MEMS and NEMS
Room: 301 - Session MN+PS-WeA

Emerging Materials and Fabrication Technologies for MEMS/NEMS

Moderator: Sushma Kotru, The University of Alabama, Meredith Metzler, Cornell University

2:20pm **MN+PS-WeA1 Organic Sensors and Actuators Patterned by Inkjet Printing**, ***Tse Nga (Tina) Ng***, PARC (Palo Alto Research Center), a Xerox Company, *J. Kim, W.S. Kim,* Simon Fraser University, Canada, *K.S. Kwon*, Soonchunhyang University, South Korea **INVITED**

Organic materials have been demonstrated as good candidates for large-area sensors, because they allow wide tolerance of sensor geometry and thickness, which would ease fabrication problems such as strain induced cracking on deformable plastic platforms. Organic electronic materials can be deposited and patterned by low-cost printing tools such as inkjet printers. Notably, the printing process is compatible with many substrates ranging from plastics to fibers, to potentially integrate electronics on any surface. At Palo Alto Research Center, we have developed processes for printed electronics that enable new form factors and applications in flexible sensors and circuits. In conjunction with university collaborators, here we present examples of organic mechanical sensors and actuators fabricated by facile solution processes.

The first example is a capacitive pressure sensor patterned by block copolymers. Different microstructures (hemisphere, cones, nano-needles) are explored for the dielectric film, and the dielectric with nano-needles showed the highest sensitivity, with the relative capacitance change up to 176%/kPa. The capacitor with the nano-needle filler was integrated with an inkjet printed OTFT to provide current output. The device sensitivity is comparable to the sensitivity of human skin and will be useful for tactile sensing applications on a wide range of surfaces.

In a second example, we have fabricated a bimorph actuator from electroactive polymer blends with ionic liquid. The polymer blends allow low-voltage operation, and we found that the actuator displacement increases with larger gradient difference in ionic liquid content. A maximum strain of 0.48% was observed. The electroactive polymers are compatible with extrusion printing and have the potential to be patterned through layer-by-layer printing for incorporation into 3d structures.

3:00pm **MN+PS-WeA3 Microfabrication by Etching for Carbon Nanotube Composite Sheets**, ***Nathan Boyer***, *J. Rowley, D.D. Allred,* Brigham Young University, *S. Liddiard,* Moxtek, Inc, *R.R. Vanfleet, R.C. Davis*, Brigham Young University

We have prepared extremely smooth carbon nanotube (CNT)/polymer composite sheets and patterned them with holes and trenches using a process of photolithography and plasma etching. The high strength patterned CNT/polymer composite could be used in MEMS applications. A CNT sheet was impregnated with polyimide and the composite was cured in a vacuum hot press at 400°C. A film of amorphous silicon nitride was deposited on the composite sheet and patterned to act as a hard mask during oxygen plasma etching. Structural and mechanical testing of the CNT composite sheets will be presented along with plasma etching results.

3:20pm **MN+PS-WeA4 High Aspect Ratio Magnetic MEMS Fabricated using Carbon Nanotube Templated Microfabrication**, ***Robert Davis***, *L. Barrett, D. Barton, R.R. Vanfleet, D.D. Allred*, Brigham Young University

We have fabricated nickel microstructures with aspect ratios greater than 20-1, and feature sizes as small as 5 um. The process involves growing a forest of carbon nanotubes in the desired pattern, and coating the tubes with an additional a layer of carbon by CVD. Then the remaining space in the forest, approximately 90%, is filled with nickel by pulsed electroplating. Because the resulting composite has a magnetic response, it is ideal for MEMS magnetic sensors and actuators. To demonstrate this, we constructed a simple MEMS scale sensor with a frame, two flexures and a proof mass. Optical measurement of the proof mass's displacement as a function of applied magnetic field will be shown.

4:20pm **MN+PS-WeA7 Sub-100nm Thin Polycrystalline Diamond Nanomechanical Torsional Resonators**, ***Rui Yang***, *Z. Wang, J. Lee, C.A. Zorman, P.X.-L. Feng*, Case Western Reserve University

We report experimental demonstration of high-frequency (HF) torsional nanomechanical resonators based on nanoscale polycrystalline diamond thin films. We fabricate devices with tethers as thin as 100nm×50nm in cross section, measure their multi-mode resonances with frequency (f_{res}) into the HF band (up to ~10MHz, while most existing sensitive torsional devices are at kHz or low-MHz), and quality (Q) factors exceeding 2000 at room temperature. We also perform temperature-varying measurements, and observe strikingly different temperature coefficients of frequency (TCf) between the torsional and flexural resonant modes.

