MEMS and NEMS Group
Room: 105 - Session MN-FrM

Characterization of Materials and Structures at the Micro- and Nano-scale
Moderator: M. Metzler, Cornell University

8:20am **MN-FrM1 Nanomechanics: Controlling Near-Field Interactions between Mechanical Systems**, ***D. Lopez***, Argonne National Laboratory **INVITED**

Metallic and dielectric objects are surrounded by fluctuating electromagnetic fields due to thermal and quantum fluctuations of the charge and current density at the surface of the bodies. Immediately outside the objects, this electromagnetic field exists partly in the form of propagating electromagnetic waves and partly in the form of evanescent waves that decay exponentially with distance away from the body's surface. These fluctuating electromagnetic modes are responsible for a great variety of near-field phenomena such as the Van der Waals force, the Casimir force, near-field heat transfer, and non-contact friction forces. As devices evolve from micro- to nanoscale structures, these forces become relatively stronger, and their effect cannot be disregarded any further. For example, researchers working to develop NEMS devices need to consider the effects caused by Van der Waals and Casimir forces which can leads to compromise in the range of motion or in the voltages required for actuation. To improve our understanding of these near-field interactions and to develop mechanisms to control them is extremely important for a diversity of seemingly different fields, such as nanomechanics, quantum computing with trapped ions, measurements of gravitational forces at the nanometer scale, and detection of single spins for magnetic resonance force microscopy.

In this presentation I will describe the fundamentals of near-field forces, I will review recent scientific advances regarding manipulation of these interactions in the field of nanomechanics, and I will illustrate novel applications that could be enabled once we are capable of control these forces.

9:00am **MN-FrM3 Pull-in Experiments on Electrostatically Actuated Microfabricated Meso Scale Beams**, *Y. Gerson, I. Sokolov,* Tel Aviv University, Israel, *T. Nachmias,* RAFAEL LTD, Israel, *S. Lulinsky,* ***S. Krylov***, Tel Aviv University, Israel

Meso scale (hundreds of micrometers to several millimeters) MEMS sensors and actuators are beneficial in applications where large displacements, manufacturability, and ease of integration with existing mechanical and packaging environments are required.

In this work we report on the results of characterization and modeling of electrostatically actuated meso scale beams. The beams with clamped ends were 5000 μm long, 150 μm thick and 10, 12 and 15 μm wide and were operated by a parallel plate electrode located at the distance of 20 μm from the beam. The goal of the work was twofold. First, we demonstrate the feasibility of electrostatic actuation of the meso scale devices and ability to achieve relatively large displacement. Second, an electrostatically actuated double clamped micro beam is viewed as a kind of benchmark problem and was intensively studied. However, the number of reported experimental results, which can serve for validation of models, is limited. We anticipate that our experimental results, obtained using larger meso scale structures and therefore relatively more accurate, could provide a reliable experimental reference for a double clamped beam actuated by a parallel-plate electrode.

The devices were fabricated by deep reactive ion etching (DRIE)-based process from highly doped Si using a silicon on insulator (SOI) wafer with [111] surface orientation and 150 μm thick device layer. The experimental approach based on the use of SOI wafers allows to fabricate devices with low residual stress and excellent mechanical properties of Si. The devices were operated in ambient air conditions. Linearly increasing (ramp) voltages were applied quasistatically to the actuation electrode and easily visualized in-plane (parallel to the wafer surface) motion of the devices was registered using an optical microscope and a CCD camera. The response was video recorded, the movie was split into separate frames and the voltage–displacement dependence was built using customized edge detection image processing procedure implemented in Matlab. The critical pull-in voltage varied between 70 V in (nominally) 10 *m*m wide beam and up to 125 V in 15 *m*m wide beams. In addition, pull-in behavior of the beams was modeled using several approaches, staring from simplified reduced order models based on the Galerkin decomposition with linear eigenmodes as base functions and up to fully coupled nonlinear large deflection three-dimensional simulations. The actual dimensions of each beam, carefully measured using scanning electron microscope (SEM) were used in calculations. Excellent agreement between the results provided by the model and the experimental data was observed.

9:20am **MN-FrM4 Absorption and Emission of Plasmonic Antenna Arrays**, ***K.E. O'Brien***, *P.H. Holloway, M.R. Davidson*, University of Florida

New and more portable means of generating narrow band radiation are of interest, especially in the terahertz (THz) range. One potential method for generating radiation involves photo-mixing over nano/micro scale plasmonic structures. The plasmonic structures can serve as antennas for absorbing incoming photons and conversely emit radiation of a lower frequency. Designs include 2-dimensional arrays of theses resonant structures fabricated on Ag thin films using electron-beam lithography and lift-off. Patterns vary from arrays of linear structures, "bowties," and interlocking structures. We have shown emission of visible radiation from similar structures when excited by space charge from electrons. The absorption and emission of light by the structures has been measured for micron-scale and nano-scale antenna arrays and has exhibited a polarization dependent behavior. The effect of different antenna structures on the absorption and emission will be discussed.

