MEMS and NEMS
Room: 206 - Session MN-MoM

Integrative Materials and Processes for MEMS/NEMS
Moderator: E. Gousev, Qualcomm

8:20am **MN-MoM1 Integrated Piezoelectric RF MEMS Front-Ends**, ***G. Piazza***, University of Pennsylvania **INVITED**

This paper reports on the work performed in Dr. Piazza's laboratory for the realization of integrated piezoelectric RF MEMS front-ends. The work deals with three different aspects of the concept of MEMS integration: (i) integration of different piezoelectric devices such as resonators, filters and switches to create single-chip RF signal processors; (ii) integration of dissimilar materials such as thin film diamond and AlN piezoelectric films to enhance device quality factor and raise frequency of operation of resonators and (iii) integration or, more appropriately, considerations for integration with state-of-the-art CMOS electronics. The fundamental challenges faced from material, fabrication and design perspectives to attain the aforementioned three levels of integration are highlighted. For example, stress control, material and processing compatibility are important components that need to be taken into account in the demonstration of AlN switched filter banks. Surface roughness and etching compatibilities pose limitation in the fabrication of thin film diamond/AlN micromechanical resonators and constrain the design space. Furthermore, the material stack, deposition temperature and etching techniques need to be selected so that they are compatible or available in CMOS foundries. Design and experimental results demonstrating, for the first time, switched piezoelectric resonators and initial steps towards the integration of thin film diamond/AlN resonators are presented. These preliminary demonstrations set the foundations for the development of new classes of devices that can disrupt the way we currently perform RF signal processing by enabling fast frequency hopping and low power frequency synthesis in a broad frequency spectrum that could not be previously covered by any other MEMS technology.

9:00am **MN-MoM3 Chemically-Modified Graphene Nanomechanical Resonators**, ***M.K. Zalalutdinov***, SFA Inc., *J.T. Robinson, E.S. Snow, Z. Wei, P.E. Sheehan, J.W. Baldwin, B.H. Houston*, Naval Research Laboratory

High quality factor (Q~4000) radio frequency (20-100 MHz) nanomechanical resonators are fabricated using suspended ultra-thin films of chemically modified graphene (CMG).[1] The films were prepared by spin-casting graphene oxide platelets onto SiO_2/Si substrates, reducing back toward graphene using chemical and/or thermal treatments, then lifting-off and transferring films to patterned substrates. Large-area continuous films can be deposited using this method, enabling batch fabrication of nanoelectromechanical devices. Membranes as thin as 4 nm can be successfully transferred and suspended over 2.7 µm diameter holes. The ability to withstand high in-plane tensile stress (T~10 N/m, deduced from membrane resonant frequencies) as well as high quality factors show that the integrity of the film is NOT compromised by the inter-platelet bonding. The extremely small mass of these CMG resonators provides an estimate for the added mass sensitivity as low as $\delta m \sim 10^{-18}$ g. In-plane stress inherent to as-fabricated CMG membranes can be dynamically tuned over a wide range due to thermoelastic effects by applying a low power localized heat source. In conjunction with the short thermal relaxation time ($\tau \sim 10^{-8}$ sec) this enables techniques such as parametric pumping for further enhancement of the performance of CMG resonators. Thicker (h>15 nm) suspended CMG films show similar quality factors, can withstand strain in excess of 0.3% and constitute a virtually unpenetrateable barrier for water or vapor as confirmed by resonant frequency measurements. Membranes encapsulating water on one side and exposed to vacuum on the other side show no frequency dependence on a time scale of days, indicating perfect sealing. In addition, both the membranes themselves and the adhesion of the CMG film to the substrate are strong enough to withstand boiling of the encapsulated water (T_{anneal}>100°C). Finally, ultra-thin CMG films are optically transparent and feature only minor e-beam scattering thereby facilitating access to encapsulated objects for imaging and/or spectroscopy. We will describe mechanical and thermomechanical properties of CMG films extracted from the behavior of the nanoresonators and discuss possible applications in sensing and nanofluidics.

This work was supported by the Office of Naval Research.

[1] Ruoff, R. Nature Nanotechnology 3, 10-11 (2008).

