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Boron-doped Diamond Superconducting Quantum Interference Devices Operating up to 10 K

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Abstract

Superconducting quantum interference devices (SQUIDs) with Josephson junctions (JJs) composed of discontinuous boundaries of (111) oriented boron-doped diamond were successfully fabricated. The operating temperature was up to 10 K which is much higher than liquid helium temperature, 4.2 K. Furthermore, comparing to previously reported diamond SQUID, the proposed devices show higher magnetic field sensitivity.

1. Introduction

Superconducting quantum interference devices (SQUIDs) are known as high sensitivity magnetic sensor in various fields, e.g. scanning SQUID microscope, resource exploration and MRI. However, there are some problems about materials such as oxidation, destruction by physical contact and so on. We had fabricated a robust SQUID with step-edge structure by boron-doped diamond having tolerance to oxidation and abrasion [1][2]. It had operated at 2.6 K, while the highest superconducting transition temperature (T_c) in diamond is 10 K of (111) boron-doped diamond [3]. In this work, in order to make it available for various fields, we aimed to improve operating temperature by using only (111) growth layer in Josephson junctions (JJs) [4] constituting the SQUIDs.

2. Experiments

Boron-doped diamond SQUIDs with two JJs composed of discontinuous boundaries of heavily boron-doped diamond epitaxially grown in (111) direction were successfully fabricated. Two SQUIDs with different size were 68×68 μm^2 and 21×56.5 μm^2 in effective area (A_{eff}), respectively. Their strip widths were 36 μm and 15 μm, respectively. The larger one is only shown in Fig. 1. Fabrication process was following; Trenches were firstly formed via focused ion beam method on (111) single crystal diamond substrate. The depth and width were 30 nm and 300 nm, respectively. Then, boron-doped diamond was selectively epitaxially grown across the trenches by microwave plasma chemical vapor deposition. The morphologies of junctions were observed by scanning electron microscope (SEM). In order to characterize electrical properties, the temperature dependence of resistance from 300 K to 1.6 K and current voltage (*I-V*) characteristics from 1.6 K to 10 K were measured. Moreover, the magnetic field dependence of voltage was measured up to 10 K.

3. Results

Fig. 2 shows SEM image of the JJ composed of discontinuous (111) sectors. Due to the difference of growth rate around trench, sectors split into right side and left side of boron-doped layer forming weak link of JJ.

Two-step superconducting transition was observed in temperature dependence of resistance. The steps were observed at 10.5 K and 8.0 K in the 36 μm striped SQUID, as shown in Fig.3. Higher and lower transition points correspond to T_c of boron-doped diamond outside the trench and on the trench, respectively.

Both two sizes of SQUIDs showed DC Josephson effect in *I-V* characteristics from 3.0 K to 10 K, and no hysteresis were observed above 4.0 K. For the larger sample, critical current I_c = 0.42 mA led to parameter of JJ characteristic I_cR_n = 0.21 mV at 4.2 K, where R_n is 0.49 Ω (the normal state resistance). For the smaller sample, I_c was 0.42 mA and I_cR_n was 0.42 mV at 4.2 K.

Fig. 4 shows the magnetic field dependence of voltage at 8.0 K. The oscillation interval (B_{ext}) was 0.52 μT for the larger sample with A_{eff} = 68×68 μm^2 and 1.70 μT for the smaller sample with A_{eff} = 21 × 56.5 μm^2. These values agreed with calculated B_{ext}; the calculated B_{ext} was obtained by Φ_0/A_{eff}, since the oscillation period corresponds to flux quantum $\Phi_0 = h/2e$ where h is Planck constant and e is the elementary charge. Therefore, we demonstrated the operation of SQUID for both samples. Such operation was confirmed up to 10 K for the larger sample, and up to 8.0 K for the smaller sample. $V_{p\text{-}p}$ was approximately 2.0 μV for the larger sample and 4.0 μV for the smaller sample, so magnetic field sensitivity $V_{p\text{-}p}/B_{ext}$ was 3.8 μV/μT and 2.4 μV/μT, respectively. The magnetic field sensitivities of both samples are higher than that of diamond SQUID with step-edge structure, 1.6 μV/μT.

4. Conclusions

Two different sizes of diamond SQUIDs were fabricated by only (111) boron-doped growth layer. Two-step superconducting transition corresponding to (111) boron-doped diamond and its JJs were observed in temperature dependence of resistance. In *I-V* measurement, there were no hysteresis in *I-V* curves from 4.0 K to 10 K. The oscillation interval in the magnetic field dependence of voltage up to 10 K agreed with calculated value, which revealed the samples were under SQUID operation. Moreover, $V_{p\text{-}p}/B_{ext}$ were higher than that of diamond SQUID with step-edge structure. Therefore, SQUID with proposed structure can operate above liquid helium temperature (4.2 K) with high magnetic sensitivity.