10:00am **MN-FrM6 Fabrication and Characterization of Structural and Electrical Properties of Ultrananocrystalline Diamond Nanowires**, ***X. Wang***, University of Puerto Rico, *A.V. Sumant, V. Joshi, L.E. Ocola, B. Kabius, D. Lopez*, Argonne National Laboratory

Due to extraordinary mechanical, optical and electrical properties as predicated by theory, there has been tremendous amount of interest in making diamond nanowires (DNWs) and diamond nano-rods (DNRs). Synthesizing or fabricating these nanostructures is proving to be very challenging. To date, only a few attempts have been reported, either by etching single crystal diamond using focus ion beam (FIB) to produce diamond NRs or by coating Si nanowires with nanocrystalline diamond to produce diamond NWs. We report a top-down method based on e-beam lithography and reactive ion etching of ultrananocrystalline diamond (UNCD) to produce UNCD nanowires (UNCDNWs) with nanowire diameters as small as 30 nm. Since they are produced by lithographic approach (top-down), they can be fabricated at well-defined position with nanometer-scale precision. Compare to other fabrication techniques like FIB, our UNCDNWs maintain intrinsic diamond structure and properties without degradation after fabrication process, which has been confirmed by Raman spectroscopy (ultraviolet and visible), transmission electron microscope (TEM) and electron energy loss spectroscopy (EELS). Preliminary electrical measurement of UNCDNWs will be discussed. The ability to fabricate UNCDNWs provides an opportunity to study the fundamental mechanism of transport processes in UNCDNWs, which will enable new ideas and possibilities for the fabrication of new functional nanoelectronic devices.

10:20am **MN-FrM7 Investigation of Heat Transfer Enhancement in Nanofluids with Molecular Dynamics Simulations – Role of Particle Charge and Fluid Polarity**, ***J.D. Schall***, Oakland University, *A.S. Comfort*, U.S. Army RDECOM-TARDEC

Thermal loads are increasing in military vehicles because of the greater use of microelectronics,

higher power density engines, and restricted air flow from up-armor kits. Conventional methods

to increase heat dissipation, such as increasing heat exchanger size produce an undesired

increase in vehicle weight and packaging issues. One approach to mitigate these issues is the

development of heat transfer fluids with improved thermal transport properties. Nanofluids are

suspension of nanometer sized particles in solvent, and represent a potential method to increase

the effective fluid thermal conductivity and heat transfer coefficient of coolants without creating

the adverse effects found in larger particle suspensions, such as settling, clogging, and abrasion.

Since their introduction by U.S. Choi in 1995, a great deal of uncertainty about the mechanisms of enhanced thermal conductivity of nanofluids continues to employ researchers and limits

the development of optimized nanofluids in heat transfer applications. In this paper,molecular

dynamics simulations are used to investigate heat conduction between model particle surfaces

separated by a liquid layer. In particular, effects of base fluid charge, polarity, and nanoparticle

surface charge on the solid-liquid interface liquid structure, thermal (i.e. Kapitza) resistance, and

thermal conductivity are investigated. Results are compared with previous simulations from the

literature which used simple monoatomic models interacting through Lennard-Jones potentials.

10:40am **MN-FrM8 Novel CMOS MEMS Double Parallel Plate Capacitive Tactile Sensors For Blood Flow Monitoring**, ***C.J. Hsieh***, *J.C. Liou, C.T. Sun, Y.C. Lin, W.-C. Tian*, National Taiwan University

This research focuses on the developments and characterizations of non-invasive tactile blood flow sensors using CMOS MEMS technologies. The capacitive sensing structure consists of two parallel plate capacitors which can be connected in different configurations in cape with different measuring ranges. Sensor detection scope is set to be from 0 to 150 mmHg according to the estimated maximum human vessel pressure. The sensor is fabricated in commercial 2 polysilicon and 4 metal CMOS technology followed by the self-developed post processes. The dimension of each sensor is 400μm in length with the membrane thickness of 1.45μm.

An anisotropic inter metal dielectric layer etch step was utilized on CMOS chips to open wet metal etching holes. After this dielectric layer etch, a metal wet etching process was applied to release sensing structures. In order to protect the metal bonding pads in post CMOS MEMS processes, an Au layer was deposited on the pad areas. Based on the experiment results, the lateral metal sacrificial layer etching rate is 1.85μm per minute and the lateral etching rate underneath gold layer is 2.9μm per minute. We have successfully demonstrated the post CMOS MEMS processes for our sensors.

Initial finite element method analysis results showed that the sensitivities of two different designs are 6.7 and 2.2 fF per mmHg with a dynamic range of 75 and 200 mmHg. The sensor behavior measurement data will be presented.

