MEMS and NEMS
Room: 102 A - Session MN+NS-TuM

Micro and Nano Systems based on Carbon and Piezoelectric Materials
Moderator: P. X.-L. Feng, Case Western Reserve University

8:00am **MN+NS-TuM1 Science and Technology of Integrated Piezoelectric and Ultrananocrystalline Diamond Films for a New Generation of High Performance MEMS and NEMS Devices**, ***O. Auciello***, University of Texas at Dallas **INVITED**

This review will focus on a discussion of the science and technology for a novel integration of ultrananocrystalline diamond (UNCD) and piezoelectric thin films to enable a new generation of hybrid piezo/diamond heterostructures for low voltage piezoactuated high-performance diamond-based MEMS/NEMS devices. A main component of the new MEMS/NEMS systems is the new UNCD film discovered, developed and patented by our group. UNCD exhibits multifunctionalities applicable to a broad range of multifunctional devices from the macro to the nanoscale. UNCD films are grown using plasma enhanced chemical vapor deposition (PECVD) with a new patented Ar-rich/CH_4 chemistry, which yields insulating films with 2-5 nm grains and 0.4 nm wide grain boundaries or electrically conductive films (NUNCD), with 10 nm grains and 1-2 nm grain boundaries, via nitrogen incorporation into grain boundaries when growing the film with an Ar/CH_4/N_2 gas mixture.

Concurrently with the development of the UNCD film technology, our group has been developing a ferroelectric/piezoelectric thin film technology, based on three main piezo materials ($PbZr_xTi_{1-x}O_3$, AlN, and the newest $BiFeO_3$), and the UNCD/piezoelectric thin films integration, which are being used to develop new low voltage/high performance piezoactuated MEMS/NEMS devices for several applications, namely: energy harvesting devices, piezoactuated NEMS switches for a new NEMS logic, biosensors, implantable MEMS/NEMS drug deliver devices, and biologically enabled piezo-MEMS micro-power generators.

In addition to the application to piezo-actuated MEMS, UNCD has been demonstrated as a unique dielectric with fast charging-discharging (in the microsecond range) layer that eliminates RF MEMS switch charging-induced failure, due to fast charge motion in and out of the film through the nano-grain boundaries, enabling a new technology based on reliable RF-MEMS switches integrated with driving CMOS devices for a new generation of phase array antennas for radars and mobile communication devices.

8:40am **MN+NS-TuM3 Utilizing Piezoelectric MEMS Across Length Scales**, ***S. Trolier-McKinstry***, Penn State University **INVITED**

Piezoelectric microelectromechanical systems offer an interesting way of achieving sensing and actuating capabilities on-chip, at voltage levels that are compatible with many CMOS devices. As a result, there is a burgeoning interest in exploiting films that can produce large strains over a wide range in length scales. This talk will address the use of perovskite thin films (especially $PbZr_{0.52}Ti_{0.48})O_3$, PZT, and $70PbMg_{1/3}Nb_{2/3}O_3 - 30PbTiO_3$, PMN-PT) in applications where the critical dimensions range from tens of nm to meters. Particular attention will be placed on 1) use of actuators to correct figure errors in next-generation X-ray space telescopes and 2) a potential CMOS – replacement technology for computation which hinges on use of a piezoelectric thin film to drive a resistance change in a piezoresistor.

On the extreme upper end are large area devices for applications such as adaptive optics. In this case, the piezoelectric film can be used to produce local deformation of a mirror surface, in order to correct figure errors associated with fabrication of the component or to correct for atmospheric distortion. For example, should a mission such as Gen-X be flown, it would require up to 10,000 m^2 of actuatable optics in order to correct the figures of the nested hyperboloid reflecting segments. The piezoelectric layers were deposited by sputtering; the best insulation properties were obtained in films that avoided lead excess phases at the grain boundaries. Measurements of the influence function resulting from actuation of one or more of the piezoelectric cells (to change the local curvature of the substrate) demonstrate that such adjustable optics should be able to increase the resolution of X-ray telescopes by an order of magnitude.

A fast, low power, transistor-type switching device has been proposed in which piezoelectric and piezoresistive materials are employed in a stacked sandwich structure of nanometer dimension. Of particular interest to this program is the functionality of the high aspect ratio piezoelectric $70Pb(Mg_{1/3}Nb_{2/3})O_3$-$30PbTiO_3$ (PMN-PT) component. PMN-PT films of 0.3 – 1.1 microns in thickness were made by a 2MOE solvent sol-gel route. These films were phase pure by XRD with dielectric constants exceeding 1500 and loss tangents of approximately 0.05. The films showed slim hysteresis loops with remanent polarizations of about 8 $\mu C/cm^2$ and breakdown field > 1.5 MV/cm. The films exhibited large signal strain > 1% with $d_{33,f}$ of approximately 80 pm/V. It has been found that laterally patterning the piezoelectric layer in this case produces an increased dielectric response indicative of a reduction in substrate-induced clamping.

9:40am **MN+NS-TuM6 Two-Dimensional (2D) MoS_2 Semiconducting Crystal Nanomechanical Resonators with Frequency Scaling**, ***J. Lee***, *Z. Wang, K. He, J. Shan, P. X.-L. Feng*, Case Western Reserve University

We report the first demonstration of resonant nanoelectromechanical systems (NEMS) based on ultrathin molybdenum disulfide (MoS_2) crystals down to only a few atomic layers, with measurements of resonances in the high frequency and very high frequency (HF/VHF) bands, and studies of frequency scaling pathways toward the ultrahigh frequency (UHF) and microwave regimes. Atomically-thin two-dimensional (2D) crystals have recently shown interesting promises for enabling new nanoelectronic and optoelectronic devices [1]. The unique mechanical properties of these 2D crystals, including excellent elastic modulus (~0.2-1TPa) and extremely high strain limits (~10^2-10^3 times higher than in 3D crystals), also make them attractive for 2D NEMS [2,3]. To date, most 2D NEMS have been based upon graphene, the hallmark of 2D crystals. 2D MoS_2, an ultrathin crystal of transition metal dichalcogenides (TMDCs), has emerged as a new class of 2D layered materials beyond graphene. Unlike graphene being a semimetal, 2D MoS_2 is a semiconducting crystal with a sizeable bandgap and hence opens up new device opportunities. In this work, we describe experiments on realizing drumhead-structured MoS_2 NEMS resonators based upon suspended MoS_2 diaphragms as thin as 6nm (9 layers of the crystal unit cell). We demonstrate resonators operating at up to ~60MHz in the VHF band at room temperature, with measurements of Brownian-motion thermomechanical noise spectra. We also measure quality (Q) factors of these MoS_2 resonators and explore the dominating energy dissipation mechanisms in these 2D structures. The extensive measurements and analysis in this work with many devices establish MoS_2 as a new material for frequency-scalable 2D NEMS resonators and transducers. Our study opens up possibilities for new types of NEMS, where the mechanical properties of 2D MoS_2 can be coupled to its semiconducting attributes.

[1] Q. H. Wang, *et al.*, *Nature Nanotechnology* **7**, 699-712 (2012).

[2] R. A. Barton, *et al.*, *J. Vac. Sci. Technol. B* **29**, 050801 (2011).

[3] J. Lee, P. X.-L. Feng, *Proc. IEEE Inter. Freq. Contr. Symp. (IFCS2012)*, DOI: 10.1109/FCS.2012.6243742

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