MEMS and NEMS
Room: 301 - Session MN-WeM

Optomechanics, Photonics, and Quantum Nanosystems

Moderator: Susan Burkett, The University of Alabama, W.K. Hiebert, University of Alberta and The National Institute for Nanotechnology

8:40am **MN-WeM3 Diamond Quantum Nanophotonics and Nanomechanics**, ***Marko Loncar***, Harvard University **INVITED**

Diamond possesses remarkable physical and chemical properties, and in many ways is the ultimate engineering material - “the engineer’s best friend!” For example, it has high mechanical hardness and large Young’s modulus, and is one of the best thermal conductors. Optically, diamond is transparent from the ultra-violet to infra-red, has a high refractive index (n = 2.4), strong optical nonlinearity and a wide variety of light-emitting defects. Finally, it is biocompatible and chemically inert, suitable for operation in harsh environment. These properties make diamond a highly desirable material for many applications, including high-frequency micro- and nano-electromechanical systems, nonlinear optics, magnetic and electric field sensing, biomedicine, and oil discovery. One particularly exciting application of diamond is in the field of quantum information science and technology, which promises realization of powerful quantum computers capable of tackling problems that cannot be solved using classical approaches, as well as realization of secure communication channels. At the heart of these applications are diamond’s luminescent defects—color centers—and the nitrogen-vacancy (NV) color center in particular. This atomic system in the solid-state possesses all the essential elements for quantum technology, including storage, logic, and communication of quantum information.

I will review recent advances in nanotechnology that have enabled fabrication of nanoscale optical devices and chip-scale systems in diamond that can generate, manipulate, and store optical signals at the single-photon level. Examples include a room temperature source of single photons based on diamond nano wires [1]and plasmonic apertures [2], as well as single-photon generation and routing inside ring [3] and photonic crystal resonators fabricated directly in diamond [4]. In addition to these quantum applications I will present our recent work on diamond based on-chip frequency combs [5], diamond nano mechanical resonators [6].

1 TM Babinec, et al,"A bright single photon source based on a diamond nanowire," *Nature Nanotechnology,* 5,195 (2010)

2 JT Choy, et al, "Enhanced Single Photon Emission by Diamond-Plasmon Nanostructures.," *Nature Photonics,* **5**,738 (2011)

3 BJM Hausmann, et al, "Integrated Diamond Networks for Quantum Nanophotonics", *Nano Letters,* **12**,1578 (2012)

4 MJ Burek, et al, “Free-standing mechanical and photonic nanostructures in single-crystal diamond”, *Nano Letters*, 12,6084 (2012)

5 B Hausmann et al, "Diamond Nonlinear Photonics", *Nature Photonics*, 8,369 (2014)

6 M Burek et al, "Nanomechanical resonant structures in single-crystal diamond", *Appl. Phys. Lett.*, **103**,131904 (2013)

9:20am **MN-WeM5 A Compact Footprint Nano-Opto-Mechanical System with Evanescent Interaction**, ***Marcel Pruessner***, *D. Park, T.H. Stievater,* Naval Research Laboratory, *D.A. Kozak,* NRC Postdoc (Naval Research Lab), *W.S. Rabinovich*, Naval Research Laboratory

We present a compact footprint, fully-integrated nano-opto-mechanical system with strong evanescent field interaction. Silicon nitride films with sub-wavelength thickness ($t_{Si3N4}<\lambda/4n_{Si3N4}$) enable low-loss waveguides [1] as well as complex photonic circuits [2], e.g. directional couplers, Mach-Zehnder interferometers, microring cavities [3], nanobeam cavities [4], etc. Furthermore, the thin core layer and air top cladding allow access to the waveguide’s evanescent field, which can be tailored by simply varying the Si_3N_4 core layer deposition thickness. We previously demonstrated evanescent field interactions in these structures using a tapered fiber as an *off-chip* perturber [2] and by performing absorption spectroscopy on a number of chemical analytes present near the waveguide [3].

We now build upon our previous work [2,3] by fabricating a suspended tensile microbridge (SiN_X) just above the waveguide surface (gap≈100-300nm) to achieve strong interactions between optical and mechanical structures in a *fully-integrated* device. For example, displacement of the mechanical perturber (microbridge) modifies the waveguide’s effective index so that the nano-opto-mechanical system acts as a high-resolution displacement sensor in which determination of the change in effective index is a measurement of displacement. At the same time, the change in the waveguide effective index as a function of displacement implies an optical force that acts on the microbridge [5].

Our nano-opto-mechanical system is compact and occupies a footprint that is essentially determined only by the waveguide since the mechanical structure is suspended directly above it. This vertical architecture enables us to optimize the optical and mechanical structures independently. Although simple, the opto-mechanical system enables complex interactions with a variety of potential applications including displacement sensing, optical-force reconfigurable photonics, and opto-mechanical oscillators. The compact footprint enables large-scale integrated opto-mechanical systems on a chip.

