EFFECTS OF HYDROGEN TERMINATION ON RESISTIVITY IN NANODIAMOND ELECTRONICS

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Background

Semiconductors are a class of solids with electrical conductivity levels between that of an insulator and a conductor, including both silicon and selenium. These semiconductors are important for electronic device chips, with efforts to continuously create chips with higher efficiency. However, as chips get smaller, transistors within them generate more heat in an equally small space (Perry, 2019). Furthermore, the closer the transistors become, the more difficult it is to dissipate the heat.

Diamond will play a vital role in the development of semiconductor chips. As the material with the highest thermal conductivity (CRC Handbook of Chemistry and Physics,1991), far surpassing that of silicon, it is far more efficient and contains a high promise for future chips. However, n-type doping is difficult in diamond. H-termination of diamond surface induces two dimensional hole-gas layer on the diamond surface, which is one of the possible ways to fabricate diamond-based field effect transistors without the need for n-type doping. Chemical vapor-deposited (CVD) diamond promises to be cost-effective (Myoshi, 1999) in depositing polycrystalline diamond on wafer-scale. The hydrogen termination was employed to manipulate the electrical properties of a nanocrystalline diamond wafer, in hopes of making diamond a more efficient semiconductor.

Abstract

Semiconductor chips are being created smaller, to keep up with new technology. The smaller semiconductor chips are overheating, adversely affecting performance. Diamond was chosen as a material for the semiconductor wafer because it has much better thermal conductivity than other materials, although making p-n junction devices is difficult. Here we studied H-termination of the diamond surface to induce 2DHG layer due to the surface charge mobility that allows for the fabrication of diamond-based surface FETs. Microwave plasma chemical vapor deposition (MPCVD) was employed to provide hydrogen termination on an ultra nanocrystalline diamond layer on a silicon wafer. The resistivity and sheet resistance of these wafers were characterized. There appears to be a decrease in resistivity and sheet resistance due to the 2DHG layer formation in many samples after hydrogen termination.

Purpose

The purpose of this investigation was to build a semiconductor wafer made of crystalline nanodiamond with hydrogen termination (H-termination) at the surface to improve its electrical conductivity properties. It was hypothesized that H-termination would induce formation of 2DHG layer thereby decreasing sheet resistance and resistivity. This work will help advance the development of sophisticated diamond electronics.

Methods

A silicon wafer underwent MPCVD (Fig. 1), to coat it with a thin layer (200 nm or 400 microns) of diamond, using a seed size of 5-10 nm in an ultrasonic bath to make a nanocrystalline structure. The wafer was then broken into six samples, each with a center, mid-center, or edge piece(s). Each piece underwent MPCVD with hydrogen (H_2) plasma treatment for 30 mins to insert hydrogen atoms at the surface, providing hydrogen termination, and was allowed to cool (Fig. 2-5). Each piece's electrical resistivity and sheet resistance were tested before and after MPCVD with an R50 sheet resistance mapper with a four-point probe. All work was performed in the clean room.

Figure 1. Diamond CVD system & schematic of Hydrogen termination process

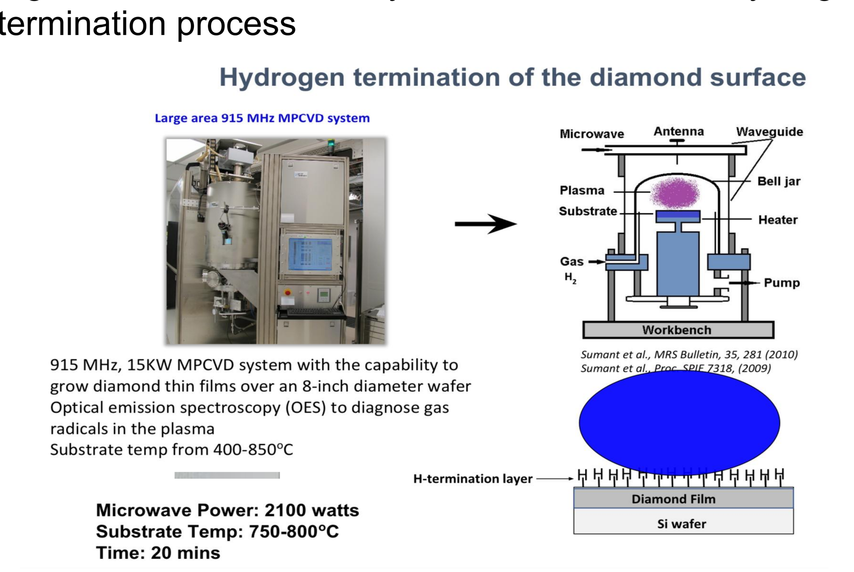
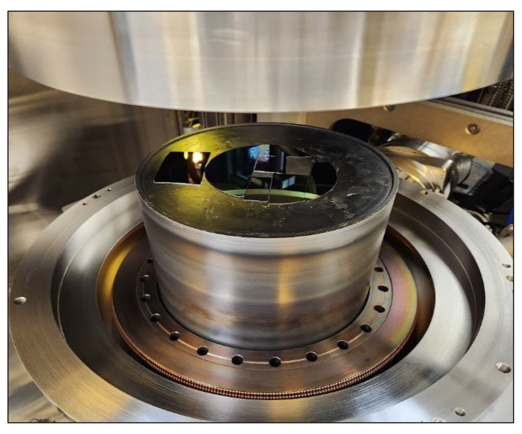


