wang,* University of Electronic Science and Technology of China

The rich properties of atomic layer crystals enable researchers to design and fabricate micro/ nanoelectromechanical devices and systems towards signal processing and sensing applications. In particular, mechanical properties of two-dimensional (2D) materials play an increasingly important role in designing devices with predictable responses in order to achieve desired device performance, such as frequency and mode sequence in 2D nanoelectromechanical systems (NEMS) resonators.

Rhenium disulfide (ReS_2) crystal is a 2D semiconductor with weak interlayer coupling which can lead to relatively low Young's modulus (E_{Yz}=0.4 GPa) along the out-of-plane direction of the layered crystal. Interestingly, it exhibits strong in-plane anisotropy. However, its mechanical anisotropy has not been experimentally demonstrated yet. Here, we experimentally demonstrate ReS_2 nanomechanical resonators, and elucidate their mechanical anisotropy using multi-mode spectromicroscopy measurements.

ReS_2 nanomechanical resonators are fabricated by mechanically exfoliating MoS_2 crystal onto Si/SiO_2 substrates with pre-patterned cavities and electrode. We measure the multi-modal resonance response using a customized scheme that incorporates electrical driving and optical detection. For each resonance peak, by using XY stage and spectromicroscopy measurement scheme, we can visualize the mode shape. We then perform extensive calculations to fit to the experimental results. Specifically, we sweep the input parameters (E_{Yx} and E_{Yy}) in an FEM model for an anisotropic circular drumhead resonator, and pinpoint the optimal input parameters by minimizing the collective difference between measurement and calculation for all modes.

The thickness t and diameter d of the ReS_2 resonator are t =106 nm and d =10 μm. The frequency response of first six vibrational modes are shown in the Figure, respectively. Using the spectromicroscopy technique [8], the mechanical vibration modes shapes are visualized. We then run numerical simulations (using both mechanically anisotropic and isotropic models) to predict multimode response and mode shape of the ReS_2 resonator, and optimize the input Young's moduli to achieve the best agreement between measurement and simulation results. We find that the best result is produced by the mechanically anisotropic model, with E_{Yx}= 191 GPa and E_{Yy}=134 GPa for our ReS_2 device. We thus quantitatively determine the mechanical anisotropy in ReS_2.

In summary, we clearly prove that ReS_2 is mechanically anisotropic, and successfully obtain its Young's moduli.

Figures and Refs in PDF.

MN-TuP-2 Frequency Scaling in Electrically Tunable WSe_2 Nanomechanical Resonators, ***Jiankai Zhu***[2], *B. Xu, F. Xiao, Y. Liang, C. Jiao, J. Li, Q. Deng, S. Wu, T. Wen, S. Pei, J. Xia, Z. Wang,* University of Electronic Science and Technology of China

Nanomechanical resonators based on atomic layers of tungsten diselenide (WSe_2)show good promises for ultralow-power signal processing and novel sensing functions. However, frequency scaling in WSe_2 NEMS resonators remains yet to be explored, which impedes the realization of 2D circuits involving WSe_2 resonators at large scale. Here, we elucidate frequency scaling law in such 2D semiconducting resonators, and determine that the Young's modulus of WSe_2 is 130GPa. Further, by operating devices from the appropriate mechanical region, we demonstrate a broad frequency tuning range (up to 230%) with just 10V gate voltage, representing some of the highest gate tuning efficiency in 2D NEMS resonators reported to date.

We fabricate a total of 26 circular drumhead WSe_2 resonators of different diameters using mechanical exfoliation and dry transfer technique, with device thickness ranging from single layer to 127 layers. We measure the resonant response of WSe_2 resonators using a custom-built 2D resonator measurement system based on laser interferometry, in which the device's vibratory motion is transduced into optical signal and detected by a photodetector.

From measured data of all the devices, we determine that the Young's modulus E_Y of WSe_2 is 130GPa, in good agreement with theoretical predictionsand nanoindentation measurements, as well as the pre-tension to be 0.05-0.4N/m, in good agreement with other measurements.