We will present the basic approach of our nano-opto-mechanical system, design and fabrication details, simulations to support strong evanescent field interaction, and initial experimental results demonstrating a strong interaction in chip-scale opto-mechanical structures.

9:40am **MN-WeM6 GaAs Disks Optomechanical Resonators in Liquid**, *I. Favero,* ***Eduardo Gil-Santos***, Université Paris Diderot, CNRS, France

Vibrating nano or micromechanical structures, such as cantilevers, have been the subject of extensive research for the development of ultrasensitive mass sensors for mass spectrometry, chemical sensing and biomedical analysis. In liquids, the energy losses due to viscous damping, acoustic losses and squeeze film effects are high and the mass sensitivity diminishes dramatically. Additionally, viscous damping in a fluid is often larger when the devices are miniaturized.

To circumvent these problems, novel structures have been proposed, such as microchannels, where the liquid is placed directly inside the resonator. They have indeed shown lower energy losses, but they can hardly be miniaturized. External feedback loops have been applied as well in order to diminish artificially energy losses [4]. Besides this, another technique to reduce mechanical losses in a liquid has been to use higher order modes or contour/extensional modes. On one hand, these modes indeed show lower dissipation, on the other hand the related displacement is extremely small, making it more difficult to detect, especially in a liquid.

Here we study the potential of GaAs disk resonators in this context, in particular focusing on mechanical radial breathing modes. GaAs mechanical disks, with their high mechanical Q even in air ($>10^3$), their low mass (pg) and high mechanical frequency (GHz), have been shown to be potential powerful sensors. Their use in liquids has been never investigated or even suggested, and it is still uncertain what energy losses and sensitivity they will present in such environment. GaAs disks support optical whispery gallery modes (WGMs), with high optical quality factor (several 10^5). This fact, together with the outmost optomechanical coupling that they possess (up to 4 MHz), provide them with an extremely high displacement sensitivity in the 10^{-18} m/√Hz range, allowing measuring the thermomechanical noise of the resonator even in a liquid.

We measure for the first time a GaAs mechanical disk vibrating in a liquid, directly in the Brownian motion regime. Employing finite element simulations and an analytical fluid-structure model, we investigate the mechanical damping mechanisms at play in this situation. We study the fluidic dissipation as a function of disk’s dimensions and of the physical properties of the liquid, such as density and viscosity, performing experiments in a family of different liquids. We finally analyze the sensing capabilities of this object and compare it to other existing approaches.

11:00am **MN-WeM10 Photonic Actuation and Detection of Higher Order Modes in Nanomechanical Resonators**, ***Jocelyn Westwood***, *V.T.K. Sauer,* University of Alberta and The National Institute for Nanotechnology, Canada, *Z. Diao,* National Institute for Nanotechnology and University of Alberta, Canada, *W.K. Hiebert*, University of Alberta and The National Institute for Nanotechnology, Canada

All-optical actuation and detection of nanomechanical devices has recently emerged as a high-bandwidth technique with high displacement sensitivity [1],[2],[3],[4],[5]. We explore optical actuation and detection of higher order vibrational modes, including even modes, in nano-optomechanical doubly clamped beams. Higher order modes have increased resonance frequencies, thereby increasing the mass sensitivity for sensing purposes and increasing the measurement bandwidth [6], [7]. Currently, higher order modes are not well studied since the symmetry of the modes causes a zero effective index shift over the vibrating beam, limiting the sensitivity of the all-optical technique. We demonstrate the fabrication of doubly clamped beams with the symmetry broken, due to a step in the substrate height under the doubly clamped beam. The doubly clamped beams are embedded in an optical racetrack resonator. This allows for the all-optical actuation and detection of the first through fifth modes of the doubly clamped beams. Additionally, the thermomechanical noise floor of the first few modes is observed.

[1] F. Marquardt and S. Girvin, *Physics*, vol. 2, pp. 40, 2009.

[2] T. J. Kippenberg and K. J. Vahala, *Science*, vol. 321, pp. 1172–6, 2008.

[3] J. Chan et al., *Opt. Express*, vol. 17, no. 5, pp. 3802–3817, 2008.

[4] M. Li et al., *Nature*, vol. 456, pp. 480–4, 2008.

[5] V. T. K. Sauer et al., *Appl. Phys. Lett.*, vol. 100, no. 26, pp. 261102, 2012.

[6] K. L. Ekinci, Y. T. Yang, and M. L. Roukes. *J. Appl. Phys.*, vol. 95, no. 5, pp. 2682–2689, 2004.

