Heteroepitaxial Growth of Diamond for Device Applications

Antanica Boneparte
Chemical Engineering, Howard University

NNIN REU Site: Center for Nanoscale Systems, Harvard University, Cambridge, MA
NNIN REU Principal Investigator and Mentor: Dr. Gary Harris, Electrical Engineering, Howard University (on sabbatical at Harvard University)
Contact: bonepartea@yahoo.com, gharris@msrce.howard.edu

Abstract:

Diamonds grown by chemical vapor deposition have many characteristics that enable their use in medical, electronic and electro-optic applications. The objective of this research was to demonstrate the growth of diamond, through microwave plasma enhanced chemical vapor deposition (PECVD), on various non-diamond silicon (Si) substrates (i.e. Si <100>, Si <111>, ^{6}H-silicon-carbide (SiC), Si coated with nickel, etc.). The substrates were coated with a diamond solution in an ultrasonic bath that created nucleation sites for diamond growth. With the specified parameters—1100 watts, 50 torr, 400 standard cubic centimeters per minute (sccm) hydrogen (H_2), 1.6 sccm methane (CH_4)—layers grew at about 0.4 μm/hr. Diamond growth was confirmed using energy dispersive spectroscopy (EDS) due to the high levels of carbon on the substrates. Scanning electron microscope (SEM) images proved that diamond layers grew in various orientations based on the substrate it grew on. Si <100> grew high faceted and high quality layers with pyramidal, hexagonal, and cuboidal structures, while Si <100> coated with nickel formed spherical shaped diamonds.

Introduction:

CVD diamonds are an important family of materials used in microelectronic and optoelectronic packaging and for laser and detector windows [1]. Diamond is the hardest known natural material. On the Mohs scale of mineral hardness (a scaling system that characterizes the scratch resistance of various minerals from 1-10) diamond is a 10. Its ultra-high thermal enhances high frequency in optoelectronic systems [2]. Diamond is chemically inert and if doped can be a strong semiconductor. Diamond can be extremely useful in devices that have extremely high power densities, high mechanical loads, and severe abrasive conditions.

Experimental Procedure:

There are essentially two methods to synthetically grow diamond: a high pressure-high temperature (HPHT) method and the chemical vapor deposition (CVD) method. In the HPHT process, graphite and a metallic catalyst are placed in a hydraulic press under high temperatures and pressure. HPHT diamonds are usually only a few millimeters across and are too flawed to apply to devices. In the CVD method, the substrate is exposed to gaseous hydrogen and methane that is heated and activated, and there is then a reaction on the surface of the substrate to produce diamond. Microwave plasma enhanced CVD (PECVD) is the method we used, because it can yield better quality material and has the potential to morph the diamond into different shapes.

The various Si wafer substrates were first ultrasonically cleaned with acetone, followed by methanol for 15 minutes each, and then dried with nitrogen (N) gas. This process removed any surface contaminations. The substrates were then seeded with a diamond solution, also referred to as "diamond dust," in an ultrasonic bath for 15 minutes. The "diamond dust" contained nanoparticles of diamonds that scratched the surface of the substrates while in the ultrasonic bath to create nucleation sites from which the diamonds would grow. After selecting a substrate, it was then put into the PECVD reactor where the growth process took place. In the PECVD reactor, H_2 and CH_4 were the two gases used for the procedure. There was a significantly larger concentration of H_2 to CH_4, making CH_4 only 0.5 - 1% of the gas concentration mixture. This was to ensure a slow and even growth rate. The gaseous mixture was heated and activated with microwaves initially generated at 350 watts. Under 10 torr of pressure, the gaseous mixture formed a plasma ball. The wattage was increased to 1100 watts and the pressure to 50 torr. These were the general growing conditions that were initially tested.

The plasma ball heated the substrate and activated hydrogen to react with methane to form hydrocarbons that absorbed and reacted with the nano diamond particles on the surface of the substrate. This process continued until the flow of methane was stopped. After the substrate was cooled, tests and data were taken.