We further analyze the frequency scaling and elastic transition of WSe_2 resonators. From the experimental data, we clearly observe the elastic transition from the "membrane" limit (left end) to "plate" limit (right end) in different devices, allowing us to fully explore resonant characteristics by leveraging the unique mechanical responses from each specific region. For example, we observe that devices with lower pre-tension see a greater relative change of total tension, and thus exhibit larger relative frequency shifts. We therefore choose the 8 μm-diameter, 18.4 nm-thickness device to demonstrate efficient gate tuning. This NEMS resonator exhibits clear and consistent gate tuning of frequency under three measurement schemes: electrical excitation, optothermal excitation, and thermomechanical resonance. We achieve an excellent tuning range $\Delta f/f_0$ reaching 230%, comparable to the best performance found in NEMS resonators, as well as a gate tuning efficiency of 23%V^{-1}, the highest among 2D NEMS resonators reported to date. Our resultsoffer important design guidelines for frequency tunable NEMS resonators based on these emerging 2D materials.

Fig & Ref in PDF

MN-TuP-3 Strain-Modulated Dissipation and Signal Transduction in Two-Dimensional Molybdenum Disulfide Nanoelectromechanical Resonators, ***Pengcheng Zhang***[3], *Y. Rui,* Shanghai Jiao Tong University, China

Resonant nanoelectromechanical systems (NEMS) based on two-dimensional (2D) materials such as molybdenum disulfide (MoS_2) are interesting for highly sensitive mass, force, photon, or inertial transducers, as well as for fundamental research approaching the quantum limit, by leveraging the mechanical degree of freedom in these atomically thin materials. For these mechanical resonators, the quality factor (Q) and signal transduction are essential, yet the mechanism for energy dissipation and accurate signal transduction model in 2D NEMS resonators have not been fully explored. Here, we present the accurate strain-modulated dissipation model and equivalent circuit model focusing on NEMS resonators based on a 2D semiconductor: MoS_2. We further show that for doubly-clamped resonators, the Q increases with larger DC gate voltage, while fully-clamped drumhead resonators show the opposite trend. Using DC gate voltages, we can tune the Q by ΔQ/Q = 120% for fully-clamped resonators, and by ΔQ/Q = 229% for doubly-clamped resonators. We develop the strain-modulated dissipation model for these 2D NEMS resonators, which is verified against our measurement data for a fully clamped resonator and a doubly clamped resonator. We find that static tensile strain decreases dissipation while vibration-induced strain increases dissipation, and the actual dependence of Q on DC gate voltage depends on the competition between these two effects, which is related to the device boundary condition. Furthermore, we find that strain also tunes the mobility and carrier density of MoS_2, and develop a strain-modulated equivalent circuit model for 2D MoS_2 NEMS resonators, to show the enhancement of signal transduction efficiency due to the strain effect. Such strain dependence is useful for optimizing the resonance linewidth and signal transduction efficiency in 2D NEMS resonators towards low-power, ultrasensitive, and frequency-selective devices for sensing and signal processing.

MN-TuP-4 Titania Nanotube Array Electrochemical Characterization and Integration Into a Mechanically-Adaptive Neural Interface, *D. Sacco, H. Wang, T. Stegall, A. Menon, Y. Yang, J. Capadona,* Case Western Reserve University*; H. Amani Hamedani,* ***Allison Hess-Dunning***, Louis Stokes Cleveland VA Medical Center

Optimizing the functional performance and lifetime of implanted biosensor technologies requires close integration and interaction at the biotic-abiotic interface. Devices that penetrate into tissue (e.g., intracortical neural interfaces) evoke biologically-mediated responses that isolate the device from the tissue and inhibit biosensing capabilities. Two materials strategies used to promote device integration with local tissue are 1) mechanically-compliant structural materials that reflect the mechanical properties of biological tissues, and 2) nanostructured materials that reflect the scales at which cells and proteins interact. Functional devices for biosensing are typically heterogeneous systems comprised of multiple materials that each

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

serve a purpose (e.g., structural vs. functional, conductive vs. insulating), suggesting that multiple strategies are needed within the same implanted device to improve integration with tissue.

