INVITED PAPER *Special Section on Recent Progress in Physics and Applications of Intrinsic Josephson Junctions*

Flux Modulation Enhancement of dc-SQUID Based on Intrinsic Josephson Junctions Made of $Bi_2Sr_2CaCuO_{8+\delta}$ Thin Films

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SUMMARY Direct-current superconducting quantum interference device (dc-SQUID) based on intrinsic Josephson junction (IJJ) has been fabricated using $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi-2212) films grown on MgO substrates with surface steps. The superconducting loop parallel to the film surface across the step edge contains two IJJ stacks along the edge. The number of crystallographically stacked IJJ for each SQUIDs were 40, 18 and 3. Those IJJ SQUIDs except for one with 40 stacked IJJs revealed clear periodic modulation of the critical current for the flux quanta through the loops. It is anticipated that phase locking of IJJ has an effect on the modulation depth of the IJJ dc-SQUID.

key words: *SQUID, intrinsic Josephson junction, phase locking, thin film*

1. Introduction

Discovery of intrinsic Josephson junction feature in Bi-2212 high T_C superconducting cuprate [1], [2] provides the potential for a variety of cryoelectronic devices, such as THz generator [3]–[6]/detector [7], [8], SQUID [9]–[15] further up to Q-bit [16]–[18]. According to the intended device application, Bi-2212 crystals are processed into an appropriate shape to develop the Josephson junction feature based on alternative stacking of superconducting CuO_2 and insulating BiO layers along the c-axis. Those IJJ devises, therefore, requires high quality Bi-2212 crystal. For this purpose, single crystal flakes cleaved out from Bi-2212 bulk grown by traveling solvent floating zone (TSFZ) method as well as self-flux method are generally used for device fabrication. In contrast, we are particular about Bi-2212 films to fabricate IJJ devices because of advantages of highly compatibility for a standard lithography and an excellent heat dissipation over Bi-2212 bulk. We have demonstrated that THz generation from large size IJJ made of the Bi-2212 film. As for the IJJ SQUID, we noticed several prior researches. Among them, Krasnov theoretically studied on stacked Josephson junction SQUID and lead to the suggestion that the flux modulation of SQUID is enhanced by stacking of identical Josephson junctions like in IJJ [9]. However, an enhancement of the flux modulation in the IJJ SQUID was not clearly shown experimentally, so far. It is mainly due to the difficulty in precise control number of junctions in IJJ. In this paper we report fabrication of the IJJ SQUIDs with a different number in stacked junctions using Bi-2212 film and discuss flux modulation of the SQUIDs with respect to the number of stacked junctions in IJJ.

Manuscript received July 19, 2022.
Manuscript revised October 25, 2022.
Manuscript publicized November 29, 2022.

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DOI: 10.1587/transele.2022SEI0003

2. Device Fabrication

Bi-2212 films were grown by the capped-LPE method [19] on MgO substrates with 0.5 µm high surface steps at 500 µm intervals. The IJJ SQUID fabricated by a standard photolithography with Ar ion etching to make a SQUID loop containing two IJJ stacks along to the step edge as shown in Fig. 1. The SQUID loop and IJJs are defined by a single resist pattern so that we measure *I*-*V* characteristic each time the SQUID definition pattern is etched. Figure 2 (a) shows an immediately preceding microphotograph to open the SQUID loop for the SQ1. Then, we make the next etching step for a short period. Figure 2 (b) shows the optical microphotograph for the same sample of Fig. 2 (a) after an additional etching for a minute further. In Fig. 2 (b), we recognize the SQUID loop on the upper section of substrate and expect that IJJs are formed underneath the Bi-2212 surface along the substrate step. Etching rate is estimated to be 13 nm/min. Since the height of a IJJ junction in a unit cell is 1.5 nm, we expect an increase in the number of stacked junctions about a ten for each etching step. Figure 3 (a) and (b) show the *I*-*V* characteristics measured for SQ1 at the

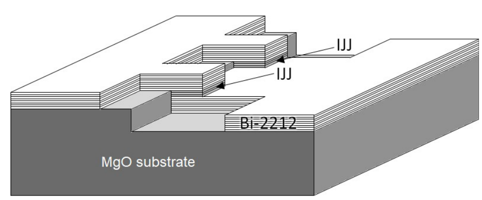

Fig. 1 Schematic illustration of IJJ SQUID on MgO step substrate.

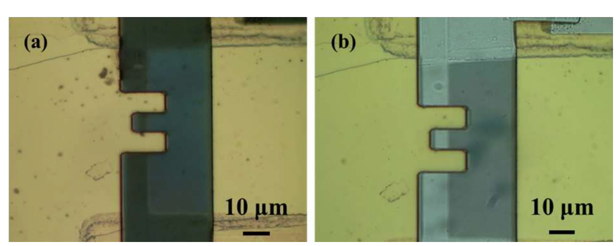

Fig. 2 (a) Optical image at the last minute before IJJ appearance. (b) Optical image of IJJ SQUID after an additional etching for a minute.

