MEMS and NEMS
Room: Santo Domingo - Session MN-FrM

Characterization for MEMS and NEMS
Moderator: A.V. Sumant, Argonne National Laboratory

8:20am **MN-FrM1 Wafer-scale Processing of Diamond Thin Films for MEMS and NEMS**, ***J.A. Carlisle***, Advanced Diamond Technologies **INVITED**

The key to enabling wafer-scale processing of thin film diamond are the specifications that the technology can meet on commercially relevant wafer sizes. Due to advances in reaction design and deposition chemistry, a variety of diamond materials can now be deposited onto wafers up to 300 mm in size, with excellent thickness and property uniformity, enabling high-yield production of microdevices. In this presentation advances made over the past several years to enable thin, smooth diamond films for MEMS will be reviewed with emphasis on materials and microfabrication strategies needed to integrate diamond with other materials for MEMS devices. UNCD® (ultrananocrystalline diamond) spans a family of thin smooth diamond materials. UNCD wafers serve to demonstrate the availability of the technology and to allow designers to integrate diamond into new process flows. NaDiaProbes®, which are all-diamond AFM probes used for metrology and nano-manufacturing, are the first example of a commercially available diamond MEMS device that leverages wafer-scale processing of UNCD wafers using established microfabrication techniques. How ADT looks at wafer-scale production of UNCD-based MEMS devices going forward as well as our technology roadmap for UNCD-enabled products under development will be presented. Particular emphasis will be placed on the development of UNCD coatings and MEMS devices for RF devices, nanomanufacturing, and chem/bio-sensing related applications.

9:00am **MN-FrM3 CMOS Integrated Ultrananocrystalline Diamond Capacitive RF-MEMS Switches**, ***S. Balachandran***, *A.V. Sumant*, *O.H. Auciello*, Argonne National Laboratory, *S. O'Brien*, *C.L. Goldsmith*, Memtronics Corporation, *J.A. Carlisle*, Advanced Diamond Technologies, *C. Gudeman*, *S. Sampath*, Innovative Micro Technology

RF-MEMS DC contact and capacitive switches are being developed, involving a broad range of designs in series and shunt configurations. The work done until now has facilitated significant maturing of the technology to overcome technical challenges such as reliability, packaging, and high power operation. In particular, the reliability of RF-MEMS capacitive switches has been limited mainly by the electrical charging of the oxide or nitride dielectric layers used until now, which exhibit discharging times in the hundred of seconds range, resulting in failure of the switches. Therefore, it is critical to develop dielectric layers with fast charging/discharging performance. In this respect, the novel ultrananocrystalline diamond (UNCD) films developed and patented at Argonne National Laboratory exhibit a unique fast charging (50-100 µsec)/discharging (≤ 100 µsec) behavior, which provides the reliability required by RF-MEMS switches. The charges are transported through a large network of grain boundaries, which occupy a large percentage of the total area of the films, characterized by a nanostructure formed by 2-5 nm grains with ~ 0.5 nm wide grain boundaries.

This paper focuses on a description of materials, materials integration strategies, device architecture and performance of prototype monolithically integrated RF-MEMS mm-wave shunt capacitive switches/CMOS devices in coplanar waveguides, using UNCD as the dielectric layer. The RF-UNCD MEMS switches are based on a MEMtronics, Inc. switch design, fabricated on sapphire wafers with high-voltage CMOS devices, provided by Peregrine Semiconductor, using standard lithography and surface micromachining techniques. Small signal measurements were performed in the frequency range of 1-20 GHz. Measurements of the UNCD dielectric layer charging and discharging were performed using both MEMS and metal-insulator-metal (MIM) capacitor device configurations, using standard I-V and C-V techniques. The charging and discharging time constants for RF-MEMS switches with UNCD dielectric were 5-6 orders of magnitude faster (≤ 100 µsec) than the discharging times (100s of seconds) exhibited by conventional oxide or nitride dielectric materials. Although static power consumption is an issue with UNCD-based capacitors, they can be used in applications, which demand little to no degradation in performance and allow microwatts of power consumption.

This work was mainly supported by DARPA, under contract MIPR 06-W238. Use of the Center for Nanoscale Materials was supported by the U. S. Department of Energy, Office of Science, Office of Basic Energy Sciences, under Contract No. DE-AC02-06CH11357.

