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Diamond Superconducting Quantum Interference Devices with New Structure of Josephson Junctions for Magnetic and Quantum Application

Yasuhiro Takahashi[1], Shotaro Amano[1], Aoi Morishita[1], Taisuke Kageura[1, 2], Yoshihiko Takano[3], Minoru Tachiki[3], Shuuichi Ooi[3], Shunichi Arisawa[3] and Hiroshi Kawarada[1, 4]

[1] Faculty of Science & Engineering, Waseda Univ.
3-4-1 Okubo, Shinjuku-ku, Tokyo, 169-8555, Japan
Phone: +81-3-5286-3391 E-mail: takayasu_takkyuu@akane.waseda.jp
[2] MANA National Institute for Materials Science
1-1 Namiki, Tsukuba, Ibaraki, 305-0044, Japan
[3] MANA National Institute for Materials Science
1-2-1 Sengen, Tsukuba, Ibaraki, 305-0047, Japan
[4] The Kagami Memorial Research Institute for Materials Science and Technology, Waseda University
2-8-26 Nishiwaseda, Shinjuku-ku, Tokyo 169-0051, Japan

Abstract

We fabricated boron-doped diamond superconducting quantum interference device (SQUID) with Josephson junctions (JJs) utilizing shallow steps on the substrate. The SQUID operations were confirmed from 6.0 K to 9.5 K. In addition, comparing to previously reported diamond SQUID, this type of SQUID shows higher uniformity and reproducibility of characteristics.

1. Introduction

Superconducting quantum interference device (SQUID) is a magnetic sensor capable of detecting extremely small magnetic field and has already been used in various fields such as material science, medical equipment, mineral exploration, and so on. In addition, SQUID has also been used in qubit. Especially in Xmon qubit [1] which is a kind of transmon qubit [2] used for quantum computer, SQUID is an important component enabling to tune qubit frequency. General problems with SQUID's materials are temperature change, natural oxidation, and deterioration due to collision. Hence, we have fabricated a highly robust SQUID with diamond which has advantages in excellent robustness and characteristics, and have demonstrated its operation [3-5]. Furthermore, boron-doped diamond enables SQUID operation under high magnetic field because of its high upper critical field which is estimated to be $H_2(0) = 11.5$ T [6]. Among such demonstrations, the SQUID composed of the trench-type Josephson junctions (JJs), which were formed in the boundary of discontinuous (111) sectors on a trench, operated at 10 K above liquid helium temperature (4.2 K) [5]. Unlike the previous structure included (001) surface ($T_c < 4.2$ K) [4], these trench-type JJs were composed of only (111) surface (T_c = 10K) [6]. Therefore, the operation at high temperature which is important for applications was realized. However, the shape of the trench formed via focused ion beam method was unstable, and it was difficult to get uniform JJ's characteristics. To improve uniformity, in this work, we have demonstrated diamond SQUID on a shallow step whose structure was simpler than that of trench-type SQUID.

2. Experiments

We fabricated JJs with epitaxially grown boron-doped diamond across shallow steps on a (111) single-crystalline-diamond substrate as shown Fig.1. The fabrication process is as follows: First, a shallow step of 40 nm depth on the substrate was formed using inductively coupled plasma reactive ion etching by O_2. Second, 140 nm thick boron-doped diamond layer was epitaxially grown across the shallow step using microwave plasma chemical vapor deposition. Like the trench-type junction [5], this JJ was formed in the boundary of discontinuous (111) sectors. The dimensions of the device are as follows: JJ's width was 15 μm and the effective loop area (A_{eff}) was 23×45 μm^2. After finishing all fabrication process, conditions of boron-doped diamond especially around JJs were observed by scanning electron microscope (SEM). In order to evaluate the SQUID, the temperature dependence of resistance, current voltage (*I-V*) characteristics and the magnetic field dependence of voltage were measured at low temperature.

3. Results

Fig.2 shows the SEM image around the JJ, and the boundary of discontinuous (111) sectors was generated in the boron-doped layer around the step on the substrate.

Temperature dependence of resistance from 300 K to 4.0 K in the inset of Fig.3 showed the sharp drop in resistance around 10 K. Moreover, in the temperature range of 12 K to 4.0 K as shown in Fig.3, two-step transition at 10.3 K and 8.1 K was observed. The former was transition temperature of the bulk boron-doped diamond, the latter was that of JJs.

In *I-V* characteristics from 4.2 K to 9.0 K as shown in Fig.4, clear DC Josephson effect was observed without hysteresis. According to the *I-V* curve at 4.2 K, the critical current I_c, the normal resistance R_n and the I_cR_n product were 0.43 mA, 1.64 Ω, and 0.71 mV, respectively.

From the measurement of the magnetic field dependence of voltage, SQUID oscillations were observed from 6.0 K to 9.5 K and the maximum amplitude of the voltage modulation was 1.4 μV at 8.0 K [Fig.5]. The oscillation interval (B_{ext}) was 2.3 μT. This experimental B_{ext} agreed with theoretical B_{ext}

(2.0 μT), which can be calculated from Φ_0/A_{eff} where $\Phi_0 = 2.07\times10^{-15}$ Wb is flux quantum. Therefore, the operation of the shallow-step-type diamond SQUID was demonstrated. In addition, since SQUID operations were confirmed in about 60% of devices with the same geometry on the same substrate, it was demonstrated that uniformity of the JJ's characteristics were improved from those of trench-type JJ.