9:20am **MN-MoM4 Electrical Transduction of Multi-layer Polysilicon Resonators**, ***J.D. Cross***, *B.R. Ilic*, Cornell University, *M.K. Zalalutdinov*, SFA Inc., *E. Yilmaz*, Cornell University, *J.W. Baldwin, B.H. Houston*, Naval Research Laboratory, *H.G. Craighead, J.M. Parpia*, Cornell University

A straightforward means of electrical transduction of resonator motion is investigated using MHz-frequency micromechanical resonators made from multi-layer film stacks. Devices are fabricated using polysilicon films stacked on top of each other with intermediate layers of insulating material. Electrical or optical drive is used to induce motion in the resonators and electrical transduction allows for direct detection of the resonator motion. A variety of structure geometries are investigated, including cantilevers, double-clamped beams, mushrooms, and domes. Quality factors of 1000-10000 are routinely observed. We discuss the transduction mechanism as well as the ability to integrate these kinds of MEMS structures into a standard CMOS foundry process with no added or modified fabrication steps. We show that the multi-layer film stack can be delaminated in the release step, resulting in stacked resonator structures with thin gaps between each vibrating surface. This work was partially supported by the Office of Naval Research, DARPA, and fabrication was performed at the Cornell NanoScale Science and Technology Facility.

9:40am **MN-MoM5 Selective Detachment of Microspheres using In-Plane Modes of Nanoelectromechanical Oscillators**, ***B.R. Ilic***, Cornell University, *S. Krylov*, Tel Aviv University, Israel, *M. Kondratovich, H.G. Craighead*, Cornell University

Manipulating dynamics of flexural and torsional vibrational modes of micro- and nanoelectromechanical systems (MEMS and NEMS) with external fields has long been a sought-after goal. A widely studied class of NEMS devices consists of surface micromachined mechanical oscillators made of thin film layers patterned into various shapes that operate by motion perpendicular to the plane of the thin film and substrate by bending in their thin direction. Conventional mechanical driving and motion transduction methods typically activate and detect only motion in this "out-of-plane", transverse direction. We previously demonstrated a robust method for driving and detecting the motion of micro- and nano-scale resonators by utilizing optical drive of resonant motion and interferometric detection of that motion by a separate laser. This technique allowed non-invasive activation and interrogation of individual oscillators or arrays of oscillators. We describe here an approach that can activate and detect the perpendicular, in-plane motion of such oscillators. We show that optical fields are efficient for excitation, direct control and measurement of in-plane motion of cantilever-type nanomechanical oscillators. Using optical excitation and interferrometric detection, we dynamically analyzed surface micromachined 200nm and 250nm thick single crystal silicon cantilevers of varying lengths and widths. We also have demonstrated the controlled capture, detection and release of submicrometer particles by the application of forces imparted by the in-plane motion of the resonators. In contrast, the out of plane motion, even in the strong non-linear impact regime, was insufficient for the removal of bound polystyrene spheres. Our results suggest that optical excitation of in-plane mechanical modes provide a unique mechanism for controlled removal of particles bound on the surface of nanomechanical oscillators.

10:20am **MN-MoM7 Synthesis and Characterization of Large Area Ultrananocrystalline Diamond (UNCD) Films using Microwave Plasma Chemical Vapor Deposition Process and Integration with CMOS**, ***A.V. Sumant***, *O. Auciello*, Argonne National Laboratory, *V. Adiga, A. Konicek*, University of Pennsylvania, *X. Zhong, B. Kabius*, Argonne National Laboratory, *H. Yuan, Z. Ma*, University of Wisconsin-Madison, *R. Carpick*, University of Pennsylvania