9:20am **MN-FrM4 Mechanical Stiffness and Dissipation in Ultrananocrystalline Diamond Resonators**, ***V.P. Adiga***, University of Pennsylvania, *S. Suresh*, *A. Datta*, Innovative Micro Technology, *J.A. Carlisle*, Advanced Diamond Technologies, *A.V. Sumant*, Argonne National Laboratory, *R.W. Carpick*, University of Pennsylvania

Nanocrystalline materials exhibit unique mechanical properties depending on the nature of the bond, co-ordination number of atoms at grain boundaries. Tetragonal sp^3-bonded diamond has the highest known atomic density. The nature of the bond and its high density enable diamond to have superior physical properties such as the highest Young's modulus, melting temperature and acoustic velocity of all materials. Recently, conformal thin diamond films have been grown at CMOS-compatible temperatures in the form known as ultrananocrystalline diamond (UNCD). We have measured the Young's modulus (E), Poisson's ratio and the quality factors (Q) for microfabricated overhanging ledges and fixed-free beams composed of UNCD films grown at lower temperatures[1]. The overhanging ledges exhibited periodic undulations due to residual stress. This was used to determine a biaxial modulus of 838 ± 2 GPa. Resonant excitation and ring down measurements of the cantilevers were conducted under ultra high vacuum (UHV) conditions on a customized atomic force microscope to determine E and Q. At room temperature we found E = 790 ± 30 GPa, which is ~20 % lower than the theoretically predicted value of polycrystalline diamond, an effect attributable to the high density of grain boundaries in UNCD. From these measurements, Poisson's ratio for UNCD is estimated for the first time to be 0.057±0.038. We also measured the temperature dependence of E and Q in these cantilever beams from 60 K to 450 K. Above ~ 150 K, temperature dependence of modulus is slightly higher than that of single crystal diamond averaged over all directions despite the presence of large fraction of disordered carbon at grain boundaries and below 150 K changes in modulus are extremely small. This is the first such measurement for UNCD and strongly suggests that the nanostructure plays a significant role in modifying the thermo-mechanical response of the material. We have measured a very low temperature coefficient of frequency at room temperature which has important technological applications including resonant mass sensors and filters. The room temperature Q varied from 5000 to 16000 and showed a moderate increase as the cantilevers were cooled below room temperature and it saturates resembling the plateaus observed in many disordered systems. The results suggest that defects in the grain boundaries significantly contribute to the observed dissipation.

"Mechanical stiffness and dissipation in ultrananocrystalline diamond resonators" **Adiga** *et al*, V 79, pp 245403.1-8, ***Physical Review B***, 2009

9:40am **MN-FrM5 Theoretical and Experimental Investigation of Optically Driven Nanoelectromechanical Oscillators**, ***R.B. Ilic***, Cornell University, *S.L. Krylov*, Tel Aviv University, Israel, *H.G. Craighead*, Cornell University

Actuation of biologically functional micro and nanomechanical structures using optical excitation is an emerging arena of research that couples the felds of optics, fluidics, electronics and mechanics with potential for generating novel chemical and biological sensors. In our work, we fabricated nanomechanical structures from 200nm and 250nm thick silicon nitride and single crystal silicon layers with varying lengths and widths ranging from 4µm to 12µm and 200nm to 1µm, respectively. Using a modulated laser beam, focused onto the device layer in close proximity to the clamped end of a cantilever beam, we concentrate and guide the impinging thermal energy along the device layer. Cantilever beams coupled to chains of thermally isolated links were used to experimentally investigate energy transport mechanisms in nanostructures. The nature of the excitation was studied through steady-periodic axisymmetric thermal analysis by considering a multilayered structure heated using a modulated laser source. Results were verified by finite element analysis, which was additionally implemented for the solution of steady-periodic and transient thermal, as well as steady thermoelastic problems. These theoretical investigations, coupled with our experimental results, reveal that the complex dynamics underpinning optical excitation mechanisms consist of two disparate spatial regimes. When the excitation source is focused in close proximity to the structure the response is primarily thermal. We show that as the source is placed farther from the clamped end of the structure, the thermal response progressively fades out indicating the possibility of mechanical wave propagation. Understanding the excitation mechanisms may be useful for applications including compact integration of nanophotonic elements with functionalized nanomechanical sensors for ultra-sensitive biochemical analysis.

10:00am **MN-FrM6 Nanotribological Studies of Adaptive Optics Sliding Components in Microprojectors**, *B. Bhushan, **H. Lee***, The Ohio State University, *S. Chaparala, V. Bhatia*, Corning Incorporated

As portable devices are increasingly developed and used, the size of their displays are getting smaller, therefore becoming harder to view. Integrated micro-projectors are an alternative way to see a big image on any surface chosen by users. Microprojectors require red, blue, and green lasers to perform. However, unfortunately the green laser is not commercially available. In order to generate the green laser, frequency doubling technique is used, doubling a semiconductor laser of a wavelength 1060nm to 530nm green laser. The best alignment of the lenses in frequency doubling technique effects on energy efficiency and performance of the devices. To align the lenses, there are reciprocating and stick-slip motions between the components in the devices. Therefore, nanotribological studies of adaptive optics sliding components in microprojectors are needed. In this study, a methodology to measure lubricant thickness and distribution is developed. Lubricant bonding techniques are identified to bond the lubricant to the surfaces with thermal, UV or plasma treatments. Friction, adhesion and wear mechanisms of lubricant on the sliding components are studied in various environments, such as different humidity and temperature.

