Delta-Doping of Diamond

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Abstract:

The nitrogen-vacancy (NV) center in diamond has emerged as a possible versatile tool for data storage in quantum information processing. The NV center consists of a substitutional nitrogen atom located adjacent to a naturally occurring vacancy within the diamond lattice. The spins of the unbound electrons within the bond can be coherently controlled at room temperature and read out optically. The focus of this project was to determine the optimal conditions for NV center production in synthetic, polycrystalline diamond by growing and doping with ^{15}N gas in a hot filament chemical vapor deposition (HFCVD) reactor. The nitrogen isotope allowed us to distinguish our deposited nitrogen atoms from other impurities, such as ^{14}N or silicon atoms, that may also be present within the grown diamond.

Materials

Introduction:

Quantum computers are considered to be the next revolution in data processing because they will have much faster computing power than modern-day computers. Quantum bits (qubits), the basic unit for quantum information, are formed by electron spins that can be controlled and manipulated to store and read out data. The NV center will allow us to implement logic in the form of these qubits.

Experimental Procedure:

Silicon (Si) and silicon carbide (SiC) samples were cleaned by sonication in acetone and then methanol for one minute each. Nanodiamonds, approximately 5 nm diamond seeds used to increase nucleation density, were deposited by sonicating the samples in an equal volume mixture of nanodiamond solution and methanol for 10 minutes, then rinsing in methanol.

The diamond films were grown in an HFCVD reactor. As seen in Figure 1, the introduction of hydrogen (H_2) and methane (CH_4) gases into the hot filament zone causes decomposition of the gases into simpler molecules and atoms. Atomic hydrogen helps to further decompose the hydrocarbon species at and above the heated substrate surface, leaving behind only carbon atoms for diamond and/or graphitic growth. The atomic hydrogen was also used to etch any graphitic material formed during the growth process.

During the diamond growth process, the flow rate of hydrogen and methane were maintained at 80 sccm and 1 sccm respectively. The chamber pressure and substrate

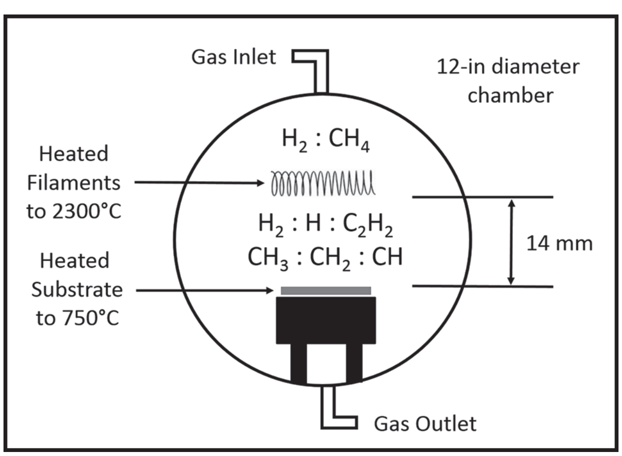

Figure 1: Diagram of HFCVD growing chamber.

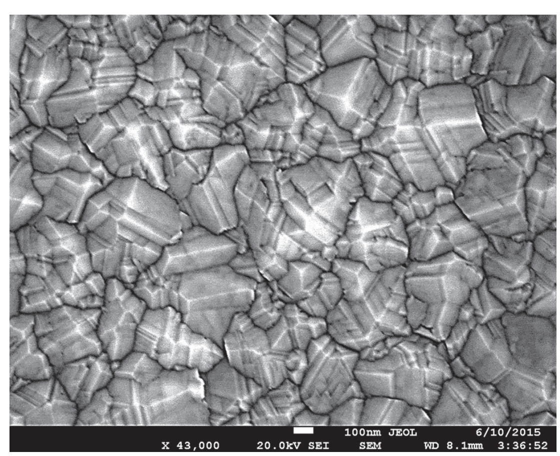

Figure 2: SEM image of diamond grown on Si.

temperature were maintained at 20 torr and 750°C respectively. These conditions yielded a diamond growth rate of 0.167 µm/hour at a substrate-to-filament gap of 14 mm. Figure 2 shows a scanning electron microscope (SEM) image of diamond grown on Si after this process.