11:00am **MN-FrM9 A Highly Sensitive Nanomachined TiO_2 Gas Sensor for Micro Gas Chromatography**, ***C.H. Chou***, *C.H. Chen, W.-C. Tian,* National Taiwan University*, T.H. Chan, C.-J. Lu*, National Taiwan Normal University

The purpose of this study is to develop a sensitive gas sensor with engineered TiO_2 nanostructures using semiconductor nanotechnologies for micro gas chromatography. Many TiO_2 nanowires for gas sensing nowadays were fabricated by chemical synthesis methods, and the nanowire arrays are in irregular formats and the amount of sensing material may be varied chip to chip. The behavior of sensing repeatability of these TiO_2 nanowires using conventional methods is hard to control.

With the combination of E-beam lithography and the TiO_2 thin film deposition, the TiO_2 sensing nanowire arrays with well-controlled structures (100-300 nm wide with 1 μm period), were placed in between the Au interdigitated electrodes. A microheater were fabricated by deposition of the 3/50 nm thick Cr/Au films on the backside of the sensor. The great linear heating with increasing input power and uniform heating (329.3 ℃ in average, STDV of 9.3 ℃, power of ~0.8 W) were obtained through an IR camera.

The performance of nanowire detector (100 nm wide, 183.5 MΩ) is compared to the microwire detector (20 μm wide, 24.6 MΩ) at various ethanol and benzene concentrations or at various operation temperatures. The measured resistance to the initial resistance ratio of the nanowire detector changed from 1 to 0.35 at 284 ℃ at 6.5% ethanol concentration. The effects of the rapid thermal annealing and an O_2 plasma treatment to improve the sensor performances is investigated and will be presented.

11:20am **MN-FrM10 Ultra-high Aspect Ratio High-speed Silicon Nanowire and Three-dimensional Formation Using a Hydrogen-assisted Deep Reactive Ion Etching**, *Z. Sanaee,* ***S. Azimi****, M. Poudineh, S. Mohajerzadeh, A. Sandoughsaz*, University of Tehran, Iran

We report the formation of ultra-high aspect ratio and three dimensional features on silicon substrates using a novel low-density capacitive-coupled plasma reactive ion etching (13.56MHz). The etching process is based on using three gases of hydrogen/oxygen and SF_6 in two sub-sequences called as passivation and etching sub-cycles. All three gases are used in the passivation step and SF_6 in the etching step. Unlike Bosch process no polymer is used for passivation. By controlling the passivation sub-cycle, one is able to allow desired under-etching followed by "recovery" of the formerly under-etched features to make unique three-dimensional structures directly on silicon substrates [1].

Cleaned silicon samples are placed in an e-beam evaporation unit to deposit a 40nm chromium layer as the mask for the subsequent processing steps. The masking layer is patterned using precision projection lithography to achieve desired features between 100nm and 20um. For ultra-high aspect ratio and scallop-free etching while keeping the etch-rate of 1um/min, it is necessary to include trace values of H_2/O_2 during the etching step. Typical flows for H_2/O_2 and SF_6 are 200/200 and 5 sccm in the passivation step while the etching is mainly practiced with SF_6 (35 sccm). The plasma power is set at 250 W for the passivation and 130 W for the etching sub-cycle. By controlling these important parameters, we have realized three-dimensional features where the vertical structures have serpentine surfaces with desired recessions of 10um. Moreover, we have been able to realize arrays of nano-metric 3-D features using Si/SiO_2 structures with a diameter of 2-3um and features of the order of 100nm.

We realized 9-10um high and 90nm wide nano-wires where the mask undercut is 30nm and the surface of the wires is almost free of "scallop". Scallop is side-effect of time-multiplexed processes where the periodic track of the etching step is seen on side-walls. To avoid this, while obtaining high-rates we have included H_2/O_2 gases during the etching sub-cycle. Normally H_2/O_2 gases act as the passivation layer, however the trace value of these gases does not affect the etching. Instead a slight passivation is formed on side-walls while the etching proceeds, prohibiting further lateral-etching of walls. We have studied the passivation layer using XPS and Ellipsometry. Thickness of the passivation layer is 2-3nm and it is mainly SiOF bonds (XPS). Field-emission SEM has been used to compare the results. Using this process we obtained high etch-rates of 0.8-1.1um/min for features around 100nm. The height of the nano-wires is around 10um, with an aspect ratio of 100 and more. This process uses low-density plasma with rapid steps and apart from MEMS/NEMS applications it can be used for "solar-cells" where nano-wires can significantly affect the efficiency and cost.

[1]. S. Azimi, A. Sandoghsaz, B. Amirsolaimani, J. Naghsh-Nilchi, S. Mohajerzadeh, "Three-dimensional etching of silicon substrates using a modified deep reactiveion etching technique", J. Micromech. Microeng. No. 21, 074005, (2011).

Authors Index

Bold page numbers indicate the presenter