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Resistance-Temperature Characteristics of Polycrystalline Diamond/Silicon Wafer Structure

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A layered structure consisting of diamond thin film was fabricated on a silicon wafer and its temperature-resistance characteristics were studied. For deposition of the diamond thin film, a microwave plasma chemical vapor deposition technique was employed. The X-ray diffraction patterns showed that the film was polycrystalline. The current-voltage characteristics of the layered structure, consisting of undoped diamond thin film fabricated on a silicon wafer, showed strong temperature dependence. The thermistor constant of this structure was about 10,000. The current-voltage characteristics of the layered structure, which consists of boron-doped diamond thin film fabricated on an n-type silicon wafer, showed rectifiability and strong temperature dependence. The thermistor constant of the boron-doped diamond/silicon structure was about 5,000.

1. Introduction

Diamond thin films have been receiving much attention as electronic devices (sensor elements) that can be used at high ambient temperatures and in a reactive environment, because of their eminent characteristics of thermal and chemical stability and wide band gap.(1–5)

In this paper, the resistance-temperature characteristics of polycrystalline diamond/Si structure deposited by the microwave plasma chemical vapor deposition technique are described. Diamond thin films have already been studied as thermistor elements.(1) Since they are planar devices, they require many processes and are difficult to miniaturize. In comparison with these thermistors, the layered structures are advantageous in that a lateral device structure can be fabricated easily and that they are small in size. In this paper, it is shown that the diamond/Si structures exhibit useful characteristics for studying the feasibility of using diamond devices in practical applications, such as thermal sensor fabrication.

2. Materials and Methods

The layered structure fabricated in this study is shown in Fig. 1. The structure, called a diamond/Si structure, consists of a Ti thin-film electrode and a diamond layer, fabricated on a low-resistivity Si wafer. An Au thin-film electrode was fabricated on the opposite side of the Si wafer. Undoped, B-doped and P-doped diamond thin films were used for these layered structures. N-type Si <100> wafers were used for the synthesis of undoped and B-doped diamond thin films, and p-type Si <100> wafers were used for the synthesis of P-doped diamond thin films. The resistivity of these Si wafers was less than 0.01 Ω·cm.

For synthesis of diamond thin films, a Si wafer substrate was cut 10 mm × 10 mm in size. The substrate was scratched with diamond powder of 28-μm average size for 20 min using an ultrasonic cleaner. A microwave plasma chemical vapor deposition technique was employed to deposit diamond films.(6–10) A schematic diagram of the deposition apparatus is shown in Fig. 2. A silica glass tube 60 mm in diameter, put into the sleeves attached to the guide tube, served as the deposition chamber. Microwaves (2.54 GHz) generated by the magnetron were transmitted to the chamber through a set of waveguides, a power monitor and a tuner. The position of the plasma was adjusted to the center of the deposition chamber where the substrate was held by a Si plate. A deposition was performed by introducing a gas mixture into the chamber and then applying microwave power to excite a glow discharge. For diamond synthesis, CH_4, B_2H_6, PH_3 and H_2 were used. The temperature of the substrate was measured by an optical pyrometer. The conditions for diamond layer synthesis are shown in Table 1. The X-ray diffraction patterns showed that the films prepared under these conditions were polycrystalline.

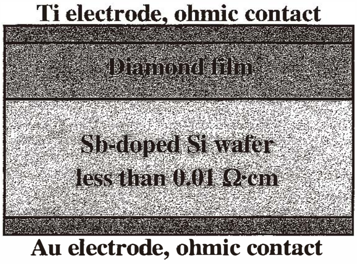

Fig. 1. Cross-sectional view of the layered structure.

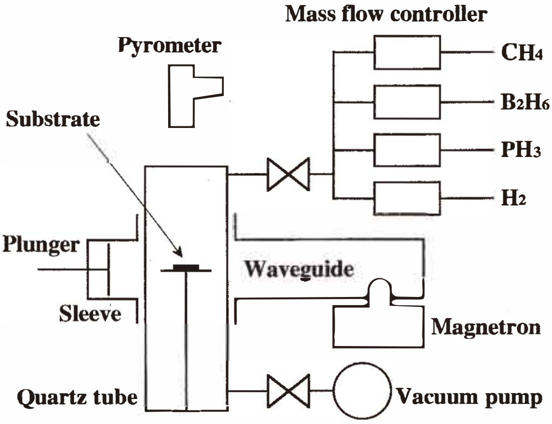

Fig. 2. Schematic diagram of the microwave plasma chemical vapor deposition apparatus.