10:20am **MN-FrM7 Nonlinear Fracture Mechanics Model for Mode I & Mode II Stiction Failure**, ***A. Mousavi***, *Z.C. Leseman*, University of New Mexico

10:40am **MN-FrM8 Novel NEMS Gas Detectors for Micro Gas Chromatograph**, *C.-H. Chen, C.-J. Hsieh, H.-K. Lin, T.-S. Lee, P.-H. Chen, C.-H. Chou,* National Taiwan University, Republic of China, *C.-J. Lu,* National Taiwan Normal University, Republic of China, ***W.-C. Tian***, National Taiwan University, Republic of China

This research reports the developments and characterizations of two types of NEMS gas detectors, based on nano-scaled titanium oxide (TiO_2) and monolayer protected gold nanoclusters (MPCs) as a sensing film of chemiresistors. For sensing films based on chemically synthesized MPCs, the diversified selectivity (>10 compound detection based on various MPC shell structures), the fast response (<10 seconds) and the low power consumption (25 μW) are its main advantages. However, the irreversible adsorption due to the strong affinity between MPCs and vapor molecules could be problematic. On the other hand, nano-structured TiO_2 film, which is operated at elevated temperature, is inherently immune from irreversible condensation. The TiO_2 sensing film is fabricated through E-beam lithography in the present study. Various shapes of nano-structures are precisely aligned and placed in between microelectrodes to mimic nano-crystalline structures for the enhancement of the detector sensitivity and robustness. In addition, these NEMS gas detectors are conditioned with integrated heaters at a controlled temperature to minimize any interfering gas adsorption in between analysis. Various performance evaluations including the characterizations of two types of detectors at different temperatures, test chemicals, detection limits, and the compatibility with a gas chromatography system, are investigated and to be presented.

11:00am **MN-FrM9 On the Impact of Relative Humidity and Environment Gases on Dielectric Charging Process in Capacitive RF MEMS Switches Based on Kelvin Probe Force Microscopy**, ***U. Zaghloul***, *B. Bhushan,* The Ohio State University, *P. Pons,* LAAS-CNRS, France, *G.J. Papaioannou,* Universite de Toulouse, France, *F. Coocetti, R. Plana*, LAAS-CNRS, France

Dielectric charging is among the major reliability issues that have prevented the commercialization of RF-MEMS Capacitive switches in spite of the extensive study performed on the topic. Moreover, a little work has been performed to study the effect of the relative humidity (RH) and environment gases on the dielectric charging process.

In this work we present the effect of RH and the environment gases on the charging/discharging processes in PECVD silicon nitride films based on Kelvin Probe Force Microscopy (KPFM) methodology. The measurements have been performed in ambient air and under N2 flow, both under different RH levels (from 6% to 40% RH). In addition, the influence of the dielectric film thickness, SiN deposition conditions and the substrate nature on the charging process have been investigated under different environment conditions. This has been done through depositing SiN films with different thicknesses ranges from 100nm to 400nm over bare silicon substrates and over evaporated Au layers and using both Low Frequency(LF) and High Frequency(HF) PECVD deposition modes.

For both measurements performed in ambient air and under N2 flow, the surface potential decay with time follows the stretched exponential law. The decay time constant decreases strongly as the RH increases (1.230E+03 sec and 650 sec for 6%RH and 40%RH respectively, for the HF 200nm thick SiN film deposited over evaporated Au). The measured decay time constant is found to be shorter in case of N2 than in ambient air measurements. The surface potential distribution is represented by the Full Width at Half Maximum (FWHM) for charges which have been injected in a single point with the AFM tip. The FWHM becomes smaller as RH decreases. Charge injection duration is controlled to range from 10 ms to 100 sec. The FWHM is found to be always larger in air comparing to FWHM measured in N2 flow for different charge injection durations. Moreover, FWHM increases almost linearly with increasing the charge injection time for different RH measurements. Charge lateral diffusion has been observed at larger RH only and is attributed to the more hydrophobic SiN material at smaller RH levels which prevents water condensation at the surface and thereby inhibits lateral charge migration due to the electrical conductivity of a possible water film. The FWHM is found to be smaller in thinner SiN films than in thicker ones and the relaxation time is found to be larger in the thinner SiN films, independently of the substrate nature. Finally, the decay time constant is found to be smaller in case of dielectric films deposited over Au layers comparing to films deposited over bare silicon substrates.