Because of exceptional mechanical, chemical, electrical and tribological properties of ultrananocrystalline diamond (UNCD), it has great potential to be used in for the development of high-performance, harsh environment-compatible devices for MEMS and NEMS, such as resonators and switches. Recent work by our group has demonstrated fabrication of functional RF-MEMS switches and resonators based on UNCD. However, transition of this technology to the industry will critically depend on the ability to produce UNCD films on wafer scale with acceptable thickness and microstructure uniformity. We have achieved 4%, 7%, and 11% uniformity in UNCD film thickness across 100 mm, 150 mm, and 200 mm diameter Silicon substrates respectively using 2.45 GHz and 915 MHz microwave plasma chemical vapor deposition (MPCVD) process. All the films were grown in the temperature range of 400-800 oC. We report on the microstructure uniformity, phase, and impurity content of UNCD films by using atomic force microscopy (AFM), Near edge X-ray absorption fine structure spectroscopy (NEXAFS), and forward recoil spectrometry (FRES) characterization techniques respectively. Additionally, we have developed a materials integration strategy to enable diamond-CMOS integration. Ultrananocrystalline diamond (UNCD), a novel material developed in thin film form at Argonne, is the only diamond film that can be grown at 400oC, and still retain exceptional mechanical, chemical, and tribological properties comparable to that of single crystal diamond. We have developed a process based on microwave plasma CVD to synthesize UNCD films on 150 and 200 mm CMOS wafers, which will open new avenues for building CMOS-driven devices for MEMS/NEMS based on UNCD. UNCD films were grown successfully on individual Si-based CMOS chips and on 200 mm CMOS wafers at 400 oC in a microwave-plasma-enhanced chemical vapor deposition (MPCVD) system with Ar-rich/CH4 gas mixture. The CMOS devices on the wafers were characterized before and after UNCD deposition. All devices were performing to specifications with acceptable degradation after UNCD deposition and processing. A threshold voltage degradation in the range of 0.08-0.44V and transconductance degradation in the range of 1.5-17% were observed. We also report the on the cross-section TEM/EELS studies of the UNCD/CMOS interface and discuss the possible mechanisms responsible for the degradation of CMOS performance.

10:40am **MN-MoM8 {100}-Textured PZT Films Grown on Chemically Deposited $PbTiO_3$ Seed Layers for MEMS Applications**, *J. Zhong, **S. Kotru**, H. Han, R.K. Pandey*, The University of Alabama

Lead zirconate titanate (PZT)-based thin films are gaining increased interest in wide variety of applications in MEMS due to their large longitudinal and transverse piezoelectric coefficients, and the compatibility with microelectronic circuits. Both micro-machined sensors (such as accelerometer and gyroscope) and actuators (such as micro-motors, micro-pumps, and micro-switches) have been fabricated based on PZT films. The piezoelectric response of PZT films is the key factor for sensing and actuation function of a device; the higher the value, the better the device will act as sensor and/or actuator. Texture of the films plays a major role in determining the piezoelectric response. So far, the highest transverse piezoelectric coefficient (-12.0 C/m^2) has been reported for {100}-textured PZT films grown on $PbTiO_3$ seed layers. These $PbTiO_3$ were sputtered at 500~600° C. High temperature sputtering limits the practical implementation of such films in MEMS devices due to process constraint and sample size limitations. In this work, highly {100}-textured PZT films have been grown with $PbTiO_3$ seed layers. However, the seed layers in our work were deposited by chemical solution deposition. The effect of both Pb content and solution concentration of $PbTiO_3$ on PZT films was investigated extensively. These PZT films show 97% of {100} texture and effective transverse piezoelectric coefficients of -13.3 C/m^2. Thus our films have higher effective transverse piezoelectric coefficient than the PZT films grown with sputtered $PbTiO_3$ seed layers. Our approach of obtaining {100}-textured PZT films with high piezoelectric response on chemically deposited seed layers has advantage of being much easy and low-cost. Such films are feasible for MEMS based device implementation.

11:00am **MN-MoM9 Suppression of Anelastic Effects in Micromechanical Resonators from Suspended Al-CNT Nanolaminate Thin-Films**, ***Y.D. Kim**, J.H. Bak, S.W. Cho, B.Y. Lee, S.R. Lee, K. Char, S. Hong, Y.D. Park*, Seoul National University, South Korea

We present evidence that the addition of Al-CNT lamina to suspended Al thin-film micromechanical resonators suppress anelastic effects. Addition of Al-CNT lamina to form a metallic-CNT nanolaminate has been shown to enhance mechanical properties, including elastic modulus as well as strengths, from dynamic and quasi-static flexural measurements of suspended doubly-clamped micromechanical beam resonator structures.[1] In this study, dynamic flexural measurements for long loading-cycles ($>10^{11}$) is presented. The micromechanical beam resonator structures, which are patterned by a combination of e-beam and photolithography methods, are fabricated from UHV sputter deposition of Al onto a self-assembled CNT network on a GaAs substrate, which is selectively removed to suspend the beam. The frequency response of the microresonators is periodically measured by a laser vibrometer-like set-up, while the beam is actuated electrostatically. For Al beam resonators, the resonance frequency (f_o), which is directly related to the its elastic modulus, varies during the duration of measurement ($\Delta f_o / f_o < 1.5\%$), while for Al-CNT beam resonators, f_o is relatively unchanged for the duration. Such observations is consistent with the view that the CNTs mechanically reinforce and is well-incorporated in the Al thin-film, as anelastic effects are attributed to grain boundary sliding and are a contributor to stress relaxation in metallic thin-films.[2]

[1] J.H. Bak, Y.D.Kim et al., Nature Materials advance online publication, 20 April 2008 (doi:10.1038/nmat2181).