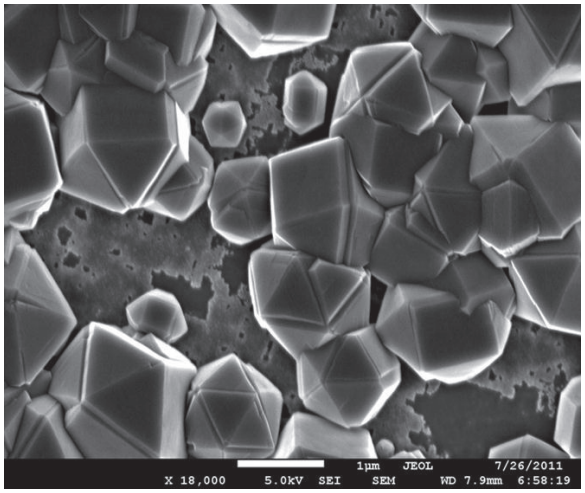

Figure 1: Silicon <100> substrate.

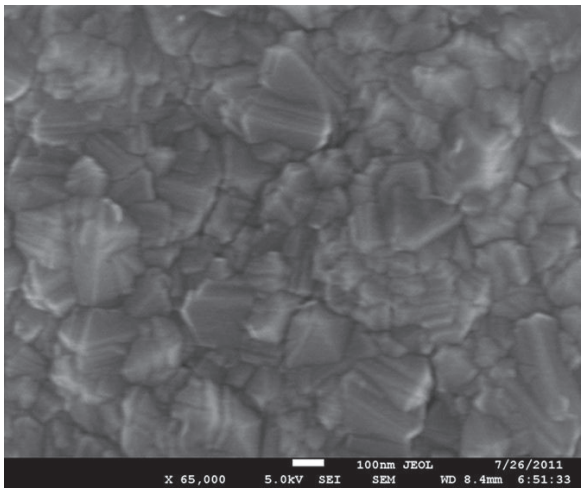

Figure 2: Silicon <111> substrate.

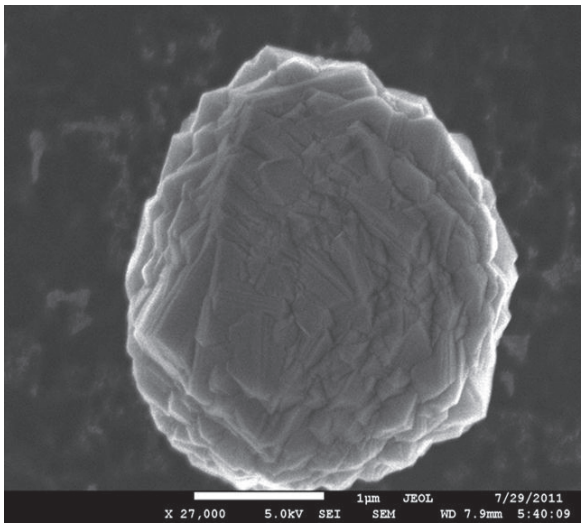

Figure 3: Silicon <100> layered with nickel.

Results and Conclusions:

Each substrate created a differently-oriented diamond film because of the substrate surface orientation.

Figure 1 shows an SEM image of Si <100>. This film yielded the highest quality diamond layers compared to all of the substrates. The Si <100> was very faceted and had highly defined shapes which ranged from octahedron and cubes, to tetrahedrons and hexagons. The diamond sizes ranged from 0.5 μm to approximately 1.5 μm in size. Likewise, 3C-SiC layered on Si grew defined facets, although it displayed only one central pyramidal structure throughout the film. The size of the individual diamond structures were approximately 0.5 μm in size. Both substrates were grown under the same parameters of; 1250 watts, 64 torr, 400 sccm of hydrogen gas to 1.6 sccm of methane gas.

Figure 2 shows Si <111>. Both Si <111> and ^{6}H-SiC, however, grew low quality diamond films. The diamond structures were not defined and were very rigid. The sizes of the individual diamonds on both films were relatively small compared to the substrates yielding higher quality diamond, with a size range from 50-100 nm. These substrates were grown under the same parameters previously stated for the Si <100> and ^{3}C-SiC.

Figure 3 shows Si <100> layered with 30Å of nickel. This substrate yielded the highest quality and most defined shapes. The films grew in spherical diamond balls, a very rare structure to form. We believe that the cause of the phenomenon was because the substrate was coated with nickel, which caused the diamond to grow in a different orientation (wet surface).

Hall measurements of diamond on Si <100> substrates were performed. The electron mobility was 403 cm^2/V·s, which is comparable to natural diamond. This indicates that the synthetic growth was successful and these substrates can be applied to devices.

Acknowledgements:

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References:

[1] K. Fabisiak, E. Staryga, CVD diamond: from growth to application, Journal of Achievements in Materials and Manufacturing Engineering 37/2 (2009) 264-269.