MEMS and NEMS
Room: 206 - Session MN-TuM

Materials Processing and Characterization for MEMS/NEMS
Moderator: B.R. Ilic, Cornell University

8:00am **MN-TuM1 Weighing of Biomolecules, Single Cells, and Single Nanoparticles in Fluid**, ***S. Manalis***, Massachusetts Institute of Technology **INVITED**

Recent advances towards developing biomolecular and single cell applications for a mass-based biosensor known as the suspended microchannel resonator (SMR) will be presented. In SMR detection, target molecules or cells flow through a vibrating suspended microchannel and are captured by receptor molecules attached to the interior channel walls. What separates the SMR from the existing resonant mass sensors is that the receptors, targets, and their aqueous environment are confined inside the resonator, while the resonator itself can oscillate at high Q in an external vacuum environment, thus yielding extraordinarily high sensitivity. This approach solves the problem of viscous damping that degrades the sensitivity of cantilever resonators in solution. We have achieved a resolution of approximately 1 femtogram (1 Hz bandwidth) which represents an improvement of six order of magnitude improvement over a high-end commercial quartz crystal microbalance. This gives access to intriguing applications such as mass based flow cytometry and real-time monitoring of single cell growth.

8:40am **MN-TuM3 Development of Superhydrophobic Biomimetic Surfaces with Hierarchical Roughness**, *B. Bhushan,* The Ohio State University, *K. Koch,* Nees Institue for Biodiversity of Plants, Germany, ***Y.C. Jung***, The Ohio State University

Superhydrophobic plant surfaces, e.g. the Lotus leaves, and theoretical calculations show that a hierarchical surfaces roughness is beneficial for superhydrophobicity. Biomimetic hierarchical surface structures were produced by multiple replication of a microstructured silicon master surface. Replicas are made in a two step process, in which a two-component silicon molding mass was applied into the micropatterned Si surfaces, followed by a filling of the mold with an epoxy resin. On these different nanostructures have been applied by physical vapor deposition of hydrophobic n-hexatriacontane ($C_{36}H_{74}$), and octacosn-1-ol. These organic molecules are able to self assembles on the substrates into three-dimensional crystals, and their shape, size and chemistry is comparable to those structures, found on water repellent surfaces. The surfaces created are fully characterized by SEM and AFM and attempted to separate out the effect of hierarchical structures on the hydrophobicity. We show how static contact angles, hysteresis and tilt angles vary with microstructure, nanostructure and hierarchical structure. We also study the effect of droplet size on contact angle by evaporation using droplets on the surfaces.

9:00am **MN-TuM4 Nanomechanical Resonators for Specific Detection of Proteins**, ***C. Guthy***, *L.M. Fischer, V.A. Wright, A. Singh, J.M. Buriak, S. Evoy*, University of Alberta and National Institute for Nanotechnology, Canada

Rapid, sensitive and inexpensive analysis of biological molecules is vital to disease detection, monitoring, drug discovery. For instance, the detection and identification of biomarker proteins of diseases such as metabolic disorders, multiple sclerosis and cancer have gained considerable attention over the recent years. Detection of such proteins with high specificity at very low concentrations would greatly facilitate diagnostic and help predict disease progression. Current analytical technologies such as DNA microarray, mass spectrometry and nuclear magnetic resonance spectroscopy are expensive and technically challenging for clinical applications. Mechanical resonators have been demonstrated as highly sensitive transducers for the detection of molecular systems. The sensitivity of resonators scales favorably as their dimensions are reduced, offering a compelling path for the development of sensors with exceptional mass sensitivities. To enable the specificity of detection, various analyte-specific functional layers need to be immobilized onto the surface of resonators. Such resonators could be then used as sensing arrays for the analysis of complex protein mixtures. As a proof of concept, we recently demonstrated the specific detection of streptavidin using doubly-clamped nanomechanical resonators (bridges) functionalized with biotin. Bridges with widths down to 300 nm were realized from silicon carbonitride (SiCN) thin films using a novel fabrication method. Based on the shift of resonant frequency, a mass of 3.6 fg/μm^2 was attributed to the added streptavidin, corresponding to one molecule per 27 nm^2. We have since further scaled down the dimensions of our devices and have demonstrated the surface machining of resonators of world record lateral dimensions of 40 nm with a yield approaching 100%. These 15 µm long resonators show resonance frequencies of ~ 11 MHz with quality factors of ~ 5000 in the mTorr pressure range. We will present a thorough investigation of the resonant behavior of these novel sub-100nm NEMS devices of various dimensions. We are also developing the attachment of antibodies onto these resonators. The specific detection of human interferon gamma (IFN-γ) protein was chosen as target system. Our ultimate goal is to use similar immobilization procedures for the detection of disease biomarkers, including but not limited to multiple sclerosis biomarkers.