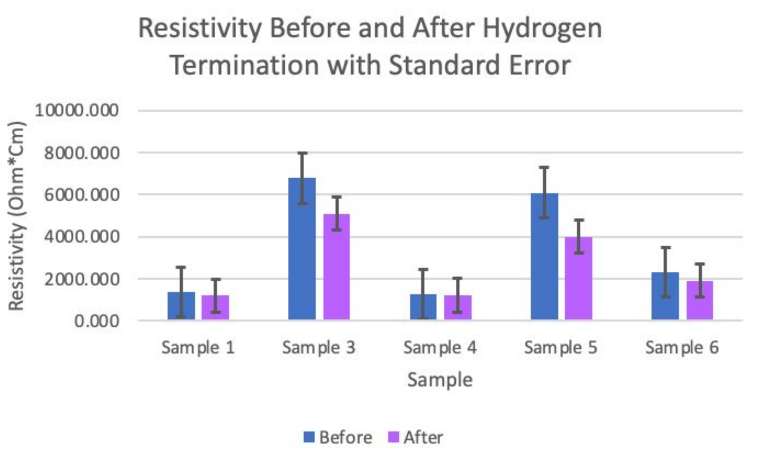
Figure 2. MPCVD parameters for H-termination

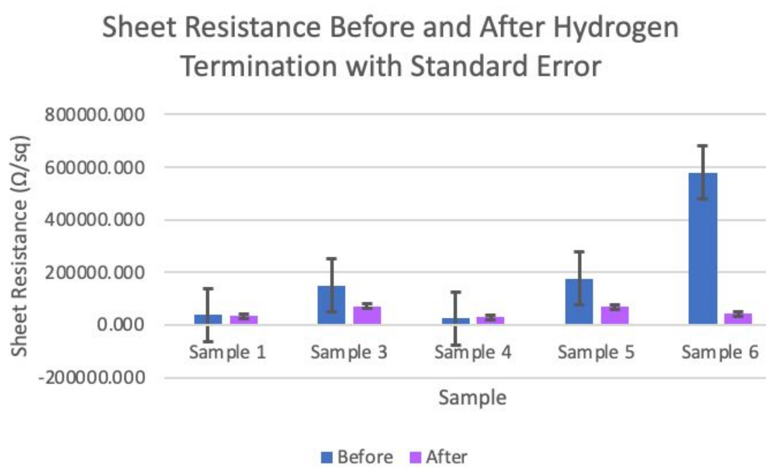
Figure 3. Wafer pieces on platform



Results

Each piece's resistivity was tested before and after MPCVD with an R50 sheet resistance mapper with a four-point probe (Fig. 6). One sample of size 14 had a statistically significant decrease ($p<0.002$) in resistivity after MPCVD and a sample of size 32 had a statistically significant decrease in sheet resistance ($p<0.01$) (paired t-test). The pieces that decreased were edge and mid-center samples. Both center pieces showed very little difference before and after hydrogen termination. One piece, sample 2, was an outlier because it had abnormally high resistivity and sheet resistance measurements, meaning it can be excluded from the data analysis.





