MEMS and NEMS
Room: 10 - Session MN-MoA

Multi-scale Interactions of Materials and Fabrication at the Micro- and Nano-scale

Moderator: M. Metzler, Cornell University

2:00pm **MN-MoA1 Acute Stress in Silicon Nitride**, ***J.M. Parpia***, *V.P. Adiga, B. Ilic, R.A. Barton, R. De Alba,* Cornell University, *I. Wilson-Rae,* Technische Universität München, Germany, *H.G. Craighead*, Cornell University **INVITED**

Mechanical structures fabricated from highly stressed silicon nitride films exhibit some of the highest Q (Quality factor) values observed in MEMS/NEMS structures at room temperatures. By varying the diameter and thickness of high stress silicon nitride circular "drum" structures, we observe that the dissipation follows generally predictable behaviors. Qualitatively we see that the fundamental out-of-plane resonance mode has the lowest Q in large structures (though it can still exceed 10^5). As higher modes with radial nodal lines (described as cake like modes) are added, the Q increases. Modes that add a nodal line at a constant radius also have higher Qs, but the Q improvement over the fundamental is not large, and can also lead to lowering of the Q in small structures. Generally thinner more uniform cross section structures reveal the higher Qs. As higher order resonances are excited, the product of the frequency times Q (*fQ*) tends to a constant. Many of these behaviors are consistent with recent models. This presentation will describe the results obtained as the diameter and thickness of the devices of these structures was varied.

2:40pm **MN-MoA3 *In Situ* SEM Micro Tension Tests on Nanoscale Single Crystal Metals and Nanocrystalline Metals**, ***M. Yilmaz***, *J.W. Kysar*, Columbia University

We developed a microscale uniaxial tension test MEMS device for in-situ SEM experimentation, with potential use for in-situ TEM experiments as well. We have characterized batch compatible integrated ultra-thin nanocrystalline gold nanoscale samples (~40nm thick), as well as externally integrated single crystal gold, and single crystal gold-silver thin-film nanoscale samples (~100nm thick) for their mechanical properties in-situ SEM.

The MEMS device is composed of an electrostatic comb-actuator, and two displacement sensors, with the purpose to mechanically characterize nanoscale samples that are located between the two displacement sensors. Sub-pixel resolution Digital Image Correlation (DIC) on SEM micrographs is used as displacement tracking technique in order to quantitatively characterize the displacement fields of the displacement sensors so as to obtain the force-elongation (hence, stress-strain) behavior of the tested samples. From the stress-strain behavior of the tested nanoscale specimens, we experimentally obtained fundamental material properties such as Young's modulus, and critical resolved shear stress for single crystal materials, and Young's modulus for nanocrystalline ultra-thin gold samples.

The method we apply in this study is the first in its field with the capability to integrate such small samples to MEMS with monolithic microfabrication. Although we worked with ultra-thin film gold, and thin-film gold and gold-silver alloy, the method can be adapted to other materials of interest, such as metals, carbon nanotubes, and graphene.

The results of the experiments are of interest to microelectronics industry, and materials research community.

3:40pm **MN-MoA6 Fabrication and Testing of Suspended Piezoelectric Nanocomposite Membranes**, ***J.R. Fox***, *S.B. Horowitz, J.P. Cortes, M.S. Allen, A.D. Mathias, L.A. Barkett,* Ducommun Miltec, *M. Sanghadasa*, U.S. Army Aviation and Missile Research Development and Engineering Center

The fabrication and testing of a novel piezoelectric microphone consisting of a suspended nanocomposite membrane of oriented hydrothermally-grown ZnO nanorods in a matrix of SU-8 photopolymer is detailed. High aspect ratio ZnO nanorods (0.5 – 1 microns long) were grown using a low temperature hydrothermal process on a patterned gold electrode on a wet-oxidized wafer. Then SU-8 photoresist was spin-coated over the rods to a thickness of approximately 1 micron and subsequently exposed and developed to reveal access to the bottom bond pads of the structure. A top electrode was deposited via sputtering and patterned on the SU-8 polymer. Finally a deep reactive ion etch (Bosch process) through-wafer silicon etch was used to release the nano-piezo-membranes in diameters of 50-400 microns. The infiltration of SU-8 photopolymer into the nanorods was observed to improve during long post-exposure bakes of the polymer as well as produce an improvement in vacuum compatibility of the polymer. Laser Doppler vibrometry (LDV) was used to characterize the actuation of the nano-piezo-membrane both under application of a driving potential as well as during acoustic load from a plane-wave tube.

