Thursday Morning, November 12, 2009

MEMS and NEMS
Room: A8 - Session MN+GR-ThM

Graphene and Carbon Based MEMS/NEMS Devices
Moderator: B.R. Ilic, Cornell University

8:00am **MN+GR-ThM1 Graphene Mechanics, Tribology, and NEMS Resonators**, ***J. Hone***, Columbia University **INVITED**

This talk will describe our work toward fundamental understanding of the mechanical and and tribological properties of graphene, and its application in nano-electromechanical devices (NEMS). We have used nanoindentation to measure the elastic stiffness and ultimate strength of single graphene sheets[1]. These measurements show that graphene is the strongest material ever measured, with an ultimate strength of 130 GPa at an ultimate strain of over 25%. As such, it is the first material whose mechanical properties can be probed deep into the nonlinear elastic regime. We have also measured the frictional behavior of graphene and other related two-dimensional materials. These materials all show an unexpected strong dependence of the frictional force the number of atomic layers, with thinner samples demonstrating larger friction. Finally, we have demonstrated electronic readout of graphene nanomechanical resonators. These devices show highly tunable mechanical resonances in the range 20-300 MHz, with large output signal compared to other NEMS of comparable size. The quality factor of these resonators increases from ~100 at room temperature to ~10,000 at low temperature. The measured sensitivity of these resonators to applied mass shows their promise as multifunctional sensors.

[1] Changgu Lee, Xiaoding Wei, Jeffrey Kysar, J. Hone, "Measured elastic properties and ultimate strength of monolayer graphene," *Science* **321**, 385 (2008)

8:40am **MN+GR-ThM3 Enhanced Stabilities in Resonant Response of Carbon Nanotube Network Reinforced Al Thin-Film Nanomechanical Resonators**, ***Y.D. Kim***, *J.H. Bak, J. Lee, S.R. Lee, K. Char, S. Hong, Y.D. Park*, Seoul National University, South Korea

With superior mechanical properties, single-walled carbon nanotubes (swCNT) are an attractive reinforcement component for nanoscale composites, based in either polymer or metal matrices [1]. Recently enhancements in mechanical properties of metallic thin-films reinforced by CNTs have been reported [2]. Self-consistent results from quasi-static and dynamic flexural measurements indicate the elastic modulus to nearly double with the inclusion of self-assembled swCNT network layer in Al thin-films [3]. Here, we present significant enhancements in resonant frequency stability of CNT network reinforced Al thin-film nanomechanical resonators. We characterize the stability in the resonant response either by long-cycle measurements or with applied stress. Long-cycle ($>10^{11}$) dynamic flexural measurements show suppression of anelastic effects, which limits the applicability of metallic thin-films nanomechanical resonators. Application of stress is accomplished by two differing methods. A tensile stress is applied by using a 'chip-bending' method. A compressive stress is applied through thermal-elastic effects from Joule heating. For both cases, a significant stability in CNT network reinforced Al thin-film resonant response is observed.

[1] W.A. Curtin and B.W. Sheldon, Materials Today 7, 44 (2004); J.N. Coleman et al., Advanced Materials 18, 689 (2006).

[2] Kang et al., Advanced Materials 19, 427 (2007).

[3] J.H. Bak, Y.D. Kim, et al., Nature Materials 7, 459 (2008).

9:00am **MN+GR-ThM4 Carbon Nanostructures on Microscrolls**, ***J.W. Choi***, Kyung Hee University, Republic of Korea

Thin bimetallic films on silicon substrates are formed in microscale scroll when the substrate temperature varies. To increase the functional properties of the bimetallic scroll, carbon nanostructures are directly integrated to the scroll. The formation of the bimetallic scroll and the direct integration of carbon nanostructures are studied for various apllications including NEMS, sensors, energy storage devices.

9:20am **MN+GR-ThM5 Thin Smooth Carbon Nanotube/Polymer Composite Membranes**, ***L. Pei***, *R. Vanfleet, M.R. Linford, R.C. Davis*, Brigham Young University

We have developed a new and straightforward method for fabricating freely suspended ultrathin carbon nanotube (CNT) membranes. A smooth transferrable CNT sheet was first made from vertically aligned carbon nanotube (VACNT) forests by placing mixed cellulose ester (MCE) filter paper on a VACNT forest and using a roller to both compress the forest and transfer the nanotubes to the filter paper. The compressed CNT film was then transferred to a solid substrate and the MCE was subsequently dissolved, leaving the CNT film on the substrate. Nanotube – polymer composite films were then fabricated by spin casting a polymer layer on top of the transferred CNT sheet. If the solid substrate was coated with a polymer film prior to CNT transfer, a polymer/CNT/polymer sandwich was created. The composite membranes were subsequently released from the substrate. Characterization of the films and membranes preformed by scanning electron microscopy, atomic force microscopy, and by strength testing will be presented.

