MEMS and NEMS Group
Room: 24 - Session MN+BI+NS-MoM

Feature Session: Large Scale Integration of Nanosensors
Moderators: Wayne Hiebert, National Institute for Nanotechnology, Canada, Robert Davis, Brigham Young University

8:20am **MN+BI+NS-MoM1 Large Scale Integration: A Not-so-simple Cure for Loneliness of Silicon Nanoresonators**, ***Sébastien Hentz***, Cea Leti, France **INVITED**

After two decades of pioneering work, Nano Electro Mechanical Systems are only starting to fulfil (some) of their huge promises, in particular for sensing. A few start-up companies have been created in the last few years, but NEMS are still far from the industrial success of their micro- counterparts. Among others, one reason is the increasing difficulty to interface the "real-world" quantities to sense with the extremely small size of nanomechanical resonators. An easy to understand example of this is mass sensing: there is huge size mismatch between the NEMS capture cross section (in the μm^2 range) and an actual particle beam size that one can produce (in the mm to $10mm^2$ range). Most of the particles to detect are lost. Industrial applications may require the use of large arrays comprising from 10's to 10000's NEMS.

LETI has been working on nanomechanical resonators for a number of applications in the last ten years and have been pioneering their fabrication with Very Large Scale Integration processes. State of the art performance (signal to background ratio, signal to noise ratio, frequency stability...) has been reached with single silicon resonators and specific transduction means adapted to VLSI technologies. The real strength of VLSI though, as evidenced every day by microprocessor fabrication is the possibility to process a large number of devices operating in sync with great reproducibility and control.

We investigated several types of NEMS arrays in the past at LETI. Arrays comprising typically a few 1000 resonators all connected in parallel for gas sensing have been demonstrated. Smaller arrays with the ability to weigh and localize single particles via frequency addressing have been tested too for mass spectrometry applications. LETI has also been pioneering NEMS co-integration with CMOS in the last decade or so and several technologies have been explored. We took advantage of this know-how to fabricate large and dense arrays of NEMS-CMOS arrays for mass sensing applications.

9:00am **MN+BI+NS-MoM3 Nanomechanical Sensors (MSS, AMA) Toward IoT Olfactory Sensor System**, ***Genki Yoshikawa***, National Institute for Materials Science, Japan **INVITED**

Owing to their intrinsic versatility, nanomechanical sensors have potential to cover a wide range of olfactory sensing applications in various fields including food, agriculture, medicine, security, and environment. Based on the newly developed platform "Membrane-type Surface stress Sensor (MSS)," we are now trying to realize useful nanomechanical sensor systems which can fulfill the practical requirements, such as portability, low-cost, ease of use, in addition to the basic specifications, e.g. high sensitivity and selectivity. While the MSS provides a practical sensing element, a consumer mobile/IoT sensor system requires further optimization and integration of lots of components including receptor layers, hardware including electronics and sample handling, multidimensional data analysis, and precise calibration for high reproducibility. To establish a de facto standard for odor analysis and sensor systems employing the nanomechanical MSS technology, the "MSS Alliance" was launched jointly with companies and a university. In addition, "Aero-Thermo-Dynamic Mass Analysis (AMA)," which we have recently developed, will provide another approach to characterizing gases by directly measuring molecular weight in ambient condition without a vacuum or ionization. In this talk, the overview of the MSS, AMA, and the related technologies ranging from the optimization scheme of the sensor chip to system level developments will be presented.

9:40am **MN+BI+NS-MoM5 Micro-Gas Chromatography Linked with Nano-optomechanical Systems for Breath Analysis**, ***Khulud Almutairi***, University of Alberta, Canada, *W.K. Hiebert*, National Institute for Nanotechnology, Canada

One of the applications of microfabrication and nanofabrication technologies is fabricating a micro-Gas Chromatography (GC) on a chip. The miniaturized GC system is designed for the rapid determination of volatile organic compounds (VOCs) that can be used in remote locations with low consumptions and cost of utilization. It was reported that specific VOCs can be found in exhaled breath sample from patients suffering from lung cancer [1]. Therefore, designing a μGC device can help in separating and analyzing VOCs that comes from exhaled breath samples, such as acetone, benzene and toluene.

