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# The electrical and optical properties of thin film diamond implanted with silicon

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## Abstract

The superb mechanical and electrical properties of diamond make it an attractive material for use in extreme conditions. Diamond devices have been fabricated, but the combination of diamond with other materials to form alloys is not yet well-understood. We have investigated the electrical and optical properties of diamond implanted with Si, which is in principle isoelectronic in diamond. The diamond layers were 23  $\mu\text{m}$  thick p-type layers grown on Si(1 0 0) substrates. Silicon was implanted at room temperature, at energy of 300 keV with doses of up to  $8.0 \times 10^{16} \text{ cm}^{-2}$ . A two-stage post-implant anneal process was then performed at 500°C for 30 min, then 800°C for 30 min. Rutherford backscattering spectrometry (RBS) measurements indicated Si concentrations up to 2 at.%, in agreement with simulations of implant profiles. X-ray measurements indicated that about 60–70% of the Si was incorporated substitutionally, corresponding to up to 1.5 at.% from linear interpolation of lattice constants. Raman spectroscopy measurements confirmed that the diamond structure was reconstructed with the post-implant anneal treatment. NEXAFS measurements confirmed the reconstruction of the  $\text{sp}^3$  diamond bonds from  $\text{sp}^2$  graphite after annealing. Electrical measurements indicated an increase in diode current density with increased Si dose and a decrease in contact resistance with contact anneals. These novel diamond alloys may be useful for electronic and optical devices. We report on the preparation and properties of these alloys. © 2001 Elsevier Science B.V. All rights reserved.

**Keywords:** Diamond; Implantation; Alloys; XRD; RBS; Raman; Heterostructure

## 1. Background

As a wide bandgap ( $E_g = 5.45 \text{ eV}$ ) semiconductor material, diamond has promise for use in high-voltage and high-power devices. Diamond layers could function

well as a wide-bandgap emitter, if a suitable second material existed for the formation of heterostructure devices. There are many applications where the superior power handling, friction coefficient, mechanical strength, and exceptional hardness properties of diamond would give an advantage over Si or GaAs technologies. Here we report on a C:Si alloy, formed by the implantation of Si into diamond. Si implantation in diamond has been used at low doses for the

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formation of surface stoichiometric SiC for the improvement of metal contacts [1]. In this case we have larger concentrations of Si that change the lattice structure and other properties, indicating a  $C_{1-x}Si_x$  alloy. This new alloy holds promise as a new material for use with diamond to make new and novel heterostructure devices.

The C:Si alloys were formed by the implantation of Si into polycrystalline diamond films grown by chemical vapor deposition. The diamond film was grown on Si(1 0 0) in a hot filament assisted chemical vapor deposition system. The gases for diamond growth: hydrogen (99.99%), methane (10% in UHP  $H_2$ ) and diborane (2000 ppm in UHP  $H_2$ ) were purified with inline purifiers. The 4" diameter Si(1 0 0) substrate was seeded with diamond by polishing thoroughly with a 2  $\mu\text{m}$  diamond slurry. Following polishing, the silicon wafer was ultrasonically cleaned, dipped in 1:1  $H_2O:HF$  and dried with a stream of dry  $N_2$  before insertion into the diamond growth reactor. The silicon substrate was rotated to ensure uniform diamond film thickness. The diamond film was  $\sim 23 \mu\text{m}$  thick following 229 h of growth. To remove residual graphite and to ensure hydrogen termination, the hydrogen flow was continued with the filament at growth temperature for 30 min after the carbon and boron gas flows were stopped. After the growth was complete, no extra precautions were taken to avoid exposure to air or ambient humidity.

Si was implanted into the diamond layer at an energy of 300 keV and a dose range of  $1 \times 10^{15}$  to  $8 \times 10^{16} \text{ cm}^{-2}$ . Graphitization of the samples after implant was observed from Raman measurements. The samples were then annealed with a two-stage treatment after Prins [2]. The first step was 500°C for 30 min in  $N_2$  ambient. A greater effect on the diamond structure was observed from the partial reconstruction of the Raman spectra than expected from

Prins. Therefore, the second step temperature was lowered from the listed value of 1000 to 800°C for 30 min. Raman spectroscopy and near edge X-ray absorption fine structure (NEXAFS) measurements confirmed that the diamond  $sp^3$  structure was reconstructed after annealing. Rutherford backscattering spectroscopy (RBS) measurements confirmed up to 2% of Si in the implanted samples. X-ray diffraction (XRD) measurements showed an increase in lattice constant, implying that some of the Si was substitutional.