Diamond is particularly interesting for micro/nanoelectromechanical systems (MEMS/NEMS), because of its exceptional mechanical properties (Young's modulus greater than 10^{12}Pa), relatively low mass density (3500kg/m^3), very high thermal conductivity (22W/(cm·K)), and excellent wear/corrosion resistivity[1]. Especially, its high sound velocity is attractive for making high frequency mechanical resonators[2]. Resonators based on diamond thin films from microwave plasma chemical vapor deposition have been demonstrated, showing mechanical properties comparable to single crystal. However, *torsional resonators* based on diamond thin films showing resonance in HF band and exceptional force and torque sensitivities have not been explored. While we demonstrated torsional resonators using 1.2μm-thick SiC film[3], *much thinner and smaller devices* are required for higher sensitivities.

Here we fabricate torsional resonators on 50 to 100nm thin polycrystalline diamond films with focused ion beam. We perform Raman spectroscopy to confirm the nanocrystalline diamond nature of the membrane. The mechanical resonances are measured by driving the mechanical motion with a modulated laser (405nm), and detecting the resonant motion with laser interferometry (633nm). These devices show force sensitivity down to the sub-fN/√Hz range, and torque sensitivity on the order of 10^{-22} (N·m)/√Hz, which is similar to the best reported results in other materials[4]. This opens up the possibility for fabricating ultrasensitive devices for force/torque, inertia, and thermal sensing, based on nanocrystalline diamond platform. TCf measurement shows clear and intriguing anti-crossing behavior, which vividly illustrates cross-mode mechanical coupling.

---

[1] O. Auciello, *et al.*, *J. Phys.-Condens. Mat.* **16**, R539 (2004).

[2] L. Sekaric, *et al.*, *Appl. Phys. Lett.* **81**, 4455-4457 (2002).

[3] R. Yang, P. X.-L. Feng, *et al.*, *Appl. Phys. Lett.* **104**, 091906 (2014).

[4] X. C. Zhang, *et al.*, *Nano Lett.* **13**, 1528 (2013).

4:40pm **MN+PS-WeA8 Temperature Compensated Graphene Nanomechanical Resonators**, ***Jaesung Lee***, Case Western Reserve University, *H.-Y. Chiu,* University of Kansas, *P.X.-L. Feng*, Case Western Reserve University

Graphene-based atomically-thin two-dimensional (2D) nanostructures have emerged as new building blocks for novel nanoelectromechanical systems (NEMS) [1], which can enable nanodevices with unprecedented performances such as ultrasensitive detectors and highly tunable oscillators [2] In addition to its excellent mechanical properties, such as ultralow areal density (r_A=0.74fg/μm^2), ultrahigh strain limit (~25%), and large Young's modulus (E_Y~1TP), graphene has superior thermal properties, which can enable large temperature range operations and ultra-stable high temperature performances. In addition, the unique negative thermal expansion coefficient of graphene can be employed to tune the device tension and thus its resonance behavior through controlling the device temperature. To date, most experimental investigations of graphene resonators are at room temperature or below, with high temperature operation remaining largely unexplored.

In this work, we experimentally study graphene resonators from room temperature to ~600K and study their resonance characteristics by measuring the thermomechanical noise. Our graphene resonators show relatively small frequency shifts from 300K to 600K due to natural temperature compensation from the different thermal expansion coefficients of graphene and other structural metals. We further examine temperature profile in graphene resonators, and establish resonator models with wide range temperature operation, elucidating temperature compensation mechanisms in graphene resonators. This study will help improve the understanding and development of both temperature-sensitive and insensitive 2D NEMS resonators, which can lead towards future large temperature range and high temperature application of 2D NEMS.

References:

[1] J. Lee, P. X.-L. Feng, *IEEE International Frequency Control Symposium (IFCS'12)*, DOI: 10.1109/FCS.2012.6243742 (7 pages), Baltimore, MD, May 21-24 (2012).

[2] C. Chen, J. Hone, *Proc. IEEE***101**, 1766-1779 (2013).

[2] C. Chen, S. Rosenblatt, K. I. Bolotin, W. Kalb, P. Kim, I. Kymissis, H. L. Stormer, T. F. Heinz, and J. Hone, *Nature Nanotech.***4**, 861- 867 (2009).