Table 1 Summary of dimensions and electric parameters of IJJ SQUIDs

#	Number of junction N	Junction area S_J (µm²)	Critical current $2I_C$ (mA)	Josephson inductance L_J (pH)	SQUID loop area S_L (µm²)	Loop Inductance L_m [21] (pH)	β_{L_m}[22]	$\Delta I_C^{L_m}$[23] (%)	Total Inductance $L_t=L_m+2NL_J$	β_{L_t}[22]	$\Delta I_C^{L_t}$[23] (%)
SQ1	3	90	0.42	1.57	60	14	2.8	24	23	4.7	16
SQ2	40	70	0.43	1.53	42	11	2.4	27	134	28	4.3
SQ3	18	100	1.6	0.41	50	13	9.7	9.4	27	21	5.1

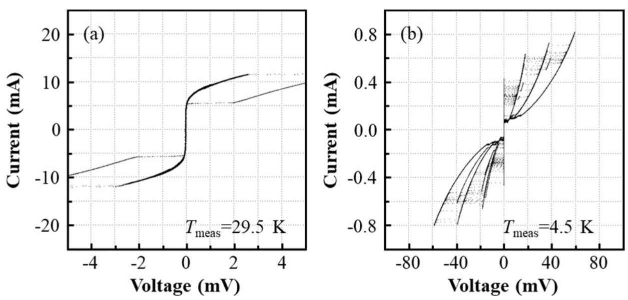

Fig. 3 (a) *I-V* characteristic measured at the last minute before IJJ appearance measured by using a single stage pulse tube cryocooler. (b) *I-V* characteristic of IJJ SQUID with an additional etching for a minute showing three quasiparticle branches corresponding to stacked Josephson junction measured by using a 4K GM cryocooler.

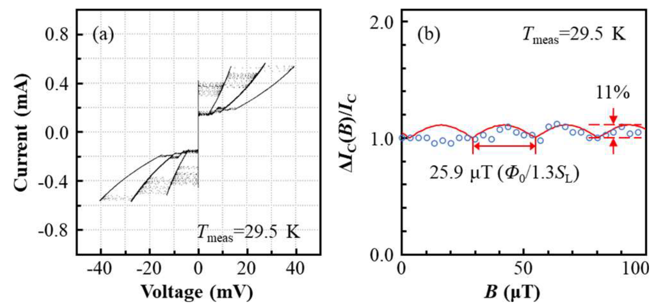

Fig. 4 (a) *I-V* characteristic of SQ1 consisting of IJJs with 3 stacked junctions. (b) *I-B* modulation of the superconducting branch. The fitted periodic flux modulation corresponds to Φ_0 over the SQUID hole area S_L taking into account of flux concentration coefficient to 1.3.

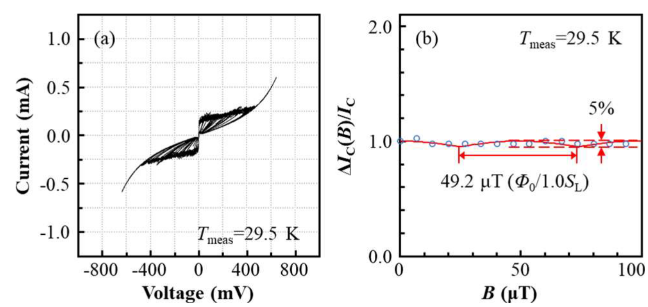

Fig. 5 (a) *I-V* characteristic of SQ2 consisting of IJJs with 40 stacked junctions. (b) *I-B* modulation the superconducting branch. The fitted periodic flux modulation corresponds to Φ_0 over the SQUID hole area S_L with no compensation of flux concentration.

etching sequence corresponding to Fig. 2 (a) and (b), respectively. The appearance of the multiple quasiparticle branch structure characteristic of the IJJ in Fig. 3 (b) indicates that the fabrication process is feasible to control the number of stacked junctions in the IJJ SQUID. We also verify the number by counting the number of quasiparticle branches except for tiny sub branches which are due to nonuniformity of junctions [20].

I-V characteristics and flux modulations on the switching current for a magnetic field applied perpendicular to the SQUID loop were measured by the four-terminal method at 29.5 ± 0.5 K using a pulse tube cryocooler.

3. SQUID Characteristics

We fabricated three SQUIDs with different numbers of stacked junctions while the other geometries are similar for each other. Table 1 summaries the geometries and characteristic parameters of those SQUIDs.

Figure 4 shows *I-V* characteristic and the dependence of the switching current of the superconducting branch on applied magnetic field measured for SQ1. In SQ1, the number of stacked junctions N in IJJs is 3. A clear periodic modulation against applied magnetic field is observed in Fig. 4 (b). The period against the applied magnetic field, B is fairly consistent the theoretical period obtained by dividing the flux quantum, Φ_0 over the geometric area of SQUID loop, S_L. While the modulation depth of stacked Josephson junction SQUIDs is deteriorated by the spread of the switching current of junctions [9], [10], it is reasonable to think that the periodic modulation is an expression of flux quantum modulation of the dc SQUID. The modulation depth of the fitted curve is 11%. The practical modulation is smaller than theoretical value 24% estimated by considering electromagnetic inductance of the SQUID loop. Kim et al. mentioned that the Josephson inductance became large to ignore for the IJJ SQUID. It is noteworthy that the theoretical modulation 16% estimated by the total inductance L_t considering Josephson inductance as well as the electromagnetic one give close agreement with the practical modulation of 11%.