Our team has augmented our previous mechanically-adaptive, polymer nanocomposite (NC) neural interfaces with nanostructured titania nanotube arrays (TNAs) as the sensing electrode material. TNAs are vertically-oriented, highly-organized arrays of nanoscale-diameter open-ended tubes that form from titanium in an electrochemical anodization process and have previously been shown to promote tissue integration. Implementing this dual-faceted approach to improving neural interfaces required 1) that the TNAs have a sufficiently low electrode-electrolyte impedance of <20 Ω·cm^2 at 1 kHz to facilitate sensing, and 2) a fabrication process to produce a functional device that incorporates TNA microelectrodes into the soft NC substrate. Electrochemical impedance spectroscopy was used to characterize a series of as-anodized and post-treated TNAs. The impedance magnitude and variability across a sample were heavily influenced by the processing conditions, with annealing at 450°C yielding the lowest impedance. Plasma-based surface modification lowered the impedance of samples by up to 83%, thereby bringing them into an acceptable impedance range. An inverted microfabrication process for integrating TNA microelectrodes into the NC structure was developed using a combination of photolithography and laser micromachining to produce a functional device with six layers in a four-photomask process. We expect that the improvements in integration with biological systems afforded by the combined tissue response mitigation strategies will enable the long-term, high-quality performance needed for advancing neuroscience and clinical brain-machine interfaces.

MN-TuP-5 One-Dimensional Photonic Crystals with Narrow-Band Defect Modes Fabricated by Direct Laser Writing, ***Victoria P. Stinson***, *M. McLamb, T. Hofmann,* University of North Carolina at Charlotte

The ability of two-photon polymerization to fabricate high contrast one-dimensional photonic crystals for the infrared spectral range has been demonstrated [1]. In general, photonic crystals induce a reflective photonic bandgap where transmission is forbidden. This is achieved by creating a dielectric periodicity in one-, two-, or three-dimensions [2]. One-dimensional photonic crystals create a dielectric periodicity in a single direction. These photonic crystals can be easily tuned to the desired spectral range by altering the geometrical structure. The introduction of defects which disrupt the dielectric periodicity of these one-dimensional photonic crystals can induce narrow band transparencies within the photonic bandgap. This spectral effect has recently been demonstrated in one-dimensional photonic crystals fabricated by two-photon polymerization [3]. Photonic crystals with defects show an increased sensitivity to layer thickness non-uniformity. For this presentation we will further analyze the sensitivity these photonic crystals have to this important fabrication parameter and discuss potential applications.

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

[2] A.H. Aly, H.A. Elsayed, Physica B **407**, 120-125 (2012).

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

MN-TuP-6 Ultra-High-Quality-Factor Membrane Resonators for Gas Pressure Sensing, ***Christoph Reinhardt***, Deutsches Elektronen-Synchrotron (DESY), Germany*; H. Masalehdan,* University of Hamburg, Germany

Nanomechanical resonators are chip scale implementations of a mechanical oscillator, which are of both practical and fundamental interest. In many applications, such as force sensing and quantum control of mechanical oscillators, it is typically advantageous to create lightweight, compliant mechanical elements with high quality factors *Q*. Recent years have seen a rapid development of devices with ever higher *Q* values, with current records approaching $Q \sim 10^{10}$ at room temperature. As a result, these devices become increasingly sensitive to smallest changes in certain environmental parameters, such as the pressure of the surrounding gas. In this work, we demonstrate the practical use of a mm-scale nanomechanical trampoline resonator with intrinsic resonance frequencies $f \sim 100$ kHz and $Q \sim 10^7$ for gas pressure sensing. To this end, we place the trampoline inside an ultra-high-vacuum chamber and interferometrically measure resonance frequency and quality factor of its fundamental out-of-plane mode as a function of gas pressure, using air and helium. In the pressure (p) range from 10^{-6} mbar to 10^3 mbar (i.e., ambient pressure), the quality factor continuously decreases from 10^7 to 15 (30) for air (helium). At ~ 10 mbar we observe a change from a $Q \sim p^{-1}$ to a $Q \sim (1+a\sqrt{p})^{-1}$ dependency, with fit parameter a, related to a transition from the free molecular to the viscous flow regime. This transition is accompanied by the onset of a decrease in the trampoline's resonance frequency towards higher pressures. Leading to a 10 % (3 %) reduction at ambient air (helium) pressure. We find excellent agreement within ~ 10 % between the measured data and a model, covering the investigated pressure range. Based on additional measurements for higher-order modes, we argue, that the estimated deviation might be mainly limited by a commercial reference pressure gauge. In this regard, we discuss prospects for nanomechanical-resonator-based pressure sensing with a precision on the order of few percent and the inherent benefit of self-calibration. In addition, we highlight the possibility for extending the measurement range with optimized devices by more than two orders of magnitude towards both lower and higher pressure ranges.