5:00pm **MN+PS-WeA9 A Porous Material for Improving Cantilever Q in Air and Liquid for Resonant Mechanical Sensing**, ***Steven Noyce***, *R.C. Davis, R.R. Vanfleet*, Brigham Young University, *H.G. Craighead*, Cornell University

Nanoporous cantilever resonators have potential performance advantages for cantilever based sensing. For porous cantilevers a high surface area leads to a high adsorbed mass which is independent of the cantilever dimensions. Larger cantilever dimensions can lead to higher quality (Q) factors in air and liquid sensing environments. Here we present work on the fabrication of nanoporous carbon/carbon nanotube composite cantilevers. Our results include characterization work on tuning the composite materials properties and cantilever geometries for high Q in fluid.

5:20pm **MN+PS-WeA10 XPS to Investigating Spatial and Temporal Modification of PDMS Platforms for Micro-Fluidic Devices**, ***Marshal Dhayal***, CSIR- Centre for Cellular and Molecular Biology, India

Spatial and temporal changes in surface chemical composition silicon (Si), carbon (C) and oxygen (O) of polydimethyl siloxane (PDMS) surfaces before and after plasma treatment were estimated from quantitative elemental analysis of X-ray photoelectron spectroscopy (XPS) wide scan spectra. Theoretical ratio of Si/C/O in repeating unit $(–[Si-(CH_3)_2-O]_n–)$ of PDMS were calculated and were compared to experimentally obtained ratio for Si/C/O obtained from untreated and plasma PDMS surfaces used for micro-fluidic devices. The contact angle measurements have shown that (PDMS) surfaces treated by air plasma can recover up to about 50% of its hydrophobic nature in less than 30 min of air exposure. These plasma modified surfaces were functionalized with poly(ethylene glycol) (PEG) silane to obtained PDMS surface as hydrophilic in nature for micro fluidic application. The surface chemistry of PEG-functionalized PDMS substrate has been studied using XPS. These different types of surfaces were used fabricate micro-fluidic devices and effects of surface nature of micro channels on fluid velocity were observed in PEG grafted micro channel in PDMS base micro fluidic devices. The effect of different pH of the fluids on the fluid velocity in PDMS-based micro channel was also studied.

5:40pm **MN+PS-WeA11 A Microplasma-based Sputtering System for Direct-Write, Micropatterning of Metal Structures**, ***Edwin Burwell***, *A.C. Barnes, P.X.-L. Feng, M. Sankaran, C.A. Zorman*, Case Western Reserve University

Patterning metal as a contact or interconnect is a critical processing step for device fabrication in a wide range of applications ranging from conventional electronics on silicon chips to implantable biosensors on flexible polymeric substrates. Traditionally, physical vapor deposition is combined with photolithography to deposit patterned metal films. Although this subtractive approach produces high pattern fidelity and conductivity, low throughput, materials wastage, and need for vacuum lead to high production costs and limited scalability. The emergence of flexible devices has stimulated the desire for additive approaches such as ink-jet printing for depositing patterned conductive materials. Ink-based printing is carried under ambient conditions and can be integrated with roll-to-roll systems for large-scale manufacturing. However, the inks can be expensive and the variety of materials that are available as printable inks is very small. In addition, the organic capping agents that are used to stabilize the particles are difficult to remove, which can compromise conductivity and mechanical integrity. Removal of the organics requires high annealing temperatures that limit the usage of certain polymers and other temperature-sensitive substrates. Adhesion of the printed structures to the substrates can also be a significant issue, especially in flexible applications.

In this paper, we describe a microplasma-based process to deposit patterned structures with micro- to nanoscale dimensions on rigid or flexible conducting and insulating substrates. This direct-write, additive process uses plasma-based sputtering to generate a physical vapor comprised of the material of interest. The plasma is generated within a small capillary tube that is capped with a micron-sized orifice. The sputtering target consisting of a micron-sized wire is positioned inside the capillary. Forced Ar flow aids in the ejection of the resulting physical vapor through the orifice, which is positioned in close proximity to the substrate. The process is performed at atmospheric pressure, thereby addressing the most significant limitation associated with conventional magnetron sputtering and thermal evaporation, and is low temperature, allowing deposition on temperature-sensitive substrates such as polymers and paper. To date, we have successfully deposited patterned Au structures that are submicron in thickness and 150 microns in width on glass substrates. Our presentation will detail the apparatus, the principal of operation, and the most current results in creating and characterizing micropatterned metal structures on insulating substrates.

Authors Index

Bold page numbers indicate the presenter