Table 1
Conditions for diamond layer synthesis.

undoped diamond film	
flow rate of H_2	200 sccm
flow rate of CH_4/H_2	0.7%
gas pressure	5 kPa
microwave power	400 W
substrate temperature	870°C
deposition period	210–2,000 min
B-doped diamond film	
flow rate of H_2	200 sccm
flow rate of CH_4/H_2	0.7%
flow rate of B_2H_6/CH_4	100 ppm
gas pressure	5 kPa
microwave power	400 W
substrate temperature	870°C
deposition period	640 min
P-doped diamond film	
flow rate of H_2	200 sccm
flow rate of CH_4/H_2	0.15%
flow rate of PH_3/H_2	1, 300,5,000 ppm
gas pressure	5 kPa
microwave power	500 W
substrate temperature	970°C
deposition period	785, 700 min

To obtain undoped diamond layers with different thicknesses for diamond/Si structures, deposition periods of 210 min, 500 min, 700 min and 2,000 min were employed. The estimated layer thicknesses were about 1.4 μm, 2.6 μm, 4.2 μm and 14 μm, respectively. The resistivity of undoped diamond films was about 8×10^{11} Ω·cm.

For the B-doped diamond/Si structure, a diamond deposition period of 640 min and a B/C ratio of 200 ppm (a B_2H_6/CH_4 ratio of 100 ppm) were employed. The estimated layer thickness was about 4.7 μm, and the resistivity of the B-doped diamond film was about 8×10^3 Ω·cm.

For the P-doped diamond/Si structure, a diamond deposition period of 785 min at a P/C ratio of 1,300 ppm, and 700 min at 5,000 ppm, were employed. The estimated layer thicknesses were about 2.1 μm and about 1.5 μm, respectively. The resistivities were about 1×10^5 Ω·cm and about 4×10^4 Ω·cm, respectively.

For metallization, a 0.5-μm-thick Ti film as an ohmic contact to diamond, and a 0.1-μm-thick Au film as an ohmic contact to Si, were deposited by sputtering, and then the samples were annealed at 400°C for 20 min in vacuum. Finally, the samples were cut into 3 mm × 3 mm pieces.

3. Results and Discussion

3.1 *Undoped diamond/Si structure*

The current-voltage characteristics of undoped diamond/Si structures showed non-linearity and were slightly rectifiable, maybe because of interface characteristics between the diamond and Si substrate. Non-linearity and rectification decreased with increasing diamond layer thickness, because of a series resistance effect of the diamond layer.

The resistance-temperature characteristics of diamond/Si structures with different diamond layer thicknesses are shown in Fig. 3. The resistance was calculated using the current under a bias of 1 V. The current direction was from the Au electrode to the Ti electrode. Since the resistance of the sample with a 4.2-μm-thick diamond layer is almost the series resistance of the diamond layer, the resistance is expressed as

$$R = R_0 \exp\left(B\left(\frac{1}{T} - \frac{1}{T_0}\right)\right), \tag{1}$$

where R_0 is the resistance at T_0, and B is the thermistor constant. The thermistor constant calculated from Fig. 3 was about 10,300. This value is almost the same as the thermistor constant of undoped diamond already reported.(1) Since the resistance of the sample with a 14-μm-thick diamond layer is also almost the series resistance, the resistance should be expressed as eq. (1). However, this is not expressed as eq. (1), because the resistance at room temperature is smaller than expected. This is caused by the measurement problem that small current measurements, below 1×10^{-10} A, are too difficult using this equipment. The thermistor constant calculated from the resistance above 150°C is almost the same as that of the sample with a 4.2-μm-thick diamond layer. On the other hand, the resistance of the sample with a 2.6-μm-thick or 1.4-μm-thick diamond layer did not follow eq. (1). The resistance of the diamond layer was the sum of the diamond crystalline resistance, the grain