## 2. Analysis

Prior to implantation, baseline scans of XRD, RBS, and Raman were performed for subsequent comparison. An unimplanted diamond sample was also processed along with the Si-implanted samples as a reference. SRIM ion implantation simulations were performed to estimate the Si concentration and depth profile. Samples were implanted with Si as listed in Table 1.

### 2.1. X-ray diffraction (XRD)

X-ray diffraction measurements were performed using a Philips X'Pert MRD materials research diffractometer with a Cu  $K\alpha$  radiation source. The Cu  $K\alpha_1$  radiation is selected by a four-bounce Ge(2 2 0) Bartels monochromator, and a triple-axis output monochromator for high resolution. The system is also equipped with a fully rotational rocking curve stage, which allows measurement of off-axis reflections. Initial XRD measurements showed the films to be highly-ordered polycrystalline, with  $\langle 1\ 1\ 1 \rangle$  being the primary (>75% intensity) orientation (see Fig. 1). Diamond reflections from (1 1 1),

Table 1

A summary of implant conditions and SRIM simulated parameters for the sample set<sup>a</sup>

Sample number	Si dose (at. $\text{cm}^{-2}$ )	SRIM implant depth ( $\text{\AA}$ )	SRIM implant straggle ( $\text{\AA}$ )	SRIM Si concentration (%)
D-13	0 <sup>b</sup>	0	0	0.0
D-14	$1.0 \times 10^{15}$	2158	390	0.026
D-15	$2.0 \times 10^{16}$	2159	391	0.52
D-16	$8.0 \times 10^{16}$	2174	392	2.05

<sup>a</sup> All implants were performed at room temperature and energy of 300 keV.

<sup>b</sup> No implant.

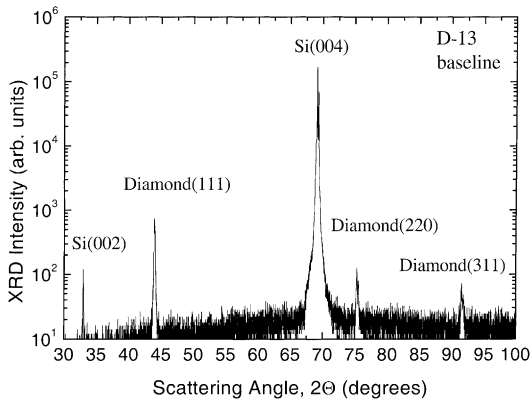


Fig. 1. Baseline  $\theta/2\theta$  XRD scan of unimplanted diamond film. Note the predominance of the  $\langle 111 \rangle$  diamond orientation and  $(004)$  and  $(002)$  reflections of the Si substrate are also present.

$(220)$ , and  $(311)$  were observed with all samples. Also observed were the  $(004)$  and forbidden  $(002)$  reflections of the Si substrate, which are observed because of the large penetration depth of the X-rays. The presence of the forbidden Si $(002)$  reflection may indicate SiC formation or mixing at the diamond/Si interface or perhaps the substrate doping. In each case, the layer reflections are referenced to the Si substrate peak present in each scan. The substrate peak is corrected to the nominal value for Si ( $a = 5.43088 \text{ \AA}$ ). Any correction in  $2\theta$  to the measured Si peak is then applied to the  $2\theta$  value of the layer peak. After implantation there was little change in the peak position. After anneal there was a definite shift of the peak towards a lower  $2\theta$  angle indicating a larger lattice constant (see Fig. 2). This is consistent with substitutional Si incorporation into the diamond lattice as the lattice constant of Si is much larger than that of diamond ( $3.5667 \text{ \AA}$ ). Using Vegard's law, interpolation between the Si and diamond lattice constant yields 1.65 at.% substitutional incorporation of Si. Based on the 2.05% theoretical SRIM concentration, we can estimate 80% substitutional incorporation of Si after anneal. This value is consistent with other measurements as shown later.