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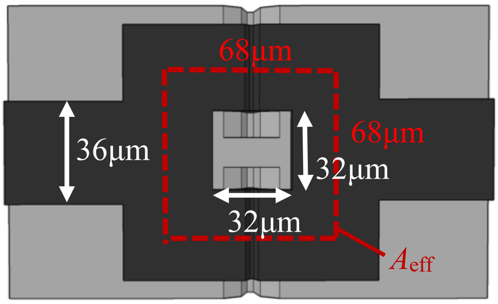


Fig. 1 Top view of the larger SQUID.

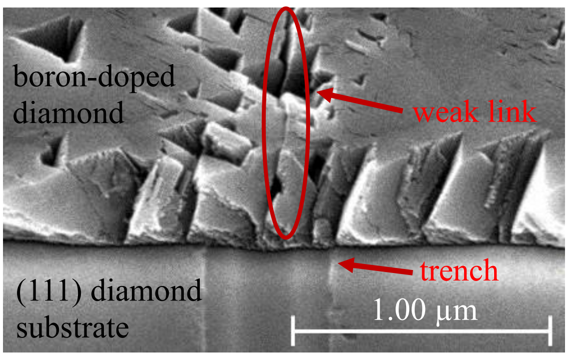


Fig. 2 SEM image of the boron-doped diamond on the trench.

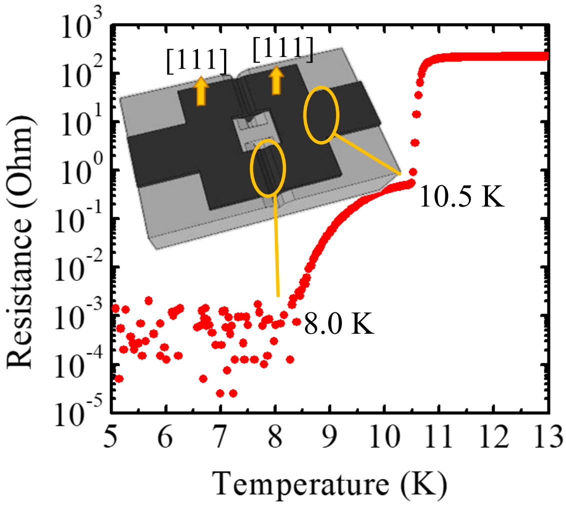
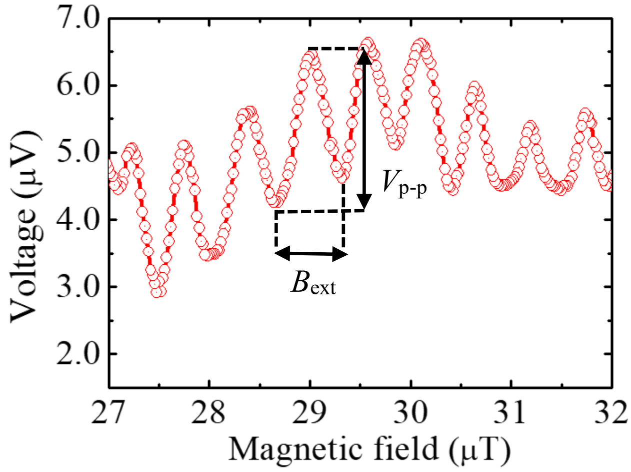


Fig. 3 Temperature dependence of resistance.

(a)



(b)

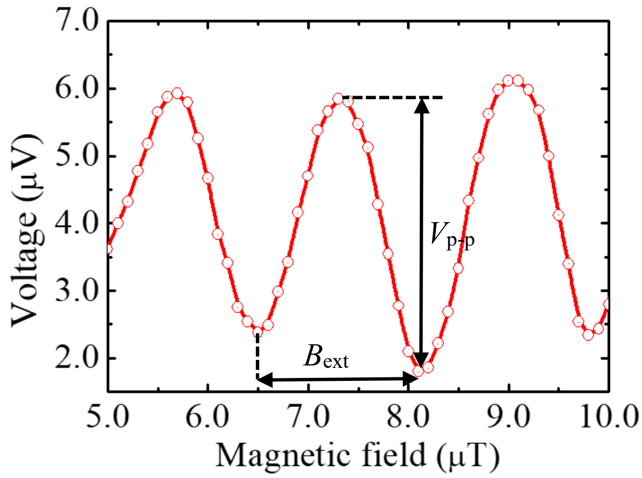


Fig. 4 SQUID oscillations of sample size with (a) A_{eff} = 68×68 μm^2 and (b) A_{eff} = 21×56.5 μm^2 at 8.0 K.