Our group has reported that connecting Nano-optomechanical systems (NOMS) to Gas Chromatography can enhance the detection sensitivity limit of VOCs up to 1 ppb [2]. This presentation will feature our first efforts in connecting μGC with NOMS for higher sensitivity and responsivity. In particular, we will discuss our NOMS sensor chips with microheaters for localized control of sensor temperature. One of our goals is to move toward large scale integration of GC analysis by simultaneously sensing at multiple temperatures.

REFERENCES:

[1] Mazzone, Peter J. "Exhaled breath volatile organic compound biomarkers in lung cancer." *Journal of breath research* 6, no. 2 (2012): 027106.

[2] Venkatasubramanian, Anandram, Vincent TK Sauer, Swapan K. Roy, Mike Xia, David S. Wishart, and Wayne K. Hiebert. "Nano-optomechanical systems for gas chromatography." *Nano Letters* 16, no. 11 (2016): 6975-6981.

10:00am **MN+BI+NS-MoM6 Micro Chladni Figures and Multimode Manipulation of Breast Cancer Cells in Liquid**, ***Hao Jia***, *H. Tang*, Case Western Reserve University, *X. Liu, H. Liu*, Northwestern University, *P.X.-L. Feng*, Case Western Reserve University

Non-invasive, microscale positioning of delicate biological cells can foster fundamental research involving probing cellular properties and controlling cellular behaviors and interactions [1-3], which lead to a multitude of applications, such as disease screening, tissue engineering, *etc.*

Here we demonstrate that microscale manipulation of breast cancer cells can be achieved in a fast and non-invasive manner through exploiting multimode micromechanical systems. We design edge-clamped diaphragm resonators (~300μm in length scale) and piezoelectrically excite their mechanical resonances (within 50–500 kHz) in fluidic environment. The transverse vibrations induce localized, microscale hydrodynamic flow that can aggregate microbeads (3.6μm-diameter) on device surfaces into a variety of one- and two-dimensional (1D and 2D) 'Chladni figures' [4] (optical images in Fig.1a & b). This phenomenon allows us to further manipulate single or a group of breast cancer cells (MDA-MB-231, 15μm-diameter), in both 1D and 2D fashions, at a speed of ~4μm/s (fluorescent images in Fig. 1a & b). By simply programming the piezoelectric excitation frequency, we achieve dynamic control of cancer cell spatial distributions, switching between mode patterns.

We further demonstrate that such multimode resonator platform can facilitate cellular-level biological studies, such as evaluating cellular adhesive interactions and its connection with cancer biomarker (*e.g.*, CD44). As shown in Fig.2, by exploiting the 'Chladni figure' phenomenon, and carefully selecting 2 resonance modes of a square diaphragm, *e.g.*, Mode (1,1) and Mode (3,3), a controlled number of MDA-MB-231 cells can be quickly manipulated into single cluster and then forced to break as the excitation voltage of Mode (3,3) gradually increases. Cancer cells with CD44 gene knocked out by CRYSPR technology are named as $CD44^-$ cells, while those with CD44 gene maintained named as $CD44^+$ (control) cells. The break of $CD44^-$ cell cluster after $0.8V_{pp}$ in Fig. 2 indicates that they form much weaker adhesive interactions than $CD44^+$ cells do, which indicates that CD44 plays a significant role in the metastatic breast cancer cell clustering.

[1] E.E. Hui, *et al.*, PNAS **104**, 2007.

[2] H. Zhang, *et al.*, J. R. Soc. Interface **5**, 2008.

[3] X. Ding, *et al.*, PNAS**109**, 2012.

[4] E.F.F. Chladni, *Entdeckungen über die Theory des Klanges*,1787.

