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Superconducting Boron-doped Diamond Josephson Junction Operating above Liquid He Temperature, 4.2 K

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Abstract

We fabricated intermittent (111) boron-doped diamond structure Josephson junctions. The temperature dependence of resistance shows two-step superconducting transition at 10.2 K and 7.0 K. Also we confirmed DC and AC Josephson-effect up to 7.0 K. Shapiro steps were observed very clearly at 4.2 K and the interval of steps agreed well with the theoretical value. These results indicate that this Josephson junction operates above liquid He temperature, 4.2 K.

1. Introduction

Diamond shows superconductivity by doping with boron at concentration of more than 3×10^{20} [cm^{-3}] [1, 2]. Superconducting transition temperature (T_C) of boron-doped diamond depends on boron concentration and plane orientation [3, 4]. T_C of (111) diamond doped with boron at concentration of 8×10^{21} [cm^{-3}] is 10 K. This value is comparable to that of NbTi widely applied as superconducting devices. In addition, since diamond has high tolerance to heat, acid and abrasion, it is expected to be applied to robust superconducting devices. One of them is Superconducting Quantum Interference Device (SQUID) which is possible to detect small magnetic fields with high sensitivity. We have been working on the production of Josephson junction [5] and demonstrated the operation of single crystal diamond SQUID by step-edge structure Josephson junction [6]. Since this junction includes (001) plane with T_C = 4 K, operating temperature is also 4 K or less. In this research, in order to improve the operating temperature, we report fabrication and measurement of Josephson junction composed of only (111) growth layer with T_C = 10 K.

2. Experiments

We fabricated Josephson junction with weak link in intermittent (111) plane as shown in Fig.1. High Pressure and High Temperature (HPHT) (111) single crystal diamond was used for the substrate. First, trench was formed on the substrate by Focused Ion Beam (FIB) method. The dose amount of FIB was set to 1.0 [nC/μm^2]. After that, a superconducting boron-doped diamond layer with a thickness of 500 [nm] and a selected width of 36 [μm] region was grown epitaxially across the trench by Micro-wave Plasma enhanced Chemical Vapor Deposition (MPCVD) method. This junction had weak links in intermittent (111) plane on the trench. (111) boron-doped diamond on the trench was observed by Scanning Electron Microscopy (SEM). As for electrical properties, we measured the temperature dependence of resistance from 2 K to 300 K and current voltage (*I-V*) characteristic in order to confirm DC Josephson-effect. AC Josephson-effect was confirmed by observation of Shapiro steps.

3. Results

We show a SEM image of the trench part of the fabricated Josephson junction in Fig.2. It can be confirmed that (111) boron-doped diamond layer was intermittently grown on the trench. Weak links were formed between the interfaces of the intermittent (111).

The inset of Fig.3 shows the temperature dependence of resistance from 2 K to 300 K, and the resistance decreased sharply around 10 K. Fig.3 shows from 2 K to 12 K, and two-step superconducting transition was observed. The transitions at 10.2 K and 7.0 K correspond to T_C of the boron-doped diamond grown from the substrate and the trench respectively. T_C = 7.0 K of this junction is higher than that of conventional step-edge structure Josephson junction (3.5 K), and it means this junction can operate above liquid He temperature, 4.2 K, which is the highest in diamond superconducting devices.

Fig.4 shows *I-V* characteristics of Josephson junction at 4.2 K and 7.0 K. Since direct current flew without voltage drop, the DC Josephson-effect was observed. Both *I-V* characteristics had no hysteresis. Critical current (I_C) was 0.025 [mA] and I_CR_n showing the characteristic of the junction was 0.125 [mV] at 4.2 K. This value is close to that of Nb and other junctions used presently.

Shapiro steps were observed much more clearly compared with our former result [5] by *I-V* characteristic with micro-wave radiation of frequency f = 25 [GHz] at 4.2K as shown in Fig.5 When the Josephson junction is irradiated with micro-wave from the outside, *I-V* characteristic changes stepwise every $V = V_n$. V_n is given by

$$V_n = \frac{nhf}{2e} \quad (n = \pm 1, 2 \dots) \qquad (1)$$

where h is plank constant, f is frequency and e is elementary charge. $V_n = 0.052n$ [mV] is obtained at f = 25 [GHz], which are the dotted line in Fig.5. It is clear that the interval between the steps agrees with the theoretical value. This steps are called Shapiro steps and said to be a proof of AC Josephson-effect. Also, Shapiro steps were observed not only at 4.2 K but also up to 7.0 K. These results confirmed the AC Josephson-effect above liquid He temperature, 4.2 K.

4. Conclusions

We fabricated intermittent (111) structure composed of only (111) diamond and observed two-step superconducting transition at 10.2 K and 7.0 K. In addition, *I-V* characteristics with no hysteresis were observed at 4.2 K and 7.0 K. $I_C R_n$ at 4.2 K was comparable to that of Nb superconductor. Furthermore, Shapiro steps were observed very clearly at 4.2 K by micro-wave irradiation. These results indicate that this Josephson junction can operate above liquid He temperature, 4.2 K. The improvement of operating temperature of diamond SQUID can be also expected.

