MEMS and NEMS Group
Room 24 - Session MN+EM+NS-MoA

Nano Optomechanical Systems/Multiscale Nanomanufacturing

Moderators: Robert Ilic, National Institute of Standards and Technology (NIST), Meredith Metzler, University of Pennsylvania

1:40pm **MN+EM+NS-MoA-1 GHz Integrated Acousto-Optics***, **Mo Li**,* University of Minnesota **INVITED**

Integrating nanoscale electromechanical transducers and nanophotonic devices potentially can enable new acousto-optic devices to reach unprecedented high frequencies and modulation efficiency. We demonstrate acousto-optic modulation of a photonic crystal nanocavity using acoustic waves with frequency up to 20 GHz, reaching the microwave K band. Both the acoustic and photonic devices are fabricated in piezoelectric aluminum nitride thin films. Excitation of acoustic waves is achieved with interdigital transducers with periods as small as 300 nm. Confining both acoustic wave and optical wave within the thickness of the membrane leads to improved acousto-optic modulation efficiency in the new devices than that obtained in the previous surface acoustic wave devices. In a photon-phonon waveguide, we further demonstrate strong Brillouin scattering of light by electromechanically excited acoustic waves. Our system demonstrates a novel scalable optomechanical platform where strong acousto-optic coupling between cavity-confined or guided photons and high frequency traveling phonons can be explored.

2:20pm **MN+EM+NS-MoA-3 Coupling Piezoelectric MEMS to Cavity Optomechanics***, **Kartik Srinivasan**,* NIST **INVITED**

Establishing a link between the radio frequency (RF) and optical domains is a topic of relevance to a variety of applications in communications, metrology, and photonic quantum information science. Acoustic wave devices represent an opportunity to mediate such transduction in a chip-integrated format. The approach we are pursuing uses materials that are both piezoelectric, to couple RF waves to strain fields, and photoelastic, to couple strain fields to optical waves.

One architecture that we have recently explored is based on exploiting these effects in GaAs. First, interdigitated transducers (IDTs) convert 2.4 GHz RF photons into 2.4 GHz propagating surface acoustic waves. These acoustic waves are routed through phononic crystal waveguides and are coupled to a nanobeam optomechanical cavity that supports both a highly localized 2.4 GHz breathing mechanical mode and a high quality factor 1550 nm optical mode. In contrast to non-resonant excitation of photonic structures with IDTs, here the phononic waveguide preferentially excites a localized mechanical mode, which in turn strongly interacts with the optical mode through the photoelastic effect. Finally, the optical mode can be out-coupled or excited via an optical fiber taper waveguide. Using this platform, we demonstrate preparation of the breathing mode in a coherent state at any location in phase space, and optically read out an average coherent intracavity phonon number as small as one-twentieth of a phonon. In the time-domain, we show that RF pulses are mapped to optical pulses, forming a resonant acousto-optic modulator with a sub-Volt half-wave voltage. We also observe a novel acoustic wave interference effect in which RF-driven motion is completely cancelled by optically-driven motion, enabling the demonstration of interferometric opto-acoustic modulation in which acoustic wave propagation is gated by optical pulses.

While the above platform has been shown to provide a coherent interface between the RF, optical, and acoustic domains, the overall efficiency is limited by imperfect matching across the various interfaces, e.g., IDT-to-phononic crystal waveguide, etc. In the final part of my talk, I will outline efforts to improve upon the transduction efficiency of the system.

3:00pm **MN+EM+NS-MoA-5 Collective Nano-optomechanics for Sensing Applications***, **Eduardo Gil Santos**, W Hease,* Universite Paris Diderot, France*; A Lemaitre,* Centre de Nanosciences et Nanotechnologies, France*; M Labousse, C Ciuti, G Leo, I Favero,* Universite Paris Diderot, France

Optomechanical resonators have been the subject of extensive research in a variety of fields, such as sensing, communication and quantum technologies. Our recent investigations on the capabilities of optomechanical semiconductor disk resonators to operate as sensors in liquids have revealed an astonishing potential. Minimum mass detection of $14{\cdot}10^{-24}$ g, density changes of $2{\cdot}10^{-7}$ kg/m^3 and viscosity changes of $5{\cdot}10^{-9}$ Pa·s, for 1s integration time, are extrapolated from our measurements in liquids.

