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Boron-doped Diamond Superconducting Quantum Interference Devices with Two Step-Edge Josephson Junctions

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Abstract

We fabricated diamond superconducting quantum interference devices (SQUIDs) with two step-edge Josephson junctions. Cross sectional Transmission Electron Microscope observation of the junction showed the step-edge structure was composed of single crystalline diamond, although there are a few defects at the slope region. Temperature dependence of resistivity showed two superconducting transition points at 9K and 3.5 K, whose values correspond to the transition temperature of (111) and (001) diamond, respectively. We confirmed SQUID operation by voltage modulation with a period of one flux quantum.

1. Introduction

Superconducting quantum interference devices (SQUIDs) are widely used as sensors that can detect small magnetic fields up to femto-tesla with high sensitivity, which are composed of superconductive loop with one or two Josephson junctions. Scanning SQUID microscope (SSM) that can obtain high resolution magnetic images is studied [1]. Superconducting materials such as Niobium (Nb) and $YBa_2Cu_3O_7$, which are used SQUIDs, are fragile and weak to acid and thermal. This is why SQUIDs can be broken during raster scan.

Diamond shows superconductivity when the doped boron concentration is more than 3×10^{20} cm^{-3} [2] [3]. Superconducting transition temperature (T_c) depends on boron concentration and epitaxial growth orientation [4] [5]. T_c of (111) diamond with doping concentration 8×10^{21} cm^{-3} is 10K, which is equal to that of Nb compounds commonly used for superconducting applications. In addition to the above superconducting properties, superconducting diamond is so hard and resistant to heat and acid that diamond is the best materials for robust SSM. There is only one report as for diamond SQUIDs [6]. However, operating temperature is as low as 400mK because of nano-bridge structure made from polycrystalline.

We valuated crystallinity cross sectional TEM image of Josephson junction and observed voltage modulation of a SQUID.

2. Experimental Details

We fabricated diamond SQUIDs with two step-edge Josephson junctions (Fig. 1). The Josephson junction has weak link structure and it is formed by boundary between (111) and (001) diamond. The fabrication process is described below. Ib (111) diamond substrate was selectively etched by reactive ion etching using O_2 gas to form a step with the height of 230nm. Then, un-doped diamond layer of 200 nm was epitaxially grown by microwave plasma-assisted chemical vapor deposition (MPCVD) method to form (001)-oriented diamond at the step region. The superconducting boron-doped layer of 200 nm was deposited selectively by MPCVD method. Step-edge structure was observed by scanning electron microscope (SEM) and its crystallinity was evaluated by transmission electron microscope (TEM). Temperature dependence of the resistivity from 300K to 2.5K was measured to decide the operating temperature of the SQUID. We measured the voltage of the SQUID under the magnetic field by placing the diamond substrate on a holder provided with a coil for magnetic field application.

3. Results and Discussion

Fig. 2 shows SEM image of the step-edge structure. The slope between two (111) diamond surfaces is confirmed to be (001). The angle between growth-induced plane and (111) plane is about 55°, which corresponds to that of (001) and (111). diamond.

Cross sectional TEM image of a step-edge structure is shown in Fig. 3. A boundary was formed between (001) and (111) growth sector of diamond, some contrast induced by defects seems to exist densely in the (001) sector in Fig.3(b). Inset 1) of Fig.3 shows the diffraction pattern of step region and it revealed that the step region was single crystalline with no planar defects like twins or stacking faults. Considering from the TEM image and diffraction pattern, Josephson effect was mainly derived from sector boundary between (111) and (001) diamond, but the defects in step region also slightly affect the formation of Josephson junction.

Fig.4 shows the temperature dependence of resistivity of the SQUID measured from 2K to 300K. Two superconducting transition points at 9K and 3.5K are observed. These values seem to correspond to the transition temperature of (111) and (001) diamond, respectively.

I-V characteristic of the SQUID at 2.6K without hysteresis is shown in Fig. 5. Critical current is 0.32 mA and $IcRn$ is 0.32 mV. This shape is called over-dumped type and it indicates the Josephson junction is caused by weak link structure.