## 2.2. Raman spectroscopy

Raman spectroscopy measurements were performed using a green laser system operating in parallel

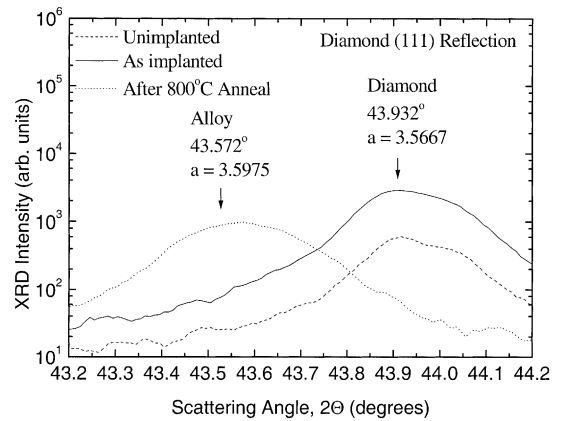


Fig. 2. Comparison of the diamond  $(111)$  XRD peak positions after implantation and anneal. Note the shift to lower angle (larger lattice constant) after anneal. Peak positions and corresponding cubic lattice constant are indicated for the peaks.

orientation. Initial Raman spectroscopy measurement of the samples showed the expected diamond peak at  $1330 \text{ cm}^{-1}$  and a small SiC peak ( $520 \text{ cm}^{-1}$ ). We do not see graphite ( $1520 \text{ cm}^{-1}$ ) peaks, indicating true diamond growth and graphite removal. After implantation, we see the amorphitization of the sample as expected for our high implant doses (Fig. 3, dotted curve). No peaks are evident, save a wide broad signal around the diamond/graphite energy range. After the first anneal step (Fig. 3, dashed curve), some evidence of reconstruction of the lattice was evident. Also appearing is a Si peak at  $485 \text{ cm}^{-1}$ . We believe this to be due to weakly ordered Si bonds which would manifest themselves at slightly lower energy than the ordered  $520 \text{ cm}^{-1}$  peak. Since this partial reconstruction is significantly more than expected from the literature, we chose to lower the second anneal step temperature from  $1000$  to  $800^\circ\text{C}$ , to avoid dissipation of the dopant. After the second ( $800^\circ\text{C}$ ) anneal step, we see full reconstruction of the diamond structure, with no graphite present (Fig. 3, solid curve). This result indicates that reconstruction is possible for implant doses that exceed the previously reported limits for the critical 'amorphitization threshold' of  $1\text{--}6 \times 10^{15} \text{ cm}^{-2}$  listed in the literature [3] for low temperature implantation. This suggests that the Si behaves differently than a dopant and seems to be more favorably incorporate into the diamond lattice.

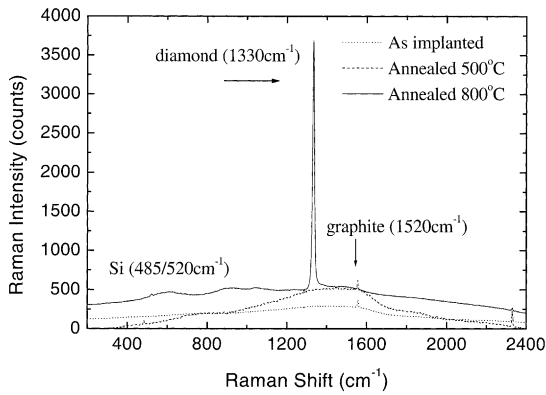


Fig. 3. Raman spectroscopy measurements of sample D-16. The dotted curve shows the amorphitization of the diamond into graphite after implantation. The dashed curve shows the partial reconstruction of the diamond and graphite phases after the first step of the anneal (500°C). The solid curve illustrates the reconstruction of the diamond lattice structure after the second stage of the anneal (800°C). Peaks at 1550 and 2330  $\text{cm}^{-1}$  are  $\text{N}_2$  and  $\text{O}_2$ , which are present in air in the beam path near the sample stage.