In accordance with the above consideration for SQ1, we measured the IJJ SQUID containing a larger number of staked IJJ, although increase in the number of junction may course further disturbance in the switching current modulation feature. Figure 5 (a) shows the *I-V* characteristic of SQ2 with $N = 40$ indicating multi quasiparticle branch structure with the critical current similar to SQ1. The spread in switching currents of whole branches in *I-V* characteristic is less than 30% for both SQ1 and SQ2 showing a fair junction uniformity. Figure 5 (b) shows dependence of the

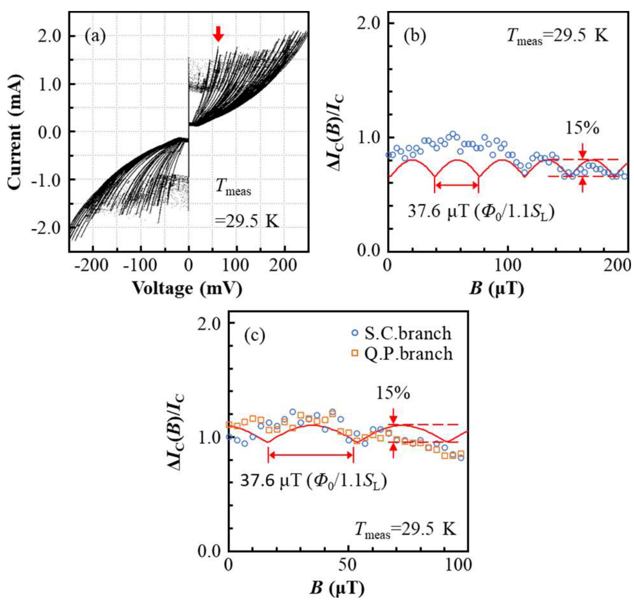

Fig. 6 (a) *I-V* characteristic of SQ3 consisting of IJJs with 18 stacked junctions. (b) *I-B* modulation of the superconducting branch. The fitted periodic flux modulation corresponds to Φ_0 over the SQUID hole area S_L taking into account of flux concentration coefficient to 1.1. (c) *I-B* modulation of the superconducting branch and quasiparticle branch marked by an arrow in (a).

switching current of the superconducting branch on applied magnetic field measured for SQ2. The modulation depth become smaller to 5% with a good agreement with theoretical modulation of 4.3% estimated by the total inductance L_t. These experimental results suggest that the Josephson inductance as well as electromagnetic inductance have an effect on the flux modulation of the IJJ SQUID. However, those results seem against the proposal of enhancement of flux modulation in stacked Josephson junction SQUIDs. A strong coupling between junctions and a junction uniformity may play an important role in the enhancement of flux modulation. Figure 6 (a) shows the *I-V* characteristic of SQ3 with $N = 18$. The critical current of 1.6 mA is about three times larger than those of SQ1 and 2. The larger critical current may reflect on a strong coupling between adjoing stacked IJJs. Furthermore, the spread in switching currents for a majority of stacked IJJs is less than 10% showing a good uniformity except for one quarter junctions of which switching current deviate above the majorities more than 30%. As seen in Fig. 6 (b), flux modulation of SQ3 is 15% although the theoretically estimated by the total inductance L_t is only 5.1%. For SQ3 we estimated a correlativeness of stacked IJJs by measuring dependencies of the switching current of the quasiparticle branch indicated by an arrow in Fig. 6 (a) among the majority junctions as well as the superconducting branch. As seen in Fig. 6 (c), a near-synchronous flux modulation is recognized between the two branches. These experimental results suggest that improvements in inter-junction coupling and junction uniformity enhanced flux modulation of IJJ SQUID.

4. Conclusions

We have successfully fabricated dc SQUIDs based on intrinsic Josephson junction using Bi-2212 thin films grown on MgO step substrates. A minute interval Ar ion etching procedure observing SQUID hole at each step provided a precise junction number control in the IJJ dc SQUID within a ten and resulted in the minimal junction number down to 3. Clear periodic flux modulation were observed and the modulation depths are consistent of those theoretical value taking into account of Josephson junction inductance of stacked IJJ as well as electromagnetic inductance of a SQUID hole. It is also shown that a strong inter-junction coupling and good junction uniformity may enhance flux modulation of the IJJ dc SQUID.

Acknowledgments

The authors would like to thank H. Kobayashi for technical assistance. This work was supported by Grant-in-Aid for Scientific Research(C) 21K04189.

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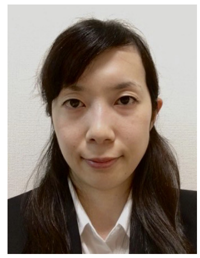

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