4. Conclusions

We fabricated diamond SQUID with JJs utilizing shallow steps on the substrate. Temperature dependence of resistance showed two-step superconducting transition at 10.3 K and 8.1 K, and SQUID operations were observed from 6.0 K to 9.5 K. In addition, because the structure of this JJ was simpler than previous structure, uniformity and reproducibility of SQUID characteristics were improved. Therefore, it was suggested that this type of SQUID is appropriate for magnetic and quantum applications.

Acknowledgements

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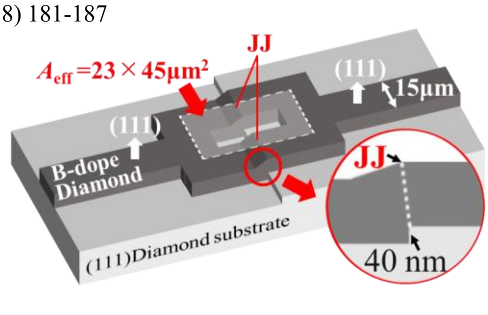

Fig.1 Schematic structure of SQUID

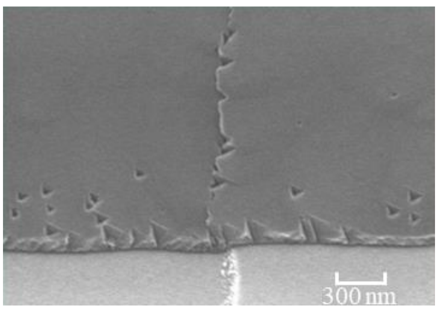

Fig.2 SEM image around the JJ within the SQUID

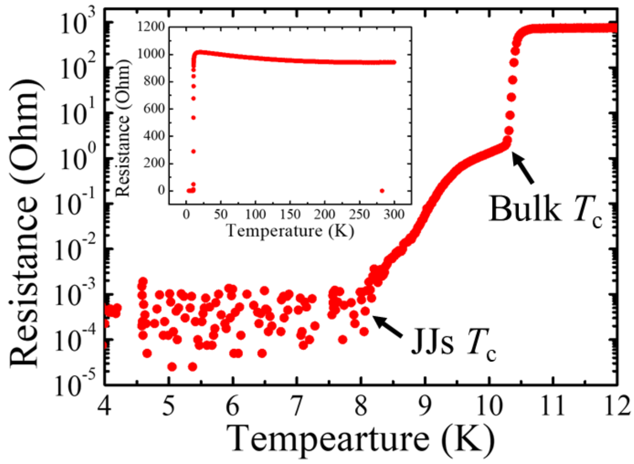

Fig.3 Temperature dependence of resistance

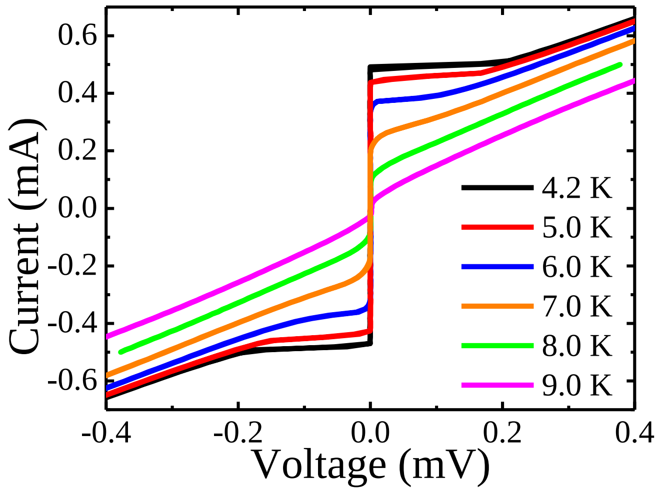

Fig.4 *I*-*V* characteristics from 4.2 K to 9.0 K

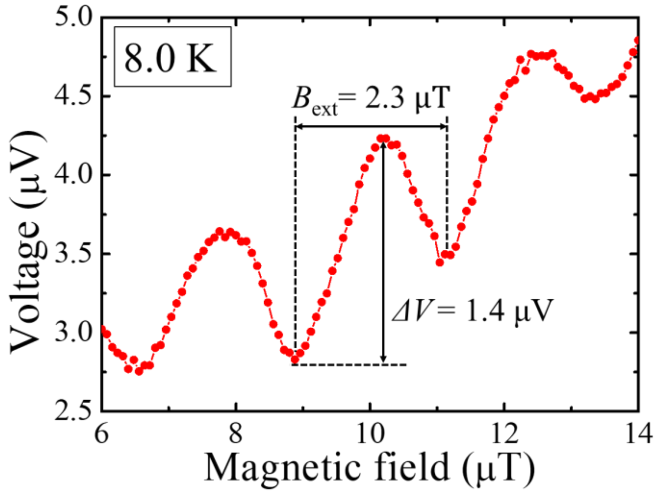

Fig.5 SQUID oscillation at 8.0 K