[7] M. K. Ghatkesar et al., *Nanotechnology*, vol. 18, no. 44, pp. 445502, 2007.

11:20am **MN-WeM11 Dynamic Range Effect on the Mass Sensitivity of Optomechanically Transduced NEMS Devices with a Poorer Q Value**, ***S.K. Roy***, *V.T.K. Sauer, W.K. Hiebert*, University of Alberta and The National Institute for Nanotechnology, Canada

Suitable control over the oscillatory properties and tunable nonlinearities has made nanomechanical resonators attractive to the research community not only for their ultra-sensing ability but also for rich physics behind their optomechanical properties. Optomechanical transduction of these devices has become promising for optimizing device applications. The present work is aimed at studying the interplay between dynamic range (DR), mass sensitivity, and mechanical quality factor (Q), and measurement bandwidth in state-of-the-art optomechanical NEMS devices. While poorer Q is normally assumed to lead to degradation in mass sensing performance, there are situations where performance can be recovered, and even improved, through the dynamic range dependencies on Q. This is welcome news for applications at atmospheric pressure such as sensitive gas sensing. In quest of an appropriate mass or gas sensor, nonlinear oscillatory behaviour was studied on a doubly clamped beam of 8.75μmx220nmx160nm which is 160 nm away from a racetrack resonator optical cavity. To get the upper end of DR, the resonator was driven close to nonlinearity, i.e. to the amplitude where 1dB compression was observed. Thermomechanical noise signals were measured to achieve the bottom end of the DR. At high vacuum ($<10^{-5}$ torr), 6 torr and 1atm the obtained experimental DR values are 53, 64 and 55 respectively. The corresponding Q values are 2866, 944 and 26. According to these experimental results, calculated mass sensitivity for the device were found 0.3, 0.2 and 28 Zepto g at high vacuum, 6 torr and 1atm respectively. An atmospheric pressure room temperature mass sensitivity of 28 zeptogram for Q value of 26 is an intriguing value. Such a surprising result of better mass sensitivity with poorer Q can be explained based on existing theories.

12:00pm **MN-WeM13 Scanning Optical Interferometric Spectromicroscopy for Mapping Multimode Resonant Motions in Planar Silicon Carbide (SiC) Micromechanical Resonators with $f\times Q$ Approaching 10^{13}Hz**, ***Zenghui Wang***, *J. Lee, P.X.-L. Feng*, Case Western Reserve University

Higher-order and multiple modes in vibrating micro/nanomechanical resonators are of great interest and promise for both fundamental research such as exploring and understanding quantum mechanics in these man-made structures, and for technological applications such as signal processing and multi-modality sensing (***e.g.***, simultaneously detecting mass and position of a physisorbed particle on resonator surface)[1][2] . It is therefore important to understand such multimode behavior in micro/nanomechanical resonators down to their fundamental limits, ***i.e.*** in their completely-undriven Brownian motions, at all conditions (***e.g.***, ranging from cryogenic to elevated temperatures). This demands ultrasensitive motion transduction schemes that would allow us to attain more comprehensive information from the devices, far beyond what can be extracted from the conventional frequency-domain resonance curves.

Over the recent few decades, various motion transduction technologies (***e.g.***, electrostatic, piezoelectric, piezoresistive, optomechanical, ***etc.***) have been developed to read out small displacements in micro/nanomechanical resonators. While the commonly-used motion readout schemes have their respective advantages and have achieved many milestones, they lack multimode capabilities, and particularly, experimental visualizations of these multiple modes. For example, optomechanical technique has demonstrated excellent displacement sensitivity (better than fm/Hz$^{-1/2}$), but is unable to experimentally determine the spatial mode shapes of 2D planar resonators, which is highly desired for determining and engineering high-order modes.

Optical interferometric techniques have been continuously advancing over the recent years [3][4]. Here, we report on the design and implementation of a scanning laser interferometry and spectromicroscopy technique, and we demonstrate direct visualization of multimode resonances in SiC micromechanical resonators with various geometries, including membranes, plates, trampolines, torsional resonators, and center-supported disks, with many resonances up in the VHF and UHF bands. Besides setting a new record of $f\times Q$ product in all SiC flexural-mode resonators ($\sim 1.0\times 10^{13}$), our devices effectively enable high-order resonances with clearly distinguishable mode shapes through their 2D nature and high-aspect-ratios.

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[2] Hanay, M. S. ***et al. Nature Nanotech.*** **7,** 602 (2012).

[3] Hiebert ,W. K., Vick, D., Sauer, V., & Freeman, M. R. ***J. Micromech. Microeng.*** **20**, 115038 (2010).

[4] Lee, J., Wang, Z., He, K., Shan, J., & Feng, P. X.-L. *ACS Nano* **7,** 6086 (2013).

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