MEMS and NEMS
Room: 301 - Session MN+NS-TuA

Multi-Scale Phenomena and Bio-Inspired MEMS/NEMS
Moderator: Philip Feng, Case Western Reserve University, Meredith Metzler, Cornell University

2:20pm **MN+NS-TuA1 MEMS-Enabled Multiscale Nanolaminated Magnetics**, ***Mark Allen***, University of Pennsylvania **INVITED**

The manufacture of materials with bulk volumes and precisely controlled nanostructure has led to the creation of materials with surprising and useful mechanical and electrical properties. Recently we have developed a 'top-down' fabrication technique that allows the creation of highly-structured multilayer metallic materials, with precisely designed characteristic lengths in the hundreds of nanometers scale, but volumes of manufactured material in the macro range. The fabrication relies on automated and repeated multilayer electrodeposition of multiple metallic materials, followed by sacrificial etching of one metal. The resultant structure consists of individualized high-lateral-aspect-ratio sub-micron metallic films. The application of these multiscale materials to ultracompact energy conversion is investigated. Metallic magnetic materials have desirable magnetic properties, including high permeability and high saturation flux density, when compared with their ferrite counterparts. However, eddy current losses preclude their use in many switching converter applications due to the challenge of simultaneously achieving sufficiently thin (100-500 nm) laminations such that eddy currents are suppressed while simultaneously achieving overall material thicknesses (0.1-1 mm) such that substantial power can be handled. Sequential electrodeposition of multiple nanoscale 'sheets', or laminations, of magnetic materials such as permalloy and NiFeCo offers an approach to fabricate the desired nanostructured magnetic core. Tests of toroidal inductors with nanolaminated cores showed negligible eddy current loss relative to total core loss even at a peak flux density of 0.5 T and a frequency of 10 MHz. The ability to operate at such high flux levels offers the possibility of dramatically shrinking the physical size of power inductors in energy converters. DC-DC converters with efficiencies of up to 93% and power handling of approximately 40W have been achieved in ultracompact form based on these materials.

3:00pm **MN+NS-TuA3 Fabrication and Electrical Performance of Through Silicon Via Interconnects Filled with a Copper/Carbon Nanotube Composite**, *Y. Feng*, ***Susan Burkett***, The University of Alabama

Three-dimensional integrated circuit (3D-IC) technology has been developed using copper (Cu) filled through silicon vias (TSVs). The vertical interconnects pass through a set of stacked die and enable many applications that benefit from increased bandwidth, reduced signal delay, and improved power management. However, the reliability of Cu interconnects is a serious concern since the performance is affected by electromigration and stress associated with mismatch in thermal expansion coefficients. Carbon nanotubes (CNTs) are nanoscale materials which possess a high Young's modulus, a low coefficient of thermal expansion, and high thermal conductivity. Compared to Cu, CNTs exhibit low resistivity due to the existence of ballistic conduction and they are capable of carrying a higher current density. In this work, we fabricated TSVs using a novel materials system consisting of a composite of Cu and CNTs as a possible solution to the problems encountered in Cu-based interconnects. First, blind TSVs were fabricated using a Bosch process. After etching, an insulating layer, a metallic seed layer, and a catalyst layer were deposited previous to CNT growth. Vertically aligned CNTs were grown by chemical vapor deposition method. Finally, Cu was deposited by periodic reverse pulse electroplating inside the vias to form a Cu/CNT composite. Polishing completed the fabrication and allowed measurement of electrical performance for TSV interconnects. The experimental results were compared for interconnects filled with Cu and those filled with the Cu/CNT composite. The results are encouraging for the Cu/CNT composite having potential application as a TSV interconnect material.

3:20pm **MN+NS-TuA4 Meso Scale MEMS Motion Transformer and Amplifier Electrostatically Actuated by Parallel Plate Electrodes**, *Y. Gerson, S. Krylov,* Tel Aviv University, Israel, ***Tali (T.) Nahmias***, *R. Maimon*, Microsystems Design Center, RAFAEL LTD, Israel

Meso scale microelectromechanical structures found on the upper scale of microelectromechanical systems (MEMS) can potentially replace conventional mechanical devices produced by common for the macro-engineering approaches such as machining and assembly of individual parts. When realized as a compliant mechanism containing a single flexible member rather than multiple parts attached by joints they provide smooth frictionless motion without backlash and exhibit improved reliability and robustness. Batch fabrication using micromachining processes established in MEMS allows improved yield and significantly lower cost. However, actuation of these devices remains challenging. Electrostatic actuation, which is the most widely used in smaller MEMS devices, is viewed to be less suitable for the actuation at the meso scale due to unfavorable scaling laws, namely quadratic reduction of the actuating force with the distance between the electrodes. For this reason, most of the meso scale micro devices are actuated by thermal transducers, distinguished by slow response and high power consumption or by piezoelectric or magnetic motors, which cannot be integrated within the device and require post-fabrication assembly.