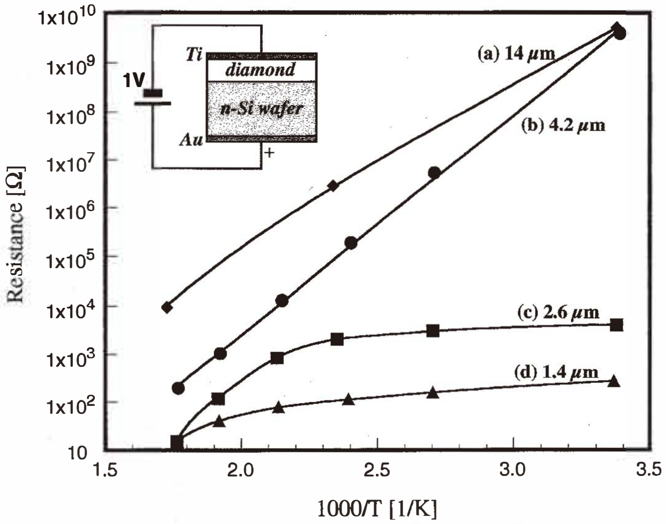

Fig. 3. Resistance-temperature characteristics of the undoped diamond/Si structure with different diamond layer thicknesses of (a) 14 μm, (b) 4.2 μm, (c) 2.6 μm and (d) 1.4 μm.

boundary resistance, and the defect resistance of the diamond layer. Since it was considered that the grain boundary resistance and the defect resistance are main for thin diamond layer samples, and that these resistances have a low resistance-temperature coefficient, the curves of these samples in Fig. 3 were non-linear.

The results show that an undoped diamond/Si structure with a diamond layer of above about 4 μm thickness, can be applied to a highly sensitive thermal sensor. Furthermore, by increasing diamond layer thickness, it is possible for a thermal sensor to be used at high ambient temperatures.

3.2 *B-doped diamond/Si structure*

The current-voltage characteristics of the B-doped diamond/Si structure at various ambient temperatures are shown in Fig. 4. The estimated layer thickness of the B-doped diamond layer was about 4.7 μm, and the resistivity was about 8×10^3 Ω·cm. In the figure, the current direction from the Ti thin film electrode to the Si substrate was forward. The current-voltage characteristics showed non-linearity, strong temperature dependence and rectifiability. Non-linearity and rectification decreased with increasing ambient temperature. In the case of the p-type Si substrate, the current-voltage characteristics showed no non-linearity and were not rectifiable. These results indicate that the B-doped diamond/n-type Si interface shows p-n junction characteristics.

The resistance-temperature characteristics of the B-doped diamond/Si structure at various bias voltages are shown in Fig. 5. The resistance-temperature curves roughly followed eq. (1). The thermistor constants calculated from Fig. 5 were about 5,000, 2,400

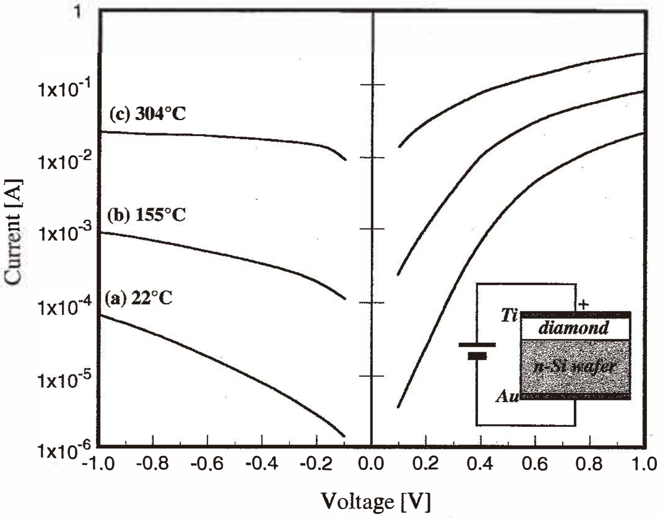

Fig. 4. Current-voltage characteristics of B-doped diamond/Si structure at various ambient temperatures of (a) 22°C, (b) 155°C and (c) 304°C.

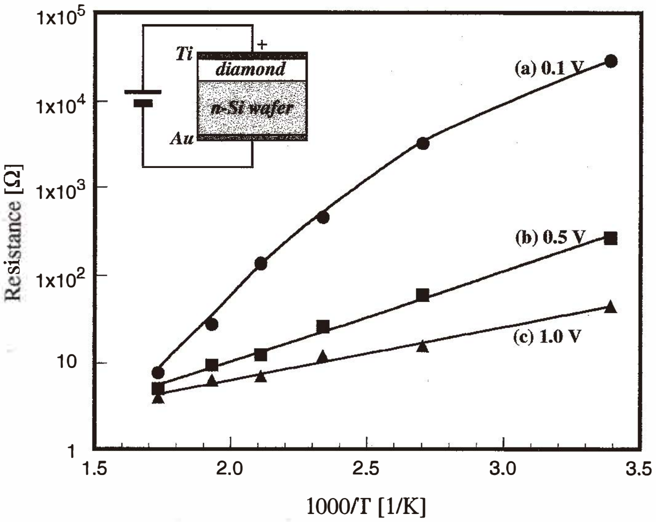

Fig. 5. Resistance-temperature characteristics of the B-doped diamond/Si structure under various bias voltages of (a) 0.1 V, (b) 0.5 V and (c) 1.0 V.