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MN-TuP-7 The Effect of Laser Processing on Drug-Loaded Polymers for Microfabricated Neural Interfaces, ***Natalie Mueller***, *M. Ya Mungu Ocoko, D. Chirra, P. Dernelle, A. Hermoso, J. Capadona, A. Hess-Dunning,* Case Western Reserve University

Drug-loaded polymers can be used in a multitude of biomedical applications, including drug-eluting, polymer-based intracortical microelectrodes to mitigate the neuroinflammatory response (Fig. 1). While these devices have shown promising results in reducing neuroinflammation around the microelectrode implant site, fabrication processes can affect the therapeutic efficacy of the drug. In our device, we load a polymer (polyvinyl acetate) substrate with the antioxidant/anti-inflammatory natural product, resveratrol. Resveratrol undergoes transformation from its more therapeutic isomer trans-resveratrol to its less potent form cis-resveratrol when exposed to heat and UV light. During our microfabrication process to integrate functional recording electrodes (Fig. 2), the resveratrol-loaded polymer substrate is exposed to both heat and UV light, particularly during the laser-micromachining step to create individual devices. We hypothesized that a higher power and laser path density would facilitate the conversion of trans-resveratrol to cis-resveratrol. Trans- to cis- conversion can be detected through a decrease in the absorbance peak in UV-vis spectrophotometry, as cis-resveratrol has a lower absorbance wavelength (287 nm) than trans-resveratrol (306-317 nm).

To test the effect of laser-micromachining on the resveratrol-loaded polymer devices, we first cut unloaded and resveratrol-loaded polymer substrates with 6 different combinations of laser power and geometry (Fig. 3). The cut devices were then incubated in 1X PBS, in which the hydrated state of the polymer allows the loaded resveratrol to elute from the sample to determine resveratrol release rate. The incubation solution was measured using UV-vis spectrophotometry at set time points (Fig. 4). The resveratrol release profile suggests that resveratrol-loaded polymer samples with a higher laser path density release more resveratrol (Fig. 5). Laser power did not strongly impact the peak absorbance or wavelength at peak absorbance. However, higher laser power corresponds to a less precise cut and increased damage to the resveratrol-loaded polymer substrate (Fig. 6). Samples with a higher laser path density (100 µm-wide serpentine, 200 µm-wide serpentine) have a lower wavelength at peak absorbance compared to samples with a lower laser path density (rectangular, 1000 µm-wide serpentine), which could be attributed to changes in the polymer, resveratrol form, or both. Together, these results inform the loading parameters for resveratrol-loaded polymer substrates, the fabrication process parameters to optimize active molecule release, and interpretation of the histology data from *in vivo* studies.

MN-TuP-8 Pressure Control During Bronze Infiltration of Binder-Jet Printed Stainless-Steel to Create Metal Microchannels, *H. Davis, J. Harkness, I. Kohls, N. Crane, B. Jensen, R. Vanfleet,* ***Robert C. Davis***, Brigham Young University

Additive manufacturing (AM) of metal microscale channels could enable microfluidic applications requiring higher temperature and higher thermal

conductivity materials. Combining these thermal properties with AM's ability to form small-scale complex flow paths could create functional structures like microscale gas chromatography columns or heat exchangers. We are developing processes to fabricate sealed metal microchannels using bronze infiltration of binder-jet printed stainless-steel parts. In this approach, bronze infiltrant must fill the porous material produced by binder jetting without filling the formed microchannels. This was achieved using pressure control reservoirs, wherein the powder filled reservoirs (pore size ~60 µm) are used to control infiltrant pressure. With pressure control, the infiltrant selectively filled the small pores between particles in the printed part (pore size ~3 µm) while leaving formed microchannels (200 to 900 µm) empty.

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