11:20am **MN-FrM10 Feature Size Etch Rate Dependence in Bosch Process Deep Silicon Etching Due to Local Thermal Loading**, *R. Kurkul, R. Gulotty, **B. VanderElzen***, University of Michigan, Ann Arbor

Aspect ratio dependent etching (ARDE) is a common issue in reactive ion etching. This phenomenon results in narrow, deeply etched features exhibiting slower etch rate and a more reentrant profile than larger, more open features. The common mechanism indicated for this effect is ion flux. The narrow features restrict the ability of ions that are not perfectly perpendicular to make it to the bottom of the feature and drive the etch. Recent data obtained at the University of Michigan Lurie Nanofabrication Facility suggests that, in some circumstances, there is a feature size effect that is independent of aspect ratio. The mechanism proposed and studied herein is local thermal loading due to exothermic etch reactions.

The evolution of faster etch rates in silicon is a key enabling factor in MEMS production. However, this fast etching results in thermal management concerns. In an effort to understand these temperature effects better, as well as to determine the evolution of aspect ratio dependence, we performed a variety of rate tests at various stages of etching on different size features. A surprising result was that, after an initial substrate warm up time where etch rates increased slightly, etching rates were flat until aspect ratios approached 10:1 after which they began to drop off slightly. Even more notable is a very significant rate variance with feature size even at very early stages of the etch. This appeared in a regime where ion flux and ARDE should not be significant. This strongly suggests a mechanism of feature size dependence separate from aspect ratio.

The mechanism proposed for this etch rate variance is local thermal loading. This agrees with data collected. Temperature is a significant factor in determining etch rate. The fluorine silicon reaction is exothermic. This has been shown to elevate the temperature of the substrate over the first few minutes of the process. The thermal load will also result in heating and a higher temperature at the etch interface within the features. Larger features will have a higher local thermal load and thus get hotter. This heating accelerates the etch and likely inhibits the ensuing etch resistant fluorocarbon deposition step that is characteristic of the Bosch Process.

We will demonstrate the evolution of this thermal loading and its effects on etch rate within an etch step and through the first few etch cycles of a Bosch Process. We will then evaluate the effectiveness of possible methods of mitigating this effect.

Authors Index

Bold page numbers indicate the presenter

— A —

Adiga, V.P.: MN-FrM4, **1**
Auciello, O.H.: MN-FrM3, 1

— B —

Balachandran, S.: MN-FrM3, **1**
Bhatia, V.: MN-FrM6, 2
Bhushan, B.: MN-FrM6, 2; MN-FrM9, 2

— C —

Carlisle, J.A.: MN-FrM1, **1**; MN-FrM3, 1; MN-FrM4, 1
Carpick, R.W.: MN-FrM4, 1
Chaparala, S.: MN-FrM6, 2
Chen, C.-H.: MN-FrM8, 2
Chen, P.-H.: MN-FrM8, 2
Chou, C.-H.: MN-FrM8, 2
Coocetti, F.: MN-FrM9, 2
Craighead, H.G.: MN-FrM5, 1

— D —

Datta, A.: MN-FrM4, 1

— G —

Goldsmith, C.L.: MN-FrM3, 1
Gudeman, C.: MN-FrM3, 1
Gulotty, R.: MN-FrM10, 2

— H —

Hsieh, C.-J.: MN-FrM8, 2

— I —

Ilic, R.B.: MN-FrM5, **1**

— K —

Krylov, S.L.: MN-FrM5, 1
Kurkul, R.: MN-FrM10, 2

— L —

Lee, H.: MN-FrM6, **2**
Lee, T.-S.: MN-FrM8, 2
Leseman, Z.C.: MN-FrM7, 2
Lin, H.-K.: MN-FrM8, 2
Lu, C.-J.: MN-FrM8, 2

— M —

Mousavi, A.: MN-FrM7, **2**

— O —

O'Brien, S.: MN-FrM3, 1

— P —

Papaioannou, G.J.: MN-FrM9, 2
Plana, R.: MN-FrM9, 2
Pons, P.: MN-FrM9, 2

— S —

Sampath, S.: MN-FrM3, 1
Sumant, A.V.: MN-FrM3, 1; MN-FrM4, 1
Suresh, S.: MN-FrM4, 1

— T —

Tian, W.-C.: MN-FrM8, **2**

— V —

VanderElzen, B.: MN-FrM10, **2**

— Z —

Zaghloul, U.: MN-FrM9, **2**