After landmark experiments realized on single resonators, the use of multiple optomechanical cavities is essential to further improve their sensing capabilities, as it enlarges the sensing area while keeping their individual assets. This evolution towards collective nano-optomechanics hence bears potential for a variety of sensing applications, but for quantum or topological photonics as well. Unfortunately, the collective configurations are usually impeded by the residual disorder imposed by nanofabrication techniques, which naturally detunes high optical Q resonators and precludes resonant interactions between them. Therefore, overcoming fabrication imperfections and allowing spectral alignment of resonators is essential.

Here, we develop a new simple and scalable post-fabrication method to achieve such alignment in a permanent manner. The method introduces an approach of cavity-enhanced photoelectrochemical (PEC) etching in a fluid (gas or liquid). This resonant process is highly selective and allows controlling the resonator size with sub-pm precision, well below the material's interatomic distance. Light resonantly injected into the optical mode of an optical resonator immersed in a fluid triggers an etching process, leading to a fine-tuning of the resonator's dimensions. The evolution of dimensions is monitored continuously by tracking the resonator's optical resonance with a laser. This tuning process is naturally scalable to multiple resonators. We demonstrate it using a cascaded configuration where optomechanical disk resonators, each supporting its own localized optical and mechanical mode, are unidirectionally coupled through a common optical waveguide. The technique is illustrated by finely aligning up to five resonators in liquid and two in air, opening the way of fabricating large networks of identical resonators.

As an example of application of this tuning technique, we explore the resonant optical interaction of multiple nano-optomechanical systems. We observe a first form of collective behavior involving several distant resonators, where a unidirectional flow of light frequency-locks a chain of nano-optomechanical oscillators.

3:20pm **MN+EM+NS-MoA-6 Microporous Nanophotonic Mechanical Cantilevers for Mass Sensing***, **Anandram Venkatasubramanian**, V Sauer, J Westwood-Bachman,* University of Alberta and The National Institute for Nanotechnology, Canada*; K Cui, S Roy, M Xia,* National Institute for Nanotechnology, National Research Council, Canada*; D Wishart,* University of Alberta, Canada*; W Hiebert,* University of Alberta and The National Institute for Nanotechnology, Canada

The Gas chromatography (GC) – Mass spectrometry (MS) system is the industry benchmark in chemical analysis. However the large size of the Mass spectrometry unit makes it unsuitable for portable applications. Hence a portable universal mass sensing device that can be used with portable GCs needs to be developed. In this regard, recent demonstration with nano opto-mechanical system (NOMS) devices in conjunction with a GC system have proven that these kinds of sensors have the breakthrough potential to improve the sensitivity of portable GCs. Those demonstrations using NOMS devices have shown these sensors to match the mass detection limits of nanoelectromechanical systems (NEMS) sensors and can potentially better their performance owing to their superior displacement sensitivity compared to NEMS.

In this regard, a free space interferometry system based nanophotonic sensor was developed and attached to a conventional GC. The nanophotonic sensor consists of a microring racetrack resonator (for concentration sensing) with a nanomechanical beam (for mass sensing) adjacent to it. Common method to improve the sensitivity of a nanomechanical beam is to apply surface coatings. However, the application of surface coatings can potentially affect its universal sensing characteristics. Hence an alternate way to improve the adsorption sensitivity is to increase the surface area of the nanomechanical sensor to aid in increasing the number of gas adsorption sites.

In this paper we increase the surface porosity of nanomechanical beam by stain etching. Care was taken to protect the adjacent microring resonator from stain etching as surface pores can negatively affect the performance of the ring resonator due to increased scattering. The stain etching was conducted using vanadium oxide/Hydrofluoric acid based chemistry to etch ~ 10nm pores of random morphology on the surface. Based on an estimated porosity of <15% by volume, we have noted an increase in mass adsorption of ≥ 50 - 100% when tests were conducted using different volatile organic compounds. In other words, a mass adsorption enhancement factor of 1.5 to 2 has been achieved. Due to this enhanced adsorption, the mass detection threshold has improved by an order of magnitude (~10^{-19} g). To the best knowledge of the authors, this is the first time NOMS based porous nanomechanical mass sensor has been developed.