9:20am **MN-TuM5 Experimental Determination of the Dynamic Spring Constants of Higher Flexural Modes of Microcantilevers**, ***G. Hähner***, *G.V. Lubarsky*, University of St Andrews, UK

Cantilever based technologies have seen an ever increasing level of interest since the atomic force microscope (AFM) was introduced two decades ago. Most recent developments employ microcantilevers as stand-alone sensors by exploiting the dependence of their oscillating properties on external parameters such as adsorbed mass, or the density and the viscosity of a liquid environment. In this context higher flexural modes have attracted significant attention due to their high sensitivity towards forces and mass changes. While some effort has been devoted to the determination of the static and the first dynamic spring constant, there are currently no equivalent simple yet reliable methods to determine the values of higher modes experimentally. We demonstrate how the spring constants of higher flexural modes of microcantilevers can be determined experimentally with high precision. We recently presented a fast and simple method to measure the dynamic spring constant of the first mode in a non-destructive and non-invasive fashion.[1] The method is based on comparing the spring constants of the cantilever to a known spring constant by measuring the change in the resonance frequency of the flexural modes as a function of the fluid flow through a microchannel. Here we will show that the same approach can also be applied to higher flexural modes. Results for both rectangular and V-shaped cantilevers will be presented and compared to theory.

[1] G.V. Lubarsky and G. Hähner Rev. Sci. Instr. 78, 095102 (2007).

9:40am **MN-TuM6 Heterodyne Optical Detection of Mechanical Resonances of Ultra High Frequency Silicon Micro-Resonators**, *L.J. Klein,* ***T. Barwicz***, *S. Guha, H.F. Hamann*, IBM TJ Watson Research Center

Recent advancement in microscale electromechanical systems fabrication and operation demonstrated ultra high mass and force sensitivity. Here we investigate the parameters affecting the ultimate sensitivity of suspended mechanical resonators, in particular the resonance frequency and quality factor scaling as the resonators dimensions are reduced. The silicon resonators are fabricated by e-beam lithography with length ranging from 20 um down to 500 nm and having a width of 500 nm. The suspended resonators are actuated using electrostatic force acting between the suspended beam and side gates and an optical heterodyne interferometry is used to detect the resonant oscillations. The heterodyne interferometry has a large bandwidth allowing resonance frequency detection above Ghz and has a detection sensitivity of 10 pm. For fundamental oscillation modes up to 220 MHz, the quality factor of resonance were over 20000 in high vacuum at room temperature and increased in the explored range. We present experimental approaches to detect both flexural and transversal oscillation modes for silicon micro-resonators using our optical detection scheme.

10:40am **MN-TuM9 The Effect of Substrate Material and Metallization Layers on the Mechanical Properties of Micromachined Amorphous Silicon Carbide Structures**, ***R.J. Parro***, Case Western Reserve University, *M.C. Scardelletti, N.C. Varaljay,* NASA Glenn Research Center, *C.A. Zorman*, Case Western Reserve University

Amorphous SiC (a-SiC) films are attractive for micromachined structures requiring the properties of SiC but whose substrates cannot tolerate the high deposition temperatures associated with the conventional CVD methods used to deposit the crystalline forms. The preponderance of data in the literature focuses on the properties of a-SiC films deposited directly onto Si; much less is known about the properties of these films when deposited onto silicon dioxide sacrificial layers. Even less is known about how metallization (required for electrostatic actuation) affects the mechanical behavior of a-SiC micromachined structures. This study examines the roles that the substrate and metallization layers play on the mechanical properties of a-SiC structures. Test specimens were fabricated from 300 nm-thick a-SiC films deposited by PECVD on bare (100) Si wafers and (100) Si wafers coated with a 3.2 um-thick PECVD silicon dioxide film. After deposition, the wafers were annealed at 450C for 30 min to convert the as-deposited compressive film stress to a low tensile stress. Suspended membranes with areas of 750x750 um2 were bulk micromachined by anisotropic etching in KOH at 50C. For the oxide-coated wafers, a 35 min immersion in BOE at 25C was performed to remove the silicon dioxide beneath the SiC membranes. The membranes were subjected to load-deflection testing at differential air pressures between 0 and 138 kPa. From the resulting pressure versus deflection data, it was found that the average Young's modulus for a-SiC films deposited on Si was 129 GPa with a residual stress of 162 MPa, while films deposited on silicon dioxide had a Young's modulus of 116 GPa with a residual stress of 154 MPa. For films deposited on oxide-coated wafers, the effect of metallization on the residual stress of the membranes was characterized. Membranes were first subjected to load-deflection testing, then coated with a Cr adhesive layer and Au structural layer by e-beam evaporation and again subjected to load-deflection testing. For a total metal thickness of 60 nm (10 nm/50 nm Cr/Au), the average residual stress increased by 52 MPa. For a total metal thickness of 125 nm (25 nm/100 nm Cr/Au), the average residual stress increased by 43 MPa, and for 250 nm (50 nm/200 nm Cr/Au) the average residual stress increased by 35 MPa.