Delta doping of diamond with ^{15}N gas was performed during diamond growth at the surface or a few nanometers below the surface. In one experiment, the ^{15}N gas flow rate was varied from 4 to 12 sccm while growing on both Si and SiC substrates with a substrate-to-filament gap of 14 mm. The goal of this experiment was to determine how NV center concentration varied with ^{15}N gas flow rates.

In a second experiment, the ^{15}N gas flow rate was varied from 2 to 12 sccm with a substrate-to-filament gap reduced to 7 mm. The goal of this experiment was to see if NV center concentration varied with substrate-to-filament gap. Since the mean-free path of atomic nitrogen is finite, reducing the distance the atomic nitrogen has to travel before incorporation in the diamond lattice may increase NV center production.

Results:

Figure 3 shows a typical Raman spectrum of HFCVD diamond grown throughout this work. This particular sample was grown on silicon and the diamond was undoped with an average roughness of 40 nm. The sharp diamond peak at 1331.34 cm^{-1} with a FWHM of 7.6 cm^{-1} is indicative of high quality diamond. All of the diamond films grown by the seeding process are polycrystalline. Because the equipment necessary for NV center detection was not available locally, the samples were sent out for characterization. Unfortunately the tool that was used did not detect any NV centers in the samples. This was believed to be an equipment malfunction and not an absence of NV centers. Previous experiments using the same tool indicated NV center presence with a 637 nm zero-phonon emission on ^{14}N doped HFCVD diamond.

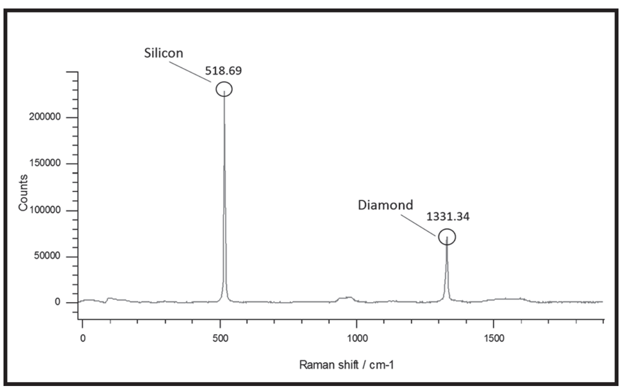

Figure 3: Raman data of undoped diamond on Si.

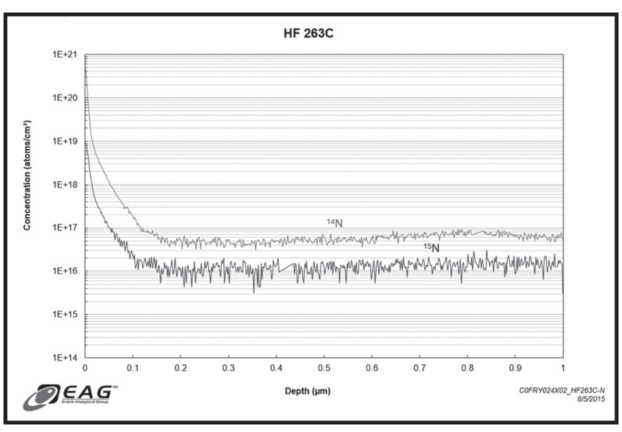

Figure 4: SIMS data indicating nitrogen concentration of a doped diamond on Si sample.

Secondary ion mass spectrometry (SIMS) analysis of one surface delta doped diamond sample was obtained, see Figure 4. This plot shows the concentration of ^{14}N and ^{15}N atoms as a function of depth from the surface. At the surface it is clear that both ^{14}N and ^{15}N were incorporated in the diamond film at very high concentrations, with ^{14}N reaching over 10^{20} atoms/cm^3 and ^{15}N reaching about 10^{19} atoms/cm^3.

Conclusions:

High quality diamond was grown on Si and SiC substrates by HFCVD. The fact that the diamond films were polycrystalline may or may not prove detrimental for NV center purposes. However, growth of diamond on diamond substrates is desirable due primarily to a much smoother surface. SIMS data indicated a delta doped behavior of both ^{14}N and ^{15}N in diamond films. Unfortunately, determination of how ^{15}N gas flow rates and filament-to-sample gaps affect NV center production is still unknown for this reactor. However, in previous experiments involving the doping of diamond with ^{14}N gas, NV centers were characterized and produced under similar parameters. Therefore, it is reasonable to conclude that NV centers exist in diamond films doped with ^{15}N gas.

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