4:00pm **MN-MoA7 Fabrication of Nanoelectromechanical Systems via the Integration of Glancing Angle Deposition Thin Films**, ***J.N. Westwood***, *V.T.K. Sauer, J.K. Kwan,* University of Alberta, Canada, *W.K. Hiebert,* National Institutute for Nanotechnology, Canada, *J.C. Sit*, University of Alberta, Canada

Nanoelectromechanical systems (NEMS) have been shown to be far more sensitive than microelectromechanical systems (MEMS). However, their smaller size also reduces the surface area of the device. This is problematic when scaling gas- and mass-sensing MEMS to the nanoscale regime because it reduces the area for analyte adsorption. Nanostructured thin films grown by glancing angle deposition (GLAD) provide a potential solution to this issue. GLAD thin films, deposited by evaporation at highly oblique angles between the source and the substrate, have extremely high surface area which can be used to counteract the decreased surface area of NEMS. The low density of GLAD films permits the increase in surface area without adding significant mass. Successful surface functionalization of GLAD films has also been demonstrated. These factors indicate that GLAD films are promising candidates for NEMS sensor applications. A major drawback, however, is that GLAD films are very difficult to pattern using lithography because they are incompatible with the wet processes required for photoresist development and removal. We have devised an alternative process that requires no lithographic patterning of the GLAD by depositing the films on patterned and released NEMS doubly clamped beams. The NEMS are fabricated from silicon-on-insulator wafers by etching away the oxide layer to give released silicon NEMS. Silicon dioxide GLAD films are then deposited. The GLAD films show good uniformity and limited edge effects. These GLAD-coated NEMS, or GLEMS, show significant potential for sensing applications. There are many parameters available for future optimization, including beam dimensions and GLAD film deposition parameters.

4:20pm **MN-MoA8 Electroactive Polymeric MEMS Actuators Fabricated by Thermal Imprinting of P(VDF-TrFE-CFE) and Poly(dimethylsiloxane) (PDMS)**, *J. Shkovsky,* ***L. Engel***, *A. Reuveny, Y. Sverdlov, Y. Shacham-Diamand, D. Schreiber, S. Krylov*, Tel Aviv University, Israel

The rapidly developing field of polymeric electronic and microelectromechanical (MEMS) devices has attracted much attention in recent years. Applications of polymeric MEMS devices include thin film transistors, waveguides for optical sensors, stretchable electronics as well as electroactive polymers (EAP) and dielectric elastomers actuators (DEAs). Polymeric actuators are distinguished by their very low fabrication cost, are often biocompatible, demonstrate large strain under small forces, exhibit fast response times, relatively large actuation forces and high efficiency. Because the electric fields required for the actuation of these devices are relatively high, of the order of tens or even hundreds of V/*m*m, reduction of the thickness of the polymeric layers is crucial for toreducing operational voltages. Thin layers of polymeric materials in MEMS devices are typically formed by spin-coating using diluted solutions of the uncured polymer. However, the spin-coating of polymers into micron scale films is challenging as there are strict requirements for film thickness, uniformity, process integration and defect density.