### 2.3. Rutherford backscattering spectrometry (RBS)

Rutherford backscattering spectrometry measurements were done in vacuum with a 2 MeV He-ion source. The data was then fit with the RUMP software analysis package. After implantation, RBS measurements verify the implantation of about 2% of Si at a depth of 2500 Å, which is in good agreement with the

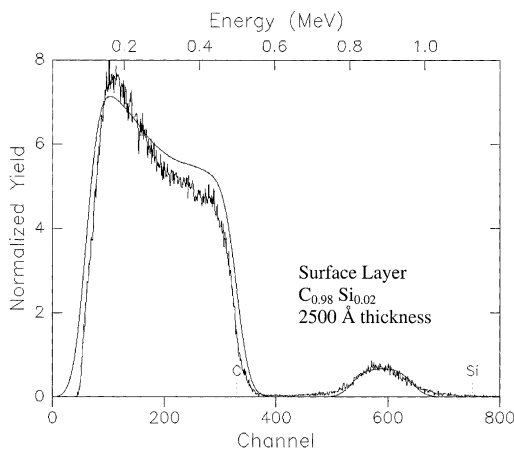


Fig. 4. RBS measurement of sample D-16 after implant. The RUMP fit to the data is shown. The datafit yields an implant layer with depth of 2500 Å and concentration of  $\text{C}_{0.98}\text{Si}_{0.02}$  as indicated.

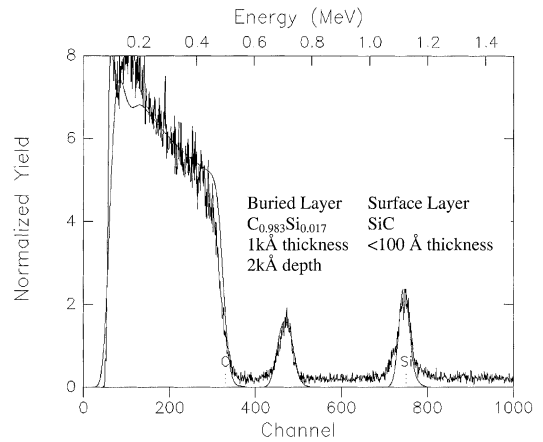


Fig. 5. RBS measurement of sample D-16 after second anneal step (800°C). The RUMP fit to the data is shown. Note the incorporation of Si into the diamond lattice at the implant depth, and some diffusion of Si to the surface. RUMP datafit yields a surface SiC layer with thickness of approximately 100 Å and a buried layer of concentration  $\text{C}_{0.983}\text{Si}_{0.017}$  at a depth of 2 kÅ.

SRIM simulations (see Fig. 4 for the RBS data after implant). After anneal (Fig. 5) RBS suggests that some of the Si has diffused through the grainy polycrystalline diamond structure to the surface. A thin layer of roughly 100 Å of SiC was formed at the surface. We also see a buried layer where the Si has incorporated into the reconstructed diamond lattice. RUMP simulation yields a concentration of  $\text{C}_{0.983}\text{Si}_{0.017}$ , which is in agreement with the XRD measurements.

### 2.4. Near edge X-ray absorption fine structure (NEXAFS)

Near edge X-ray absorption fine structure measurements of sample D-14 and D-16 were performed after the second anneal (800°C) (see Fig. 6 for a plot of the NEXAFS data). The 292.6, 297.8, and 305.2 eV peaks correspond to  $\text{sp}^3$  bonds, which comprise the diamond lattice. The 285.6 eV peak corresponds to the graphite  $\text{sp}^2$  bond. Note the dominance of the  $\text{sp}^3$  bonds, which confirms the reconstruction of the diamond lattice. The graphite bonds may occur in the diffused SiC layer on the surface.

### 2.5. Electrical characterization

Electrical contacts were formed by e-beam evaporation of Ti/Au directly onto the front and backside

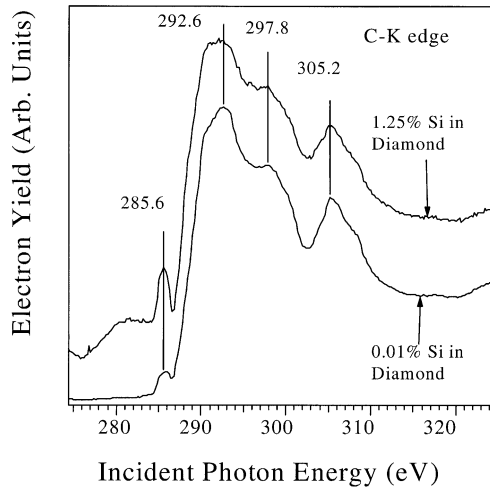


Fig. 6. Plot of NEXAFS measurement of sample D-14 and D-16 after second anneal (800°C). The 292.6, 297.8, and 305.2 eV peaks correspond to  $sp^3$  bonds, which are dominant over the 285.6 eV  $sp^2$  bond peak.