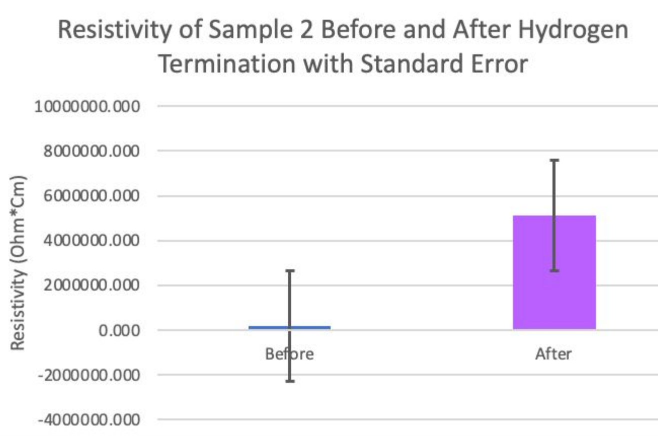


Figure 6. Characterization of electrical properties

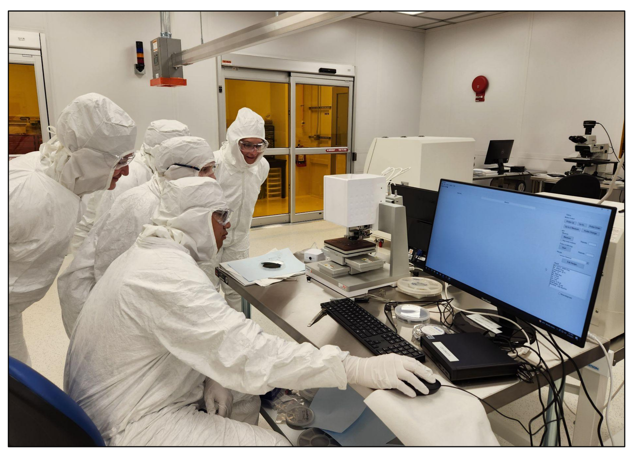


Figure 4. Plasma

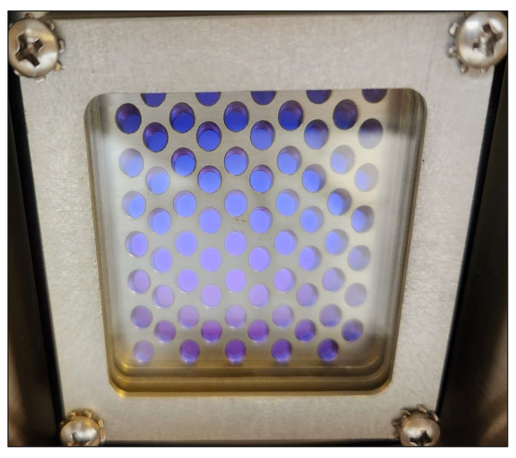
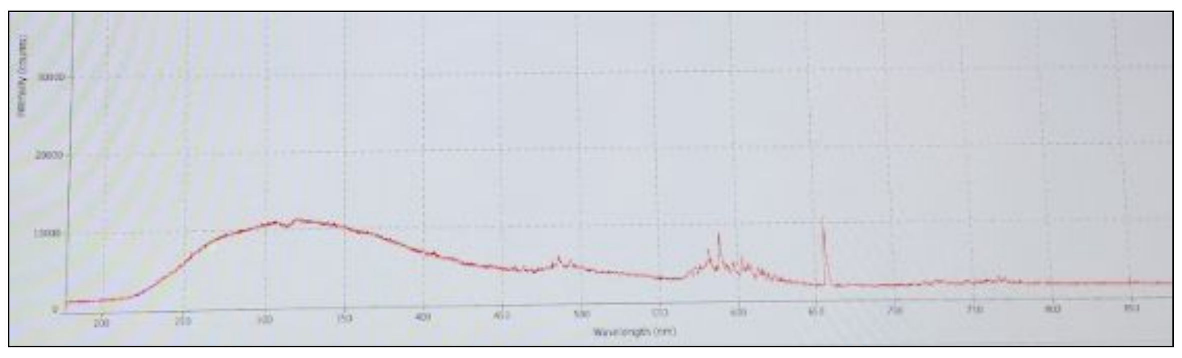


Figure 5. Optical emission spectrometry confirming H-termination (peak at far right is H-alpha peak indicating atomic hydrogen).



Conclusion

- The resistivity showed a statistically significant decrease after H-termination process (n=14).
- The sheet resistance showed both a statistically significant decrease (n=32), but in some cases, stayed the same after H-termination.
- Because the sheet resistance is a surface quality, it could have been affected by exposure to air.
- H-termination process was observed to induce 2DHG layer that reduced the resistivity, but sheet resistance values were not consistent, as they may have been affected by exposure to air.

Next steps

- As transistors and semiconductor junctions are advancing, electronic computing power is increasing.
- This generates more heat which reduces the speed and efficiency of the electronic.
- Diamond has a lot of potential to allow for the advancement of electronics to catch up with their increasing power.
- The next step would be to make surface FET based on 2DHG on nanocrystalline diamond wafer and measure the mobilities to get a better understanding of the performance of devices.

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