In this work we report on the design, fabrication and characterization of an electrostatically actuated meso scale microelectromechanical motion transformer and amplifier. The actuator corporate a transducer with multiple parallel plate electrodes and is realized as a compliant mechanism relying on flexible pseudo hinges. The 5000 µm × 4000 µm device converts linear motion of the transducer into mechanically amplified angular motion of a rotating lever. By combining a highly efficient small-gap parallel plate electrode and a motion amplification the device is designed to provide a lever tip displacement of 60µm, an initial blocking force of 0.001N at zero displacements and a blocking force of 0.012N in the maximal displacement configuration when the parallel plate actuator is in its closed position. The devices were fabricated using DRIE from a SOI wafer with (111) front surface orientation and a 150µm thick device layer. The devices were operated in ambient air conditions and the functionality of the device was demonstrated experimentally. The voltage-displacement dependence and resonant curves were built using image processing procedure implemented in Matlab. Excellent agreement between the results provided by the Finite Elements models and the experimental data was observed. The results of the work demonstrate an ability to achieve both large displacements and high blocking forces in an electrostatically actuated meso scale compliant mechanism.

4:20pm **MN+NS-TuA7 Bio-Inspired Microlenses and Their Biomedical Applications**, ***Hongrui Jiang***, University of Wisconsin - Madison **INVITED**

Optical detection and imaging have wide applications in biomedicine and biological and chemical analyses. With continuing miniaturization effort to realize integrated microsystems, micro-scale optical components become more and more important. For any optical system, lenses are critical elements. In this talk, I will present our work on liquid microlenses. I will first introduce a few types of microlenses and microlens arrays, including tunable liquid microlenses actuated by temperature-, pH- and infrared light-responsive hydrogels, microlens arrays for light-field imaging, microcamera arrays mimicking compound eyes, and artificial reflecting superposition compound eyes. Then, I will discuss about potential applications of these lenses in medical instruments. I will describe miniaturized cameras capable of multiple viewpoints, prototype flexible endoscopes implementing infrared-light responsive liquid microlenses at their distal ends, and prototype multiple-camera laparoscopes.

5:00pm **MN+NS-TuA9 The Development of a Valve Based Microfluidic Biofilm Reactor for Biofilm Studies with Reliable Controls**, ***Sowmya Subramanian***, *M.T. Meyer, Y.W. Kim, W.E. Bentley, R. Ghodssi*, University of Maryland, College Park

We present a multi-experiment PDMS based biofilm analysis platform using a valve-actuated microfluidic system, designed to reduce growth variance of *in-vitro* biofilms to less than 10%. This was achieved by integrating hydraulic push-down valve actuators to section a uniform biofilm grown in a channel by maintaining a single source of bacterial suspension [1, 2]. In this work, we establish a simplified process flow for the fabrication of a multi-depth device mold and demonstrate the high throughput capability of the microfluidic biofilm reactor.

Bacterial biofilms are the primary cause of infections in medical implants and catheters. The widespread use of high doses of antibiotics to treat biofilm infections is leading to the emergence of antibiotic resistant strains, necessitating the development of alternative methods of treatment [3]. However, the experimental evaluation of new treatment techniques is strongly hindered by the stochastic nature of biofilm growth [1]. Therefore, it is required to develop a microsystem that can not only facilitate multi-experiment studies for new treatment evaluation but also enable the growth of uniform biofilms that can be used as reliable controls.

Figure 1 shows a single uniform biofilm grown in the horizontal center channel of the device is sectioned into multiple sections, by hydraulically actuating the push-down valves thereby enabling multi-experiment studies on the same biofilm. Figure 2 shows the schematic of the operation of a "push-down" valve [4], the schematic of the CAD layout of the two-level microfluidic device and its two modes of operation. The two-step photolithography of the molds (Figure 3) using negative photoresists, SU8-2015 and KMPR1050, allows for the patterning of the multi-depth microfluidic mold without the need for additional passivation of the first resist layer, thereby simplifying fabrication. The mold can be reused to produce multiple devices; a photograph of the valve region of a used multi-depth mold is shown in Figure 4. Photographs of the device operating in different modes are shown in Figure 5.

The unique capability of this valved microfluidic biofilm reactor to section uniform biofilms can facilitate high-throughput biofilm studies, including new drug discovery. The push-down valve configuration allows for easy integration of electrodes for the study of alternative treatment methods like electric fields. Furthermore, the integration of the biofilm reactor with a real-time measurement system will enable high-throughput continuous analyses on uniform biofilms while ensuring tight and reliable controls.

5:20pm **MN+NS-TuA10 Multimode Silicon Carbide (SiC) Microdisk Resonator in Liquid**, ***Hao Jia***, *P.X.-L. Feng, J. Lee*, Case Western Reserve University

We experimentally demonstrate, for the first time to our knowledge, the operation of silicon carbide (SiC) microdisk resonators in fluidic and viscous environments (particularly in water) with robust multiple flexural-mode resonances in the high and very high frequency (HF/VHF) radio band. We observe ~8 resonance modes in a 20µm-in-diameter SiC microdisk resonator with resonance frequencies up to ~120 MHz and quality *Q* factors as high as ~40 in water.