[2] S. Hyun et al., Appl. Phys. Lett. 87, 061902 (2005).

11:20am **MN-MoM10 An Opto-Thermo-Mechanical MEMS Sensor for Direct Thermal Imaging**, *P. Apte, **B. Seth**, O. Karhade, S. Chiluveru*, IIT Bombay, India

Infrared imaging plays a critical role in many applications ranging from night vision, environmental monitoring and astronomy. The paper describes a room-temperature compensated opto-thermo-mechanical un-cooled infrared imaging system with a direct color display. The sensor consists of an array of sensing elements suspended from the substrate using bimorph beam elements. Infrared radiation incident on a sensing element is absorbed and leads to a rise in temperature. The heat conducted from the sensing element to the bimorph beam elements leads to a deformation of the beam elements and results in a displacement of the sensing element in a direction perpendicular to the plane of the sensing element. Thus the lateral positions of the sensing elements is influenced by the infrared energy received by the sensing elements in addition to the room temperature. The lateral movement of sensing element is converted into a color image by interference of reflected light from the sensing element and another parallel element with an air gap suitable for creating a constructive interference in the visible spectral range. This second parallel element is also mounted using similar bimorph beam elements and is made of a material transparent to infrared radiation. Thus the transverse position of the transparent element does not depend on the incident infrared radiation but only the ambient temperature. This way it is possible to cancel the effect of room temperature on the interference pattern. The design considerations for the above device are described here. Various configurations of arranging the elements and the bimorph are discussed along with their relative merits. Simulations were conducted using Ansys© software. For an incident radiation of 100 W/m^2, the rise in temperature of 0.3mm x 0.3mm sensing element was about 5 degrees C. The sensitivity of the device was found to be of the order of 4 nm^3/W. The time constant of the device was found to be about 2 seconds.

11:40am **MN-MoM11 An Optical MEMS Sensor for Catechol Detection**, ***P.H. Dykstra**, J. Hao, S.T. Koev*, University of Maryland, *G.F. Payne*, University of Maryland Biotechnology Institute (UMBI), *L. Yu, R. Ghodssi*, University of Maryland

Catechol is a widely studied phenol which is a common byproduct of factory waste. Its presence in drinking water and food poses a safety concern due to its toxic and possibly carcinogenic effects. We report the successful fabrication and testing of an optical MEMS sensor for the detection of catechol. Other reported sensors suffer from a lack of selectivity. This sensor marks the first time optical measurements have been utilized for catechol detection on chip. In addition, it provides improved selectivity over conventional detection methods. Typically used detection techniques involve electrochemically oxidizing catechol solution and measuring the current from the reaction over time. However, these methods are prone to false positives since any other easily oxidized chemicals present, such as ascorbic or citric acid, will create a current. Other studies involving catechol detection have shown that byproducts from catechol oxidation will induce a significant absorbance change in an aminopolysaccharide film of chitosan. Chitosan is derived from the biopolymer chitin and has been well characterized by our group in the past. This absorbance change in chitosan caused by catechol oxidation is shown to be the highest in the UV and near UV range of the spectrum. Our reported device takes advantage of this unique absorbance property to detect catechol by measuring the change in light intensity at 472 nm. The device consists of a single microfluidic channel patterned in SU-8 with perpendicular waveguides for guiding light through a deposited chitosan film. Indium Tin Oxide (ITO), a transparent conductor, is used as the cathode on the waveguide facet to facilitate the chitosan film deposition. Chitosan forms a solid film at pH higher than 6.3 which allows it to be selectively deposited onto a cathode during an electrochemical reaction. As catechol flows down the channel it is electrochemically oxidized via patterned electrodes and causes the absorbance change in the chitosan film. Blue laser light is coupled in and out of the device using multimode optical fibers and the intensity is measured by an external spectrophotometer. The higher concentration of catechol contributes to a higher absorbance as expected while oxidizing buffer solution and ascorbic acid display no measurable change in the absorbance through the chitosan film. The data displays a considerable response even for the lowest measured concentration (0.001 M).

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