Mass Adsorption Enhancement Factor = Adsorption frequency shift for porous beam/Adsorption frequency shift for non porous beam

4:00pm **MN+EM+NS-MoA-8 Tunable Resistivity in Inkjet Printed Circuit by Plasma Reduction of Particle-free, Stabilizer-free Ink**, *Y Sui, S Ghosh, C Miller, M Sankaran,* ***Christian Zorman,*** Case Western Reserve University

Inkjet printing offers a low-cost, rapid methodology to produce patterned metal thin films on flexible substrates. The most commonly used ink consists of colloidal suspensions of nanoparticles prepared by wet chemical reduction of metal salts. Even after concentrating the nanoparticles through solution processing, the as-printed ink usually exhibits a low conductivity due to the presence of organic molecules that help stabilize the nanoparticles from agglomeration and precipitation. High temperature (>200 C) treatment is then required after printing to remove the insulating organics and sinter the nanoparticles. The thermal step can limit printing on polymers such as PDMS, paper, and 3D printed polymers.

Here, we present a particle-free, stabilizer-free ink and a low-temperature plasma reduction process to produce electrically conductive metallic patterns on temperature-sensitive without any additional thermal step. The ink is comprised of a metal salt, a solvent, and a viscosity modifier, and is absent of any large organic molecules that cannot be evaporated after printing. The as-printed and dried metal salt is then treated with a plasma formed in a low-pressure argon environment. Even without the presence of highly reactive atomic and molecular hydrogen, this process is found to be sufficient to reduce the metal salt to highly conductive metal with resistivities approaching bulk values. More importantly, we found the resistivity of the printed structure can be tuned over a range of 2 orders of magnitude by varying the plasma power and treatment time. Thus far, we have demonstrated this general approach for silver (Ag) and tin (Sn) from silver nitrate (AgNO3) and tin (II) chloride (SnCl2), respectively. Details of the material properties as assessed by materials characterization and electrical conductivity measurements, device application to RC filter circuits, and applicability to other metals will also be discussed.

4:20pm **MN+EM+NS-MoA-9 Cold Forming of Shallow Spherical Micro Caps by Nano Imprinting**, ***Asaf Asher,*** *E Benjamin, L Medina, S Lulinsky,* Tel Aviv University, Israel; *R Gilat,* Ariel University, Israel; *S Krylov,* Tel Aviv University, Israel

Many nonlinear systems are distinguished by bistability, which manifests itself as the coexistence of two equilibria under the same loading. Progress in the development of micro and nano structures stimulated renewed interest in the mechanics of bistable elements. Applications of these devices in the realm of micro and nanoelectromechanical systems (MEMS/NEMS) include switches, sensors, non-volatile memories, micro-pumps, micro-resonators and deformable mirrors. While curved beam-type bistable micro structures were intensively investigated both theoretically and experimentally much less attention was paid to two-dimensional bistable structures such as initially curved plates and shells (caps). One of the reasons is that lithography-based processes commonly used in MEMS/NEMS are essentially planar and are not suitable for fabrication of cap-like structures with an out-of-plane curvature. Existing approaches include gray-scale lithography or a glass blowing technique.

In this work we discuss several approaches for fabrication of shallow micro shells. One of the directions is the use of the cold forming techniques, when stamping changes a flat thin foil of ductile material into double-curvature components. While multiple variations of this process were used at the macro scale, much less works reported the implementation of this technique in MEMS. In the framework of the fabrication process used in our work, a layer of Al or Cu is deposited on top of a Si wafer. Sputtering is implemented for the creation of a thin seed layer, followed by electrodeposition used to increase the layer thickness to a desired value. Next, an opening is etched through the wafer using deep reactive ion etching (DRIE). Finally, the forming process is performed using nano-imprinting lithography tool. The tool allows very precise control of the force applied to the structure as well as the stamp temperature, displacements and rate of loading. Finite elements analysis and compact reduced order models are used for the evaluation of the desired parameters. Prior to forming, residual stress of the thin suspended membranes is estimated using a resonance method, by means of comparison of the measured natural frequencies of the device with the model predictions. We discuss suitability of different structural materials, deposition methods and stamping techniques for the formation of non-planar three-dimensional micro structures.