Acknowledgements

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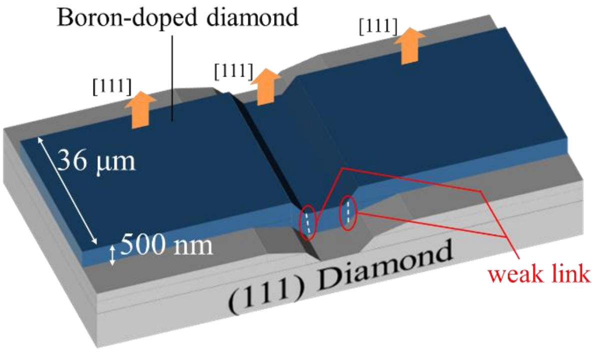

Fig.1 Intermittent (111) structure Josephson junction

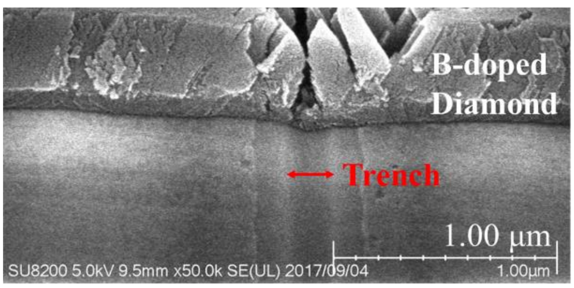

Fig.2 SEM image of the trench part of intermittent (111) structure

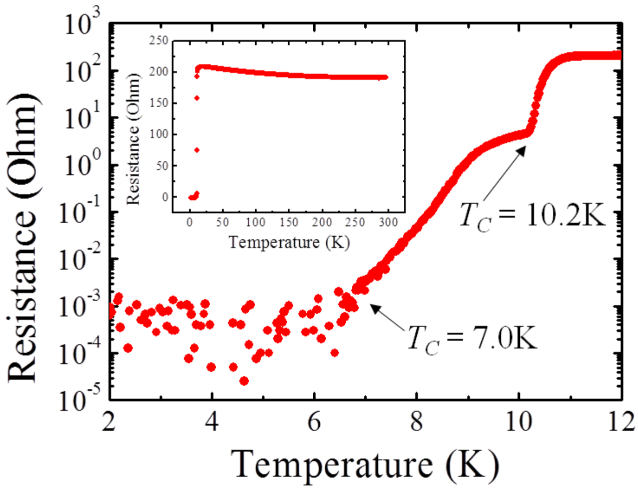

Fig.3 Temperature dependence of resistance

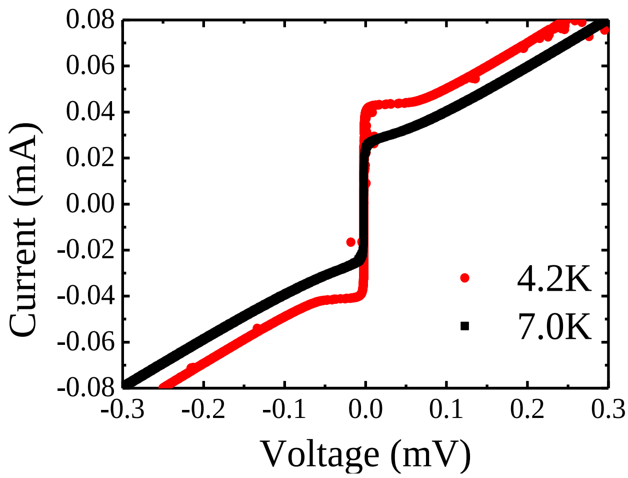

Fig.4 *I-V* characteristics at 4.2 K and 7.0 K

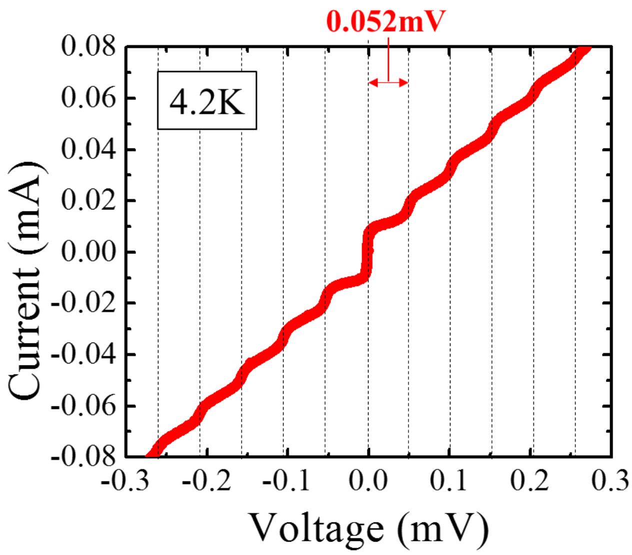

Fig.5 Shapiro steps at 4.2 K