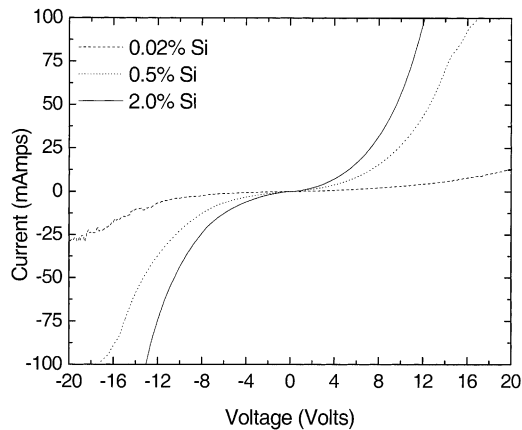


Fig. 7. Plot of current–voltage characteristics of diamond heterostructure diodes after contact anneal (450°C). Note the increase in current with Si dose.

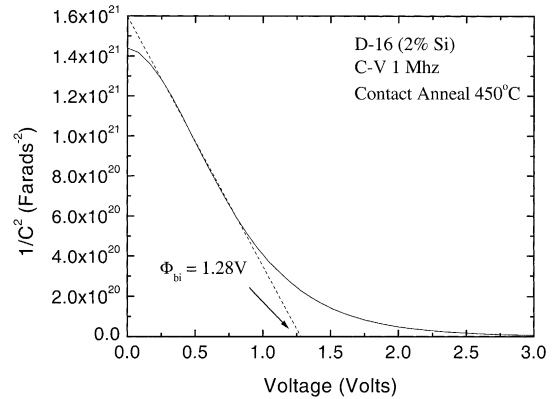


Fig. 8. Plot of capacitance–voltage characteristics of diamond heterostructure diodes after contact anneal (450°C). The extrapolated built-in voltage was found to be 1.28 V.

f the wafer. The contacts were then annealed in a RTA to 450°C. Devices were formed using a simple circular diode structure, with the backside of the sample as a large area contact. Current–voltage measurements were performed using a Hewlett Packard 4156 parameter analyzer. The  $I$ – $V$  data was taken before and after contact annealing for comparison. The  $I$ – $V$  data after contact anneal is plotted in Fig. 7. One should note the clear trend of increasing current with Si concentration. There is also a trend in increasing rectification ratio (forward current/reverse current) with increased Si concentration, indicating hetero-junction behavior (Table 2).

Capacitance voltage measurements were performed using a Hewlett Packard 4284A precision LCR meter in conjunction with the 4156 parameter analyzer. The  $C$ – $V$  measurements were performed on the same circular diode structures. Then,  $C$ – $V$  data was taken at a range of frequencies from 100 Hz to 1 MHz (see Fig. 8 for a plot of  $1/C^2$  versus voltage for sample D-16 and extrapolated value of  $\Phi_{bi}$  at 1 MHz). The

Table 2

A summary of the current–voltage characteristics of the heterostructure diodes

SRIM Si concentration (%)	Forward current (8 V) (mA)	Reverse current (8 V) (mA)	Rectification ratio
0.026	2.53	2.49	1.02
0.52	15.52	12.73	1.22
2.05	31.56	24.33	1.30

incorporation of Si into the diamond was also found to lower the built-in voltage, but the trend was not as clear as with the  $I$ - $V$  measurements.

### 3. Conclusions

In this paper we report on a new C:Si alloy formed by ion implantation and annealing. RBS and XRD measurements confirm the substitutional incorporation of Si into the diamond at concentrations of up to 1.7%. Raman and NEXAFS measurements confirm the reconstruction of the diamond lattice even at dose levels above the previously published ‘amorphitization limit’. C:Si heterostructure devices have been fabricated and tested. The incorporation of Si into the diamond has been shown to increase currents and decrease the built-in voltages of the heterostructure

diodes. These novel diamond alloys may prove useful for electronic and optical devices.

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