11:00am **MN-TuM10 Effects of Actuation Voltage and Relative Humidity on Polycrystalline Silicon Corrosion**, ***F. Liu****, C.S. Roper, C. Carraro, R. Maboudian*, University of California at Berkeley

The effects of relative humidity and actuation voltage in MEMS have been investigated using polysilicon electrodes. The results indicate occurrence of anodic oxidation under positive bias and absence of cathodic protection under negative bias that leads to the precipitation of dissolved species. We will also report on the effect of electrode geometry and surface termination. Our results show that corrosion can be the dominant failure mechanism of polysilicon MEMS when driven by large electrostatic voltages in humid environments.

11:20am **MN-TuM11 Gold-Tantalum Nanocomposites as Structural Material for Nanomechanical Sensors**, ***N. Nelson-Fitzpatrick****, C. Ophus, E. Luber*, University of Alberta, Canada, *Z. Lee, V. Radmilovic*, Lawrence Berkeley National Laboratory, *D. Mitlin, S. Evoy*, University of Alberta, Canada

Micro and nanomechanical cantilevers and resonators have received significant attention as a technological solution for ultra-sensitive mass detection.[1] One promising approach to enable specific nanoresonator-based biosensing would be to coat the devices with a thin film of gold in order to exploit thiol-based chemistries for the functionalization of these surfaces. However, such metal coatings would significantly lower its resonance quality, impairing its mass sensitivity.[2] Alternatively, we are currently developing of a novel Au/Ta alloy that would allow the machining of micro and nanomechanical devices directly out of the metal.[3] Metals have been largely overlooked as a structural material for NEMS since most deposition methods tend to yield films with large grain structures complicating reliable machining at the nanometer scale, and containing differential stresses which result in the deformation of released devices. To remedy these problems, we must be able to deposit a metal that is either amorphous or has extremely small grain sizes in order to fabricate a device with nm size critical dimensions. Previously we reported on the deposition of Au/Ta nanocomposites for the purpose of making NEMS resonators.[3] We reliably realized 50nm thick Au/Ta nanoresonators with low stress (~20MPa), reduced grain size and RMS roughness. The devices also retained the gold's <111> texture important for the formation of thiolized SAMs. We have now moved on to the development of micro-cantilevers operating in the static regime with this material. The fine grain size of this alloy enables the realization of ultra-thin, ultra-compliant, released cantilevers directly out of Au/Ta composite. The distinctive grain structure of this material, as well as the inclusion of tantalum impacts the dynamics of molecular attachment, which will affect the response of static cantilevers to the target analyte. To that end, we intend to present a full study on the impact of the alloy nanostructure and its composition on the surface stresses induced by the chemical attachment of a thiolized SAM.

[1] Ilic B, Czaplewski D, Craighead H G, Neuzil P, Campagnolo C and Batt C, 2000 Appl. Phys. Lett. 77 450

[2] Sekaric L, Carr D W, Evoy S, Parpia J M and Craighead H G, 2002 Sens. Act. A 101 215

[3] Nelson-Fitzpatrick N, Ophus C, Luber E, Gervais L, Lee Z, Radmilovic V, Mitlin D, and Evoy S, 2007 Nanotechnology 18.

11:40am **MN-TuM12 Theoretical and Experimental Investigation of Electrostatically Actuated Bistable Micro and Nano Structures**, ***S. Krylov****, Tel Aviv University, Israel, *B.R. Ilic*, Cornell University, *D. Schreiber*, Tel Aviv University, Israel, *S. Seretensky*, Smart Team inc., *H.G. Craighead*, Cornell University

In this work, theoretical and experimental study of initially curved electrostatically actuated micro and nanobeams with clamped ends was performed. Due to unique combination of non-monotonous stiffness-deflection dependence typical for mechanically bistable structures and of nonlinear electrostatic force abundant in micro and nano systems the structure exhibits sequential snap-through buckling and electrostatic pull-in instability as well as multiple stable configurations at the same voltage (bistability). Reduced order Galerkin and consistently constructed lumped models were built and verified by numerical analysis and experimentally. The minimal initial elevation required for appearance of the bistability in the electrostatically actuated beam is smaller than in the case of an uniform deflection independent loading; closed form approximation of this elevation was evaluated. The devices were fabricated from silicon on insulator (SOI) wafer using deep reactive ion etching and in-plane responses were characterized by means of optical and Scanning Electron microscopy (SEM). In addition, out-of-plane moving nano scale devices made of a intrinsically pre-stressed polysilicon were fabricated and characterized. Characterization inside a SEM was found to be a useful experimental approach providing stable operational in-vacuo conditions while higher magnification improves the quality of data processing. Model results obtained for the actual dimensions of the device were in good agreement with the experimental data. Designs incorporating bistable beams have clear functional advantages and may result in improved performance of switches, capacitive based sensors and MEMS/NEMS based nonvolatile memory devices.

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