SiC is a highly attractive material for microelectromechanical systems (MEMS) due to its superior mechanical (***e.g.*** high elastic modulus, E_Y~450 GPa), optical (wide bandgap, >2.3eV) and thermal properties (thermal conductivity of 320-490 W/[m×K]) [1].These advantages make SiC especially suitable for sensing applications in liquid for its transparency from visible to mid-infrared light and high optical power handling ability, facilitating efficient laser actuation and detection. Meanwhile, two dimensional (2D) microdisk structure exhibits multiple flexural-mode resonance characteristics, which can enhance sensing performances in liquid with the additional degrees of freedom and larger sensing area. Further, the unique biocompatibility of SiC allows potential in-liquid biosensing applications be developed.

In this study, we demonstrate the operation of high frequency SiC microdisk resonators in liquid. The SiC microdisk resonators are completely immersed in water, and are optically driven by an amplitude-modulated 405nm laser. The multimode resonances are detected with optical interferometry using a 603nm He-Ne laser. We observe ~8 resonance modes up to ~120 MHz with *Qs* as high as ~40 in water. To our best knowledge, both the number of resonance modes and *Qs* measured are the highest among flexural-mode resonators operating in water reported to date[2],[3],[4],[5]. Such high frequency SiC microdisk resonators with robust multimode resonances and high *Qs* in water may provide an appealing platform for particle and biological sensing applications in liquid.

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[3] S. Sawano, T. Arie, and S. Akita, *Nano. Lett.* **10**, 3395 (2010).

[4] J. H. Park, T. Y. Kwon, D. S. Yoon, H. Kim, and T. S. Kim, *Adv. Func. Mater.* **15**, 2021 (2005).

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5:40pm **MN+NS-TuA11 Development of CMOS-based Capacitive Micromachined Ultrasonic Transducers Operated in Collapsed Mode**, ***Wei-Cheng Chung***, *M.-C. Tsao, P.-C. Li, W.-C. Tian*, National Taiwan University, Taiwan, Republic of China

In this work, experimental results of complementary metal-oxide-semiconductor (CMOS)-based capacitive micromachined ultrasonic transducers (CMUTs) operated in the collapsed mode will be reported. Our CMUT is fabricated by TSMC 0.35µm two poly Si and four metal layer (2P4M) CMOS-MEMS standard process followed by a post customized wet etching. Conventionally, the applied DC bias is 80% of the collapse voltage during the CMUT operation. Compared to the conventional operation, the CMUT membrane will be snapped-down on the bottom electrode and this will change the center frequency of the transducers. The collapsed voltage of our CMUT is designed at approximately 40V. The center frequency (in immersion) of our CMUT in conventional mode operation is 2.89MHz while the frequency is shifted to 9.12MHz in collapsed-mode operation. The sensitivity is proved to be 4-times larger in the collapse-mode operation because the increased electrical-mechanical coupling efficiency.

The comparison of single-electrode and double-electrode design will be reported as well. With the double-electrode design, the collapse voltage is first applied to the center electrode while a separated DC bias is applied to the side electrode to actuate our CMUTs. The maximum displacement of the CMUT membrane will be appeared on the side electrode. It is proved that CMUTs with the double-electrode design can transmit a higher output pressure and receive signals with a higher sensitivity compared to CMUTs with the single-electrode design. It is believed that the our CMUTs with standard CMOS-based process will broaden the application spaces such as in biomedical imaging and nondestructive evaluation.

6:00pm **MN+NS-TuA12 Development of Micro Gas Preconcentrator Using Electroless Gold Deposition for Human Breath Analysis**, ***ChunYen Kuo***, *C.-L. Hsu,* National Taiwan University, Taiwan, Republic of China, *H.-Y. Kuo, C.-J. Lu,* National Taiwan Normal University, Taiwan, Republic of China, *W.-C. Tian*, National Taiwan University, Taiwan, Republic of China

The detection of the volatile organic compounds (VOCs) in human breath can be analyzed by gas chromatograph (GC) as a non-invasive diagnosis for lung diseases. However, the gas concentration of the VOCs in human breath is low, approximating in the ppb to sub ppb range, and thus a gas preconcentrator (PCT) must be placed before a GC to collect and preconcentrate trace compounds. Early µPCTs using commercially available adsorbents and microheaters were demonstrated. However, the heating efficiency of the device is limited either by a large thermal mass or a poor heat transfer.

In this study, we present a gas PCT using a simple one-photomask micromachined process and the electroless gold deposition method to form the gold film, serving as a thin film microheater, on the inner surface of the microchannel . An amorphous and porous carbon film that functions as an adsorbent is grown on microheaters inside the microfluidic channel followed by the electroless gold deposition. The developed gas PCT can be heated to >300℃ by applying a constant electrical power of ~5W with a heating rate of 60℃/sec.. Four suspected lung cancer biomarkers, acetone, benzene, toluene and xylene, are collected through the proposed gas PCTs and separated successfully using a 17-m-long gas chromatography (GC) column. Compared with previous works, the more simple fabrication process, more stable heating element, more uniform temperature distribution and more efficient heating rate of the micro gas preconcentrator are developeddemonstrated.

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