Fig. 6 shows magnetic field dependence of voltage of the SQUID at 2.6K. The periodic oscillation of the voltage as a function of the magnetic field has been seen with a period of 2.9 μT. Theoretically, this value corresponds to a flux quantum $\phi_0 = h/2e = 2\times10^{-15}\,Wb$. The period calculated from SQUID size and flux quantum ϕ_0 is 2.0 μT, which is close to the period measured experimentally. Measured voltage amplitude ΔV was 1.2 μT. This value is higher than that of polycrystalline diamond SQUID [6].

3. Conclusions

We measured boron-doped diamond SQUID with two step-edge Josephson junctions. SEM, TEM observation and RT measurement revealed (001) sector was grown at slope and it has defects there. The Josephson effect seems to be caused by not only the interface between (001) layer and (111) layer but the defects in (001) region. The SQUID shows the voltage modulation as a function of the magnetic field at 2.6K. The periodic oscillation of the voltage has been observed with a period of 2.9 μT and voltage amplitude ΔV was 1.2 μT. These results showed possibility that boron-doped diamond SQUID can use for SSM.

Acknowledgements

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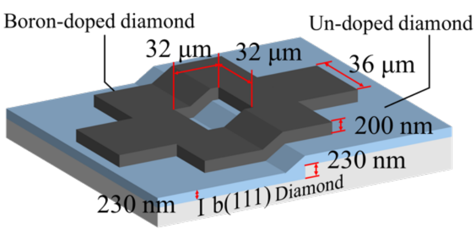

Fig. 1 Diamond SQUID with two step-edge Josephson junction

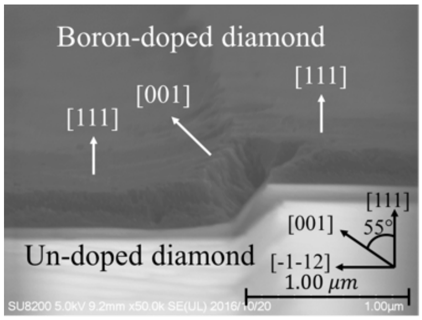

Fig. 2 SEM image of the step-edge structure of the SQUID

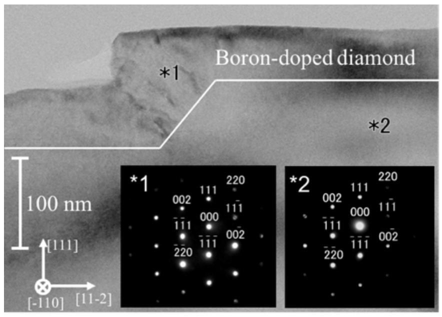

Fig. 3 Cross section TEM image of step-edge structure and diffraction patterns of 1) step region and 2) (111) substrate region.

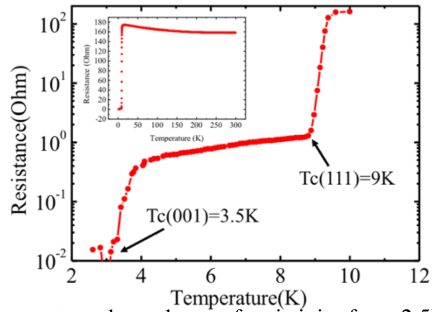

Fig. 4 Temperature dependence of resistivity from 2.5K to 300K

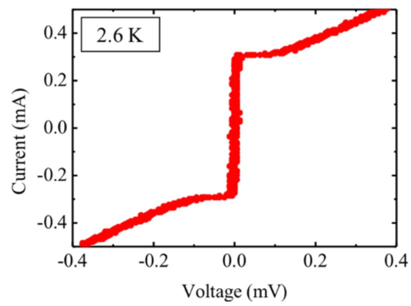

Fig. 5 The current voltage (*I-V*) characteristic at 2.6K

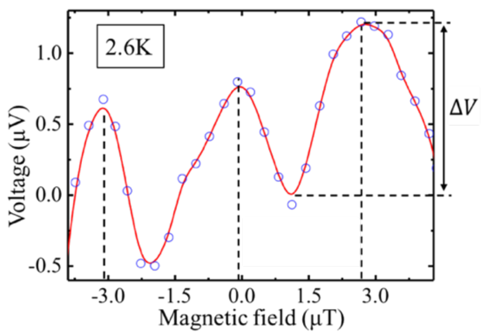

Fig. 6 Magnetic field dependence of Voltage at 2.6K