4:40pm **MN+EM+NS-MoA-10 Plate Mechanical Metamaterials: The Thinnest Plates You Can Pick Up by Hand**, ***Igor Bargatin,*** University of Pennsylvania **INVITED**

Recently, my group has demonstrated a new class of ultra-lightweight plate-shaped mechanical metamaterials, which we named "plate mechanical metamaterials". Using a periodic three-dimensional patterning, we fabricated free-standing plates up to 1 cm in size out of aluminum oxide (alumina) films as thin as 25 nm. Weighing as little as 0.1 gram per square meter, they are among the thinnest and lightest freestanding solids that can be handled with bare hands. We also combined multiple ultrathin layers of alumina to create a nanoscale analog of paper-based corrugated cardboard. Unlike cardboard, these plates have the ability to “pop back” to their original shape, without damage, even after undergoing multiple sharp bends by more than 90 degrees.

Like the nanotruss -based mechanical metamaterials reported by other groups, plate mechanical metamaterials are extremely lightweight and resilient due to their nanoscale thickness and microscale cellular structure. However, in contrast to the cube-shaped metamaterials that typically form a lattice easily penetrated by the ambient air, our plates form flat continuous plates. Ultralow weight, mechanical robustness, thermal insulation, as well as chemical and thermal stability of alumina make plate metamaterials attractive for numerous applications, including structural elements in flying microrobots, high-temperature thermal insulation in energy converters, testing of nanoscale strength enhancement, new types of optical and acoustic metamaterials, as well as ultrathin MEMS/NEMS sensors and ultra-lightweight hollow MEMS/NEMS resonators.

Author Index

Bold page numbers indicate presenter

— A —
Asher, A: MN+EM+NS-MoA-9, **2**
— B —
Bargatin, I: MN+EM+NS-MoA-10, **2**
Benjamin, E: MN+EM+NS-MoA-9, 2
— C —
Ciuti, C: MN+EM+NS-MoA-5, 1
Cui, K: MN+EM+NS-MoA-6, 1
— F —
Favero, I: MN+EM+NS-MoA-5, 1
— G —
Ghosh, S: MN+EM+NS-MoA-8, 2
Gil Santos, E: MN+EM+NS-MoA-5, **1**
Gilat, R: MN+EM+NS-MoA-9, 2
— H —
Hease, W: MN+EM+NS-MoA-5, 1
Hiebert, W: MN+EM+NS-MoA-6, 1
— K —
Krylov, S: MN+EM+NS-MoA-9, 2
— L —
Labousse, M: MN+EM+NS-MoA-5, 1
Lemaitre, A: MN+EM+NS-MoA-5, 1
Leo, G: MN+EM+NS-MoA-5, 1
Li, M: MN+EM+NS-MoA-1, **1**
Lulinsky, S: MN+EM+NS-MoA-9, 2
— M —
Medina, L: MN+EM+NS-MoA-9, 2
Miller, C: MN+EM+NS-MoA-8, 2
— R —
Roy, S: MN+EM+NS-MoA-6, 1
— S —
Sankaran, M: MN+EM+NS-MoA-8, 2
Sauer, V: MN+EM+NS-MoA-6, 1
Srinivasan, K: MN+EM+NS-MoA-3, **1**
Sui, Y: MN+EM+NS-MoA-8, 2
— V —
Venkatasubramanian, A: MN+EM+NS-MoA-6, **1**
— W —
Westwood-Bachman, J: MN+EM+NS-MoA-6, 1
Wishart, D: MN+EM+NS-MoA-6, 1
— X —
Xia, M: MN+EM+NS-MoA-6, 1
— Z —
Zorman, C: MN+EM+NS-MoA-8, **2**