In this work we report on a novel fabrication process based on thermal imprinting for the formation of micron-scale, freestanding, layers of two polymeric materials, the dielectric elastomer poly(dimethylsiloxane) (PDMS) and the electroactive relaxor P(VDF-TrFE-CFE). We have fabricated freestanding, smooth, defect-free membranes with thicknesses in the range of 0.4–4.8 μm and with diameters of several millimeters . Since the ability to detach the membrane from the chips after imprinting is critical for the production of freestanding layers, the adhesion between the polymers and the silicon (Si) stamp and the Si substrate is reduced by the deposition of a hydrophobic dodecyl-trichlorosilane monolayer on the chips prior to imprinting. We demonstrate the feasibility of patterning the devices at the time of imprinting to create freestanding patterned micron-scale structures. A simple device made up of a freestanding circular membrane with electrodes on the circumference demonstrating the application of the method is presented . The results of the device's electromechanical characterization revealed that a free-standing PDMS membrane 1 mm in diameter and 5.3 *m*m thick demonstrated displacements of 5 *m*m at an actuation voltage of 300 V.

Acknowledgements

This project was supported by Arkema/Piezotech . P(VDF-TrFE-CFE) materials were supplied by Piezotech S.A.S

4:40pm **MN-MoA9 A CMOS MEMS Gas Sensor Using Monolayer Protected Gold Nano-Clusters Coating on Three-Dimensional Interdigitated Electrodes**, *Y.C. Chen*, ***C.Y. Chang***, National Taiwan University, *H.L. Lu, C.-J. Lu,* National Taiwan Normal University, *W.-C. Tian*, National Taiwan University

In this work, a novel gas sensing platform using the TSMC 0.35μm CMOS-MEMS process was developed. Three-dimensional interdigitated sensing electrodes (3D IDEs) with a polysilicon microheater and a polysilicon thermometer were integrated in this CMOS-based platform. Compared to conventional 2D IDEs, our 3D IDEs not only extended the sensing surface area to the vertical sidewalls but also decreased the gap (the inter metal dielectric layer, IMD, thickness) between electrodes. The micoheater of 2.6kΩ resistance and the thermometer of 2kΩ resistance were designed to provide on-chip heating, which could facilitate the deposition and/or activation of the sensing material. The sensing material, monolayer protected gold nanocluster (AuC8), was coated onto the electrodes through the air brush spraying. The sensor performance was demonstrated with three compounds (Octane, Butanol, and Toluene) of concentrations in the range of 2000ppm to 5000ppm and manifested the good linearity and sensitivity.

The backend of CMOS processes for interconnects were utilized to provide microstructures which offer many potential advantages for sensors including low power consumption, low fabrication cost, high sensitivity and reliability. In the CMOS etching process, the design rules of a released (RLS) mask limit the minimum gap between electrodes to 3μm. Hence, 3D IDEs were used to decrease the gap between electrodes to 1μm (the IMD thickness) so as to increase the sensitivity of the designed sensor as well as to lower the resistance of the deposited sensing material. In addition, the consumption of the sensing material was reduced significantly.

When exposing to Toluene at different concentrations, the transient responses of the sensor were changed accordingly. The exceptional linearity of the sensor responses on targeted compounds at high concentrations was demonstrated. The great sensitivities, defined as the ratio of the impedance before and after exposing to the target gas, of the three compounds were obtained (Toluene: 3.66E-5/ppm, Octane: 3.30E-5/ppm, and Butanol: 5.71E-5/ppm). The differences in sensitivities are largely affected by the target gas and its affinity to AuC8 surface. These variations in sensitivity for different compounds can enhance the specificity of our CMOS-based gas sensor platform.