10:40am **MN+BI+NS-MoM8 Microfabrication and Assembly Processes for Integrating Microelectrode Arrays into Tissue-Engineered Scaffolds for Novel Nerve Interfaces**, ***Jack Judy***, *C. Kuliasha, P. Rustogi, S. Natt, B. Spearman, S. Mohini, J.B. Graham, E.W. Atkinson, E.A. Nunamaker, K.J. Otto, C.E. Schmidt*, University of Florida **INVITED**

To advance fundamental understanding and develop therapies for neurological disease or injury, microfabricated implantable electrode arrays have been designed and manufactured to stimulate and record neural activity. The materials in these implants, as well as the processes used to integrate them together, must be carefully selected to maximize biocompatibility, device performance, and overall reliability. For upper-limb amputees, nerves are a promising neural-interface target to control sophisticated robotic limbs. Recent advances have shown that nerve stimulation can provide natural sensory feedback. In contrast, it is currently not possible to extract large-scale, high-resolution, and reliable movement-intent signals from nerves. To

provide rapid and precise limb control and elicit high-resolution sensory percepts, a nerve interface needs many independent motor and sensory channels. Unfortunately, all existing non-invasive and non-regenerative nerve interfaces grossly under-sample the heterogeneous population of efferent and afferent axons. Although tissue engineering, nerve regeneration, and implantable neural-electronic interfaces are individually well-established fields, the concept of merging these fields to create scalable, and high-performance neural interfaces has not been extensively explored. To overcome the scalability challenge, we present a novel approach. Specifically, we describe a hybrid tissue-engineered electronic nerve interface (TEENI), which consists of multi-electrode polyimide-based "threads" embedded into a biodegradable hydrogel composite scaffold that is sutured to the ends of a transected nerve. Single or multiple thread sets can be incorporated in the hydrogel to enable the TEENI implant to comprehensively engage with the nerve. These polyimide threads will be fully enveloped and held precisely in position during implantation by the hydrogel scaffold, which has properties optimized to reduce foreign-body response. Eventually, the hydrogel will degrade and be replaced with regrown and maturing axons. Since the TEENI approach is scalable to high channel counts over the nerve volume, we believe TEENI nerve interfaces are well positioned to comprehensively capture movement-intent information and impart sensory-feedback information so that upper-limb amputees can get the most out of their prosthetic limbs.

11:20am **MN+BI+NS-MoM10 Magnetically Actuated Synthetic Cilia for Microfluidics**, ***Peter Hesketh***, *S.K.G. Hanasoge, M. Ballard,* Georgia Institute of Technology, *M. Erickson*, University of Georgia, *A. Alexeev*, Georgia Institute of Technology **INVITED**

Many bacteria use cilia for swimming, sensing and signal transduction. These functions are achieved by manipulating the fluid around the cilia with continuous and synchronised asymmetric beating patterns . We have fabricated arrays of synthetic cilia using thin film deposition of NiFe thin films. The cilia are able to manipulate fluid in these creeping flow regimes by creating an asymmetry in the forward and recovery strokes. We propose to use artificial cilia in microfluidic devices to perform different functions including mixing, fluid transport, and particle capture.

We use a simple rotating magnet to actuate the cilia array and observe a large asymmetry in the bending pattern of these cilia in the oscillation cycle. We analyze the asymmetric strokes of the cilia by imaging from the side view and quantify the asymmetry between forward and recovery strokes as a function of drive frequency. These asymmetric oscillations are important in creating any microfluidic transport phenomenon such as pumping, mixing and capture in a microchannel as demonstrated in this work. Computational modeling was also used to simulate the motion of the cilia over a broader range of design parameters. We show the dependence of the ciliary performance on several non-dimensional numbers based on the balance of magnetic, viscous and elastic forces acting on the cilia.

The motivation for this work is to improve the quality of sampling for the detection of bacteria and virus in food. Detecting low concentrations of bacteria in food samples is a challenge. The pre-concentration and separation of the target bacteria from the food matrix can be enhanced using improved fluid handling. We demonstrate particle capture with cilia, by functionalizing the surface of the cilia with streptavidin protein and capturing biotin labelled particles on its surface. The functionalized cilia are incorporated inside a microchannel and biotin labelled particles are introduced into array of the cilia. Likewise, these artificial cilia find varied application in many lab on a chip devices where active fluid transport is needed.

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