9:40am **MN+GR-ThM6 Nanostructuring of Ultrananocrystalline Diamond (UNCD) Thin Films Via Block Copolymer Lithography**, ***M. Ramanathan***, *S.B. Darling, A.V. Sumant, O.H. Auciello*, Argonne National Laboratory

Diamond is in many ways an optimal material for numerous technological, industrial and biological applications because of its exceptional physical and chemical properties. In addition to high hardness, diamond is stiff, biocompatible and wear resistant. Nanopatterning of diamond surfaces is critical for the development of diamond-based MEMS/NEMS, such as resonators or switches. Micro/nano structuring of diamond materials is typically associated with conventional lithographies such as photolithography or electron beam lithography. In this paper, we demonstrate a simple process, known as block copolymer (BCP) lithography, of nanostructuring ultrananocrystalline diamond (UNCD) surfaces. In BCP lithography, nanoscale self-assembled polymeric domains serve as an etch mask for pattern transfer. We used thin films of a cylinder-forming organic–inorganic BCP, poly (styrene-*block*-ferrocenyldimethylsilane), PS-*b*-PFS, as an etch mask on UNCD. Orientational control of the etch masking cylindrical PFS blocks are achieved by manipulating the polymer film thickness in concert with the annealing treatment. For films much thinner than the equilibrium periodicity of the microdomains, the cylinders spontaneously orient themselves perpendicular to the substrate. On the other hand, films with thickness close to the equilibrium periodicity exhibit in-plane orientation. We have observed that surface roughness of UNCD plays an important role in transferring the pattern. Reactive ion etching (RIE) using oxygen gas was used to etch the exposed areas of UNCD. Arrays of both UNCD posts and wires have been created using the same starting polymeric materials as the etch mask.

10:40am **MN+GR-ThM9 Fabrication of a Reusable Template Based on Ultrananocrystalline Diamond for Electrodeposition of Metal and Semiconductor Micro/Nanowires**, ***D.B. Seley***, *D.A. Dissing*, University of Wisconsin - Stevens Point, *A.V. Sumant, R. Divan, S. Miller*, Argonne National Laboratory, *E.A. Terrell*, University of Wisconsin - Stevens Point, *O.H. Auciello*, Argonne National Laboratory, *M.P. Zach*, University of Wisconsin - Stevens Point

Electrodeposition is a versatile technique that has been used for the synthesis of nanowires. There are several methods available for the synthesis of nanowires, each requiring some form of template, which is not easily reusable. A recent report uses a combination of optical lithography, and the conductive edges of a metal for the deposition of nanowires, but the patterned metal is sacrificial, requiring a multi-step process to regenerate the electrode (1).

We demonstrate a top-down approach involving lithography and reactive ion-etching of ultrathin (150 nm) undoped and N-doped ultrananocrystalline diamond (UNCD) stack defining nanoelectrodes for subsequent electrodeposition of micro/nanowires of desired materials. Once this template consisting of arrays of nanoelectrodes of various shapes has been made, it is a permanent reusable template for synthesis of micro- and nanowires. Subsequent manufacture of nanowires becomes almost as simple as using a rubber stamp and ink. The multilayer diamond electrode provides low adhesion to the deposited materials which allows for easy transfer of the resulting electrodeposited micro- or nanostructures onto an adhesive polymer. Each set of structures is removed, regenerating a pristine electrode surface for multiple depositions without needing to repeat the difficult lithography steps for each batch of wires made. The combination of unique electrical and chemical properties of UNCD is promising to allow mass production of uniform patterned nanostructures. Materials electrodeposited until now include: Pb, Au, Cu, Pd, Pt, Co (non-aqueous), Te, CdTe, and CdS.

Acknowledgments

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

Additional support was provided by UPDC Fund (UWSP), WiTAG and University of Wisconsin-System.

1. E. J. Menke, M. A. Thompson, C. Xiang, L. C. Yang and R. M. Penner, *Nature Materials*, **5**, 914 (2006).

11:00am **MN+GR-ThM10 Fabrication and Characterization of Ultrananocrystalline Diamond Nanowires for Developing Next Generation of Nanoelectronic Devices**, ***A.V. Sumant***, *L.E. Ocola*, Argonne National Laboratory, *X.P. Wang*, University of Puerto Rico, *D.O. Lopez, O.H. Auciello, D.C. Mancini*, Argonne National Laboratory

Recently, there is tremendous amount of interest in making diamond nanowires (DNWs) and diamond nano-rods (DNRs), due to their extraordinary mechanical, electrical, and optical properties as predicated by theory, however, synthesizing or fabricating these quasi1-dimensional sp^3 nanostructures is proved to be very challenging. To date, only few attempts have been reported either by etching single crystal diamond from top-down process to produce diamond nano-rods (DNRs) or by coating Si nanowires with nanocrystalline diamond. We report a method based on e-beam lithography and reactive ion etching of ultrananocrystalline diamond (UNCD), to produce UNCD nanowires (UNCDNWs) and UNCD nano-rods (UNCDNRs) with nanowire diameter as small as 20 nm. Since they are produced by lithographic approach, they can be fabricated almost at will in well defined position with nanometer scale precision. We have fabricated Nitrogen doped UNCDNWs and characterized them using Raman spectroscopy (UV and visible) and TEM microscopy. We will discuss about preliminary nanostructural studies of UNCDNWs and electrical measurements. The ability to fabricate UNCDNWs and UNCDNRs gives an opportunity to study fundamental mechanism of transport processes in diamond nanowires, which will enable new ideas and possibility of fabricating new functional nanoelectronic devices and sensors with increased sensitivity for a variety of applications in nanotechnology.

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