5:00pm **MN-MoA10 Integration of Functionalized Biological Nanostructures with Conventional Transducer Fabrication Schemes**, ***X. Fan***, *N. Siwak, A. Brown, J. Culver, R. Ghodssi*, University of Maryland

Nanoscale technologies have the potential to revolutionize a broad range of fields. Already, there have been a plethora of synthesis and fabrication techniques of nanostructures and devices utilizing both organic and inorganic materials. Biological molecules have transformed chem-bio detection, due to their innate ability to be tailored and engineered via genetics. These nanostructures can be versatile in their various binding properties making them attractive for a variety of applications. These biomolecules, often self-assembled or synthesized with a bottom-up approach, are used for scaffolding and functionalization purposes, while inorganic materials utilize conventional top-down lithographic techniques to pattern transducers. The integration of these two different technologies is challenging due to fabrication incompatibility. While inorganic materials are robust, biomolecules are highly sensitive to pH levels, temperature, and chemical compositions, making them incompatible with top-down techniques. Thus, their integration is often withheld until the final step of device fabrication. This prevents further backend processing once the biomolecules have been deposited, limiting the degree of integration of nanoscale platforms and restricting the full potential of nanotechnology.

Our team has developed a method to pattern a type of nano-biomolecules onto the active region of a photonic device using a hybrid top-down and bottom-up approach. An optical ring resonator, highly sensitive to refractive index changes, was fabricated using E-beam lithography to investigate the assembly of biomolecules on its surface. *Tobacco mosaic virus* (TMV) was then self-assembled onto the transducer's active area. TMV is a rod like structure with coat proteins that are genetically modified to allow for the self-assembly of viruses onto surfaces and the expression of functionalization on the outer surface. The TMV structure is stable in a pH 2-11 and temperature up to 60^{o}C that survives the conventional lift-off patterning process. This enables the patterning and alignment of biologically functionalized structures on lithographically fabricated transducers post self-assembly.

By integrating TMV structures onto the surface of the ring resonator, we will report on the optical properties of the TMV assembly, including its refractive index and optical loss, for sensing applications. This photonic platform with patterned TMV provides a compatible process to integrate biological nanostructures with conventionally fabricated transducers. This integration scheme we have developed will allow for an additional degree of control when developing nanoscale based hybrid platforms.

5:20pm **MN-MoA11 A Novel Computational and Experimental Methodology for Development of Therapeutic Microdevices for Rapid Reconstitution**, *S. D'hers,* Buenos Aires Institute of Technology, Argentina, *A. Alexander-katz*, ***N.M. Elman***, Massachusetts Institute of Technology

Rapid Reconstitution Packages (RRPs) represents a breakthrough microfluidic platform to use pharmaceutical drugs in ambulatory settings without the need for refrigeration. RRPs were designed as microfluidic cartridges, keeping drugs in lyophilized form (powder) for years and perform on demand reconstitution in the order of milliseconds. The unique integration of a dual multi-scale computational and experimental model with nano-materials and microfluidics provides the scientific basis towards the development of an ultra-portable platform for long term storage and extremely rapid reconstitution. The device architecture consisted of mixing microstructures, fabricated with Stereo Lithography Apparatus (SLA) with biocompatible materials. Rapid prototyping provided a quick turnaround experimental model for validating computational models, rendering a unique methodology for optimization. Experimental setup was intended to emulate temperature fluctuations in ambulatory environments. Experiments were performed using standard analytical methods on RRPs containing drugs exposed to temperatures in the range of 25-65 C. High Performance Liquid Chromatography (HPLC) assays for quantifying reconstitution, and Enzyme-Linked Immunosorbent Assays (ELISA) for activity were performed. Several drugs were tested, including atropine for resuscitation, and tissue plasminogen activator (tPA) for treatment of thrombosis. The design was optimized in parametric software and tested for manufacturability and functionality using Computed Fluid Dynamics (CFD) analyses. Design optimization using the CFD models was performed with the goal of reducing drug retention in the device and tailoring drug concentration profiles during activation. A consistent fluidic representation was adopted to model drug dissolution and diffusion. The numerical scheme was validated through computational and laboratory tests for drug dose and concentration profile. Experimental results reveal the importance of the combined use of computational and experimental techniques. The convergence of these unique techniques allows exploitation of physical processes at the nanometer and micrometer scales to investigate the lyophilization and reconstitution processes, overall rendering a synergistic computational and experimental methodology for development of therapeutic microdevices. The use of RRPs will result in significant improvement in logistics for a number of civilian and military applications.

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