**BRIEF PAPER**

**Flux modulation enhancement of dc-SQUID based on intrinsic Josephson junctions made of Bi$_2$Sr$_2$CaCuO$_{8+\delta}$ thin films**

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**Abstract**

Direct-current superconducting quantum interference device (dc-SQUID) based on intrinsic Josephson junction (IJJ) has been fabricated using Bi$_2$Sr$_2$CaCuO$_{8+\delta}$ (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 research. 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.

2. **Device fabrication**

Bi-2212 films were grown by the capped-LPE method [19] on MgO substrates with 0.5µm high surface steps at 500µm intervals. The IJJ SQUID fabricated by a...
standard photo-lithography 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 13nm/min. Since the height of a IJJ junction in a unit cell is 1.5nm, we expect an increase in the number of stacked junctions about a ten for each etching step.

**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) taking into account of flux concentration coefficient to 1.3.

**Table 1 Summary of dimensions and electric parameters of IJJ SQUIDs**

<table>
<thead>
<tr>
<th>#</th>
<th>Number of junction ( N )</th>
<th>Junction area ( S_J ) (μm²)</th>
<th>Critical current ( 2I_C ) (mA)</th>
<th>Josephson inductance ( L_J ) (pH)</th>
<th>SQUID loop area ( S_L ) (μm²)</th>
<th>Loop Inductance ( L_{Lm} ) [21] (pH)</th>
<th>( \beta_L ) [22]</th>
<th>A( \Delta I_C )% [23]</th>
<th>Total Inductance ( L_{t} = L_{Lm} + 2NL_J L_J ) [22] (pH)</th>
<th>( \beta_L ) [22]</th>
<th>A( \Delta I_C )% [23]</th>
</tr>
</thead>
<tbody>
<tr>
<td>SQ1</td>
<td>3</td>
<td>90</td>
<td>0.42</td>
<td>1.57</td>
<td>60</td>
<td>14</td>
<td>2.8</td>
<td>24</td>
<td>23</td>
<td>4.7</td>
<td>16</td>
</tr>
<tr>
<td>SQ2</td>
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<td>70</td>
<td>0.43</td>
<td>1.53</td>
<td>42</td>
<td>11</td>
<td>2.4</td>
<td>27</td>
<td>134</td>
<td>28</td>
<td>4.3</td>
</tr>
<tr>
<td>SQ3</td>
<td>18</td>
<td>100</td>
<td>1.6</td>
<td>0.41</td>
<td>50</td>
<td>13</td>
<td>9.7</td>
<td>9.4</td>
<td>27</td>
<td>21</td>
<td>5.1</td>
</tr>
</tbody>
</table>

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 \( \Phi_0^\ast \) 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 \( \Phi_0^\ast \) over the SQUID hole area \( S_L \) with no compensation of flux concentration.

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 \( \Phi_0^\ast \) 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 quasi particle branch marked by an arrow in (a).
4 (b). The period against the applied magnetic field, $B$ is fairly consistent the theoretical period obtained by dividing the flux quantum, $\Phi_0$ over the geometric area of SQUID loop, $S_2$. 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 stacked 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 quasi particle 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 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 adjoining 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 quasi particle 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.

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References


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