Synthesis, Characterization, and Fabrication of Ultrananocrystalline Diamond Based NEMS

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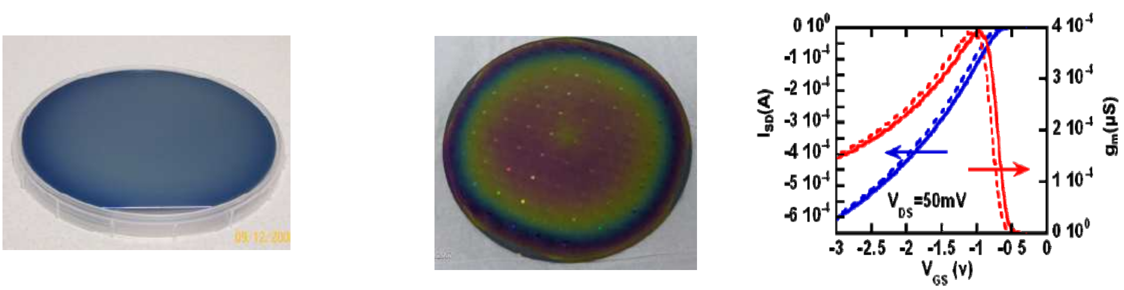
Scientific Thrust Area: Nanofabrication and Devices

Research Achievement:

We have studied the fundamental electrical and mechanical properties of ultrananocrystalline diamond (UNCD) films, which will enable fabrication of new generation of nanoelectromechanical systems (NEMS) integrated with complementary-metal-oxide-semiconductor (CMOS) devices to enable the development of nanodevices with advanced functionalities.

a) Synthesis and characterization of large-area, low-temperature UNCD films and integration with CMOS:

The first important step in developing diamond based NEMS is the ability to synthesize diamond thin films on a wafer scale with thickness and nanostructure uniformity acceptable for nanodevices. The new 915 MHz microwave plasma chemical vapor deposition (MPCVD) system from Lambda Technologies installed in the clean room at CNM enabled the development of a process to synthesize UNCD at 400 ^{o}C and demonstrated film thickness uniformity in the range of 5-11% on 150-200 mm diameter silicon wafers respectively (fig. 1(a-c)) with excellent nanostructure uniformity as characterized by Raman spectroscopy and near edge x-ray absorption fine structure spectroscopy. The level of uniformity achieved is unmatched with any other diamond MPCVD process. More importantly, we have developed scheme to monolithically integrate low temperature UNCD with CMOS. The ability to preserve the functionality of CMOS devices was demonstrated by depositing UNCD directly on the CMOS wafer at 400^{o}C (fig. 1(b)) and measuring I-V characteristics before and after UNCD deposition (fig. 1(c)). This process enabled later development of monolithically integrated CMOS with RF-MEMS switches based on diamond as a dielectric. This first successful demonstration of integration of UNCD with CMOS devices is a major breakthrough that opens new pathways for fabricating CMOS-driven NEMS based on UNCD.



(a) (b) (c)

Figure 1. Photographs of uniform UNCD film deposited on (a)150 mm diameter si wafer and (b) 200 mm diameter Si-CMOS wafer respectively and(c) I-V measurements on CMOS before (solid lines) and after (dashed lines) UNCD deposition demonstrating no appreciable change in CMOS device performance.

b) Integration of UNCD films with piezoelectric films for high-frequency resonators:

The integration of piezoelectric $Pb(Zr_xTi_{1-x})O_3$ (PZT) thin films with the UNCD opens up the possibility of advanced piezo-actuated devices, which can be actuated at lower voltages (< 5 V) compared to typical electrostatic actuation requiring higher voltages (30-

50V). The integration is challenging, because PZT films are grown in an oxygen-rich environment and oxygen reacts with carbon, resulting in the chemical etching of the UNCD and thus degrading the PZT/UNCD interface. We developed Ti-Al as an oxygen diffusion barrier layer and demonstrated PZT/UNCD piezo-actuated resonator structures with actuation voltage as low as 1 volt, enabling a new class of piezo-actuated high frequency UNCD resonators.

c) Mechanical dissipation in UNCD microresonators:

We have carried out fundamental studies to investigate the origin of dissipative losses in diamond. Dissipation in the UNCD cantilevers is determined using ring-down measurement under UHV conditions and the quality factor Q was measured to be in the range of 5000–16,000 at kHz resonance frequencies. The UNCD cantilever resonators exhibited higher dissipation compared to microcrystalline diamond cantilevers with comparable resonant frequencies, but less dissipation than amorphous carbon cantilever resonators. We attribute higher dissipation in the UNCD resonators mainly to the presence of defects such as carbon bonding at grain boundaries and surfaces.

Future Work:

(a)UNCD nanowire: A new platform for developing next generation diamond based nanoelectronic devices:

UNCD nanowires are quasi 1-dimensional sp^3 nanostructures and are predicted to have exceptional electronic and mechanical properties. We used e-beam lithography and reactive ion etching of UNCD, to fabricate nanowires with diameter as small as 20 nm. The effective surface area of the grains and grain boundary in nanowire is large and any small chemical changes on the surface could greatly affect electrical transport properties of these nanowires. We will fabricate UNCD nanowires and perform detailed studies on their electronic, mechanical and thermal properties. This may enable fabrication of new functional nanoelectronic devices for a variety of applications.

(b) Dielectric properties of nitrogen doped UNCD:

We have made preliminary measurements of optical dielectric properties of undoped and nitrogen doped UNCD films. We will make detailed measurements across the entire electromagnetic spectrum from DC to RF to UV correlating these electro-optic properties as a function of nitrogen content in UNCD in order to understand the role of nitrogen in determining the dielectric properties of UNCD.

Publications:

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2. J. E. Butler and A. V. Sumant, "The CVD of nanodiamond materials," *Chem. Vap. Deposition*. 14, 145 (2008). Invited Review Article.
3. A.V. Sumant, D. S. Grierson, J. E. Gerbi, J. Carlisle, O. Auciello, R. W. Carpick, "The surface chemistry and bonding configuration of ultrananocrystalline diamond surfaces, and their effects on nanotribological properties," *Physical Review B* 76 235429 (2007).
4. O. Auciello, S. Pacheco, A. V. Sumant, C. Gudeman, S. Sampath, A. Dutta, R. W. Carpick, V. Adiga, P. Zurcher, Z. Ma, H. Yuan, J. A. Carlisle, B. Kabuis, J. Hiller, S. Srinivasan, "Are diamonds MEMS' best friend?" *IEEE Microwave Mag.* 8(7), 61 (2007).
5. S. Srinivasan, J. Hiller, B. Kabius, O. Auciello, "Piezoelectric/ultrananocrystalline diamond heterostructures for high-performance multifunctional micro/nanoelectromechanical systems", Appl. Phys. Lett., 90, 134101 (2007).

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