and 1,400, under bias voltages of 0.1, 0.5 and 1.0 V, respectively. It was considered that the resistance-temperature coefficient of interface resistance between B-doped diamond and n-type Si under the bias voltage of 0.1 V was higher than that under the bias voltage of 1.0 V, because the p-n junction was almost off at the bias voltage of 0.1 V. Furthermore, it was considered that the resistance-temperature coefficient of interface resistance between B-doped diamond and n-type Si under the bias voltage of 0.1 V was higher than that of the B-doped diamond layer. Therefore, the B-doped diamond/Si structure under the bias voltage of 0.1 V shows a high thermistor constant.

These results show that the B-doped diamond/Si structure can be applied to a highly sensitive, wide-temperature-range thermal sensor.

3.3 *P-doped diamond/Si structure*

The current-voltage characteristics of the P-doped diamond/Si structure at various ambient temperatures are shown in Fig. 6. The estimated layer thickness of the P-doped diamond layer was about 2.1 μm, and the resistivity was about 1×10^5 Ω·cm. In the figure, the current direction from the Ti thin-film electrode to the Si substrate was forward. The current-voltage characteristics showed non-linearity, strong temperature dependence and rectifiability. Non-linearity and rectification decreased with increasing ambient temperature. The current-voltage characteristics of the P-doped diamond/Si structure that had an estimated P-doped diamond layer thickness of about 1.5 μm and a resistivity of about 4×10^4 Ω·cm shows the same tendency. However, the degrees of non-linearity and rectification were smaller than those of the sample illustrated in Fig. 6. In the case of an n-type Si

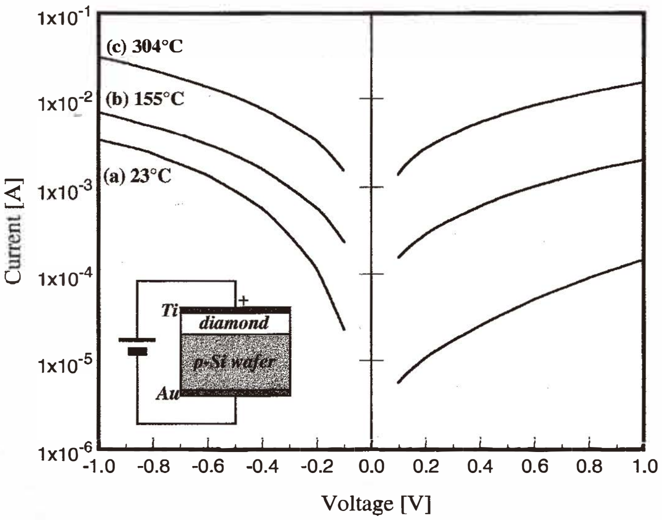

Fig. 6. Current-voltage characteristics of the P-doped diamond/Si structure at various ambient temperature, (a) 23°C, (b) 155°C and (c) 304°C.

substrate, the current-voltage characteristics showed no non-linearity and they were not rectifiable. These results indicate that the P-doped diamond/p-type Si interface shows p-n junction characteristics.

The resistance-temperature characteristics of P-doped diamond/Si structures roughly followed eq. (1). The thermistor constants of the samples of P-doped diamond layers with resistivities of 1×10^5 and 4×10^4 Ω·cm, were about 2,500 and 1,600, respectively. The bias voltage was -0.1 V, and the current direction was from the P-doped diamond layer to the p-type Si substrate.

This proves that the P-doped diamond/Si structure can also be applied to a highly sensitive, wide-temperature-range thermal sensor.

4. Conclusion

The thermistor constant of a polycrystalline undoped diamond/Si structure with a 4.2-μm-thick diamond layer was about 10,300. This indicates that an undoped diamond/Si structure with a diamond layer of above about 4 μm thickness may be applied to a highly sensitive thermal sensor. Furthermore, by increasing diamond layer thickness, this structure may be applied to a thermal sensor to be used at high ambient temperatures.

The current-voltage characteristics of the doped diamond/Si structure showed non-linearity and strong temperature dependence. The thermistor constant of a B-doped diamond/Si structure was about 5,000 under the bias voltage of 0.1 V. This shows that the doped diamond/Si structure can be applied to a highly sensitive, wide-temperature-range thermal sensor.

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