Influence of charging energy on Cooper-pair tunneling in Bi-2212 small intrinsic Josephson junctions

Influence of Charging Energy on Cooper Pair Tunneling in Bi-2212 Small Intrinsic Josephson Junctions

T. Kawae, T. Yasuda, S.-J. Kim, K. Nakajima, and T. Yamashita

***Abstract*—We have investigated the properties of submicron intrinsic Josephson junctions (IJJs) fabricated on $Bi_2Sr_2CaCu_2O_{8+\delta}$ liquid phase epitaxy film. The IJJs with junction area $S < 2\ \mu m^2$ showed individual current-voltage curves, which have suppressed 1st branch and unsuppressed other branches. This suppression was observed systematically as an increase the ratio of charging energy and Josephson coupling energy. It is expected that such suppressions are due to charging effect in IJJs.**

***Index Terms*—Charge soliton, charging effect, intrinsic Josephson junctions, superconducting films.**

I. Introduction

It is well known that $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi-2212) high-T_c superconductors (HTS) can be considered as a stack of Josephson junctions, i.e., intrinsic Josephson junctions (IJJs) that consist of superconducting CuO_2 double layers and insulating BiO and SrO layers in Bi-2212 [1], [2]. Latyshev *et al.*. have successfully reported fabrication of submicron IJJs and the first observation of charging effects on HTS by using Bi-2212 whiskers and a focused ion beam (FIB) etching method [3], [4]. Also, reducing the junction area of IJJs is known as an effective way of avoiding self-heating in IJJs, and it is suitable for studying the fundamental properties of HTS [5].

It is known that charging effect for Cooper-pair tunneling is caused from competitions between charging energy and Josephson coupling energy, and Josephson currents are suppressed as increasing of the charging energy [6], [7]. Hence, experimental investigation of the influence of charging energy on Cooper-pair tunneling in IJJs is needed.

For investigating the properties of submicron IJJs, high quality crystals with perfect stacks are needed. Recently, quite high quality c-axis oriented Bi-2212 films have been successfully grown on MgO substrates by the liquid phase epitaxy (LPE) method [8], [9]. Also, Kim *et al.*. have introduced a new fabrication technique of submicron IJJs for c-axis oriented $YBa_2Cu_3O_{7-\delta}$ thin films using a 3D FIB etching method [10]. Therefore, films with high crystalline quality and the 3D FIB etching method provide us many advantages to investigate various properties of submicron IJJs.

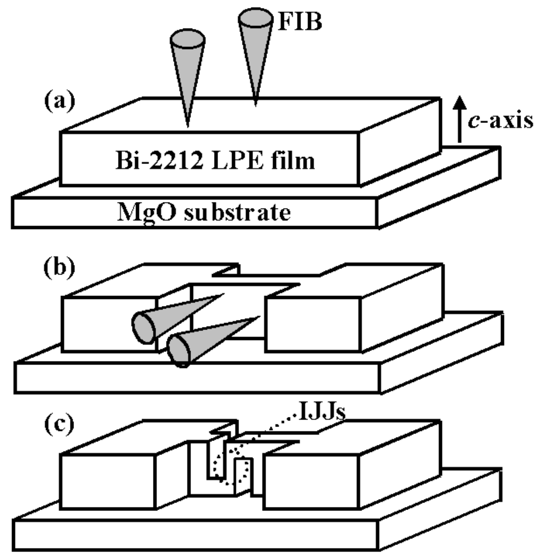

Fig. 1. Fabrication steps of IJJs on Bi-2212 LPE film by 3D FIB etching method.

In this paper, we report the change of Cooper-pair tunneling characteristic in submicron IJJs fabricated on the Bi-2212 LPE films when the charging energy becomes comparable to the Josephson coupling energy.

II. Experimental

We used c-axis oriented Bi-2212 films, which were grown on MgO (100) substrates by the LPE method using a focused infrared beam furnace [8], [9]. The thickness of the films is typically 1–2 μm. Our as-grown film with superconducting transition temperature T_c of 78–80 K can be regarded as overdoped Bi-2212 HTS.

Firstly we etched the edges of the films by chemical etching to make four terminal structures and to shape the width. Secondly we made four electrodes for measurements using silver paste and annealed in 1 atm of flowing oxygen at 440°C for 10 min in a furnace to decrease the contact resistance between the film and the electrodes.

For fabrication of IJJs we used the 3D FIB etching method; the steps of the fabrication process were shown in Fig. 1. The width was patterned from perpendicular direction etching of the film [Fig. 1(a)]. By tilting the sample stage up to 90°, two

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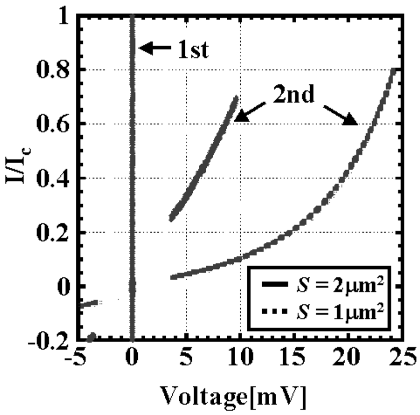


Fig. 2. Normalized current-voltage characteristics on low bias region for IJJs with junction area $S = 1\ \mu m^2$ and $2\ \mu m^2$. The temperature is 4.2 K.

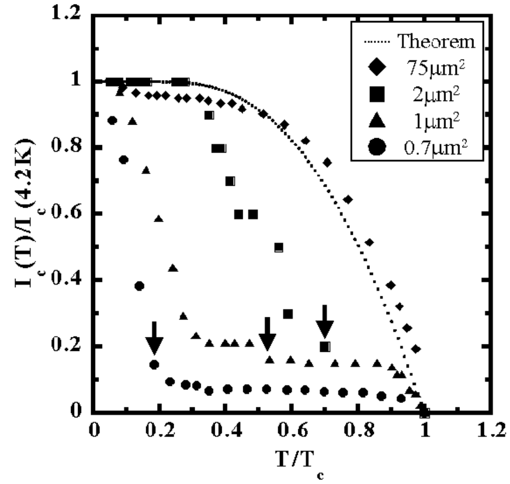


Fig. 3. Temperature dependence of normalized critical currents of IJJs with various S. Theoretical curve estimated from A-B relation is also plotted. The allows indicate the threshold temperature T_t, which corresponds to E_J/k_B for each IJJs.

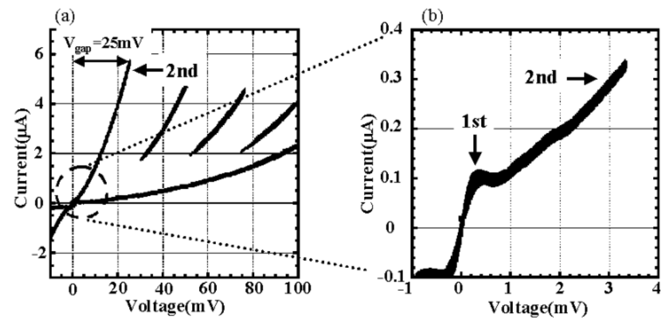
grooves of the bridge were then completely etched from the lateral sides to create the required junction size [Fig. 1(b)]. The scheme of fabricated sample is shown in Fig. 1(c). The junction area S of the IJJs ranged from 0.4 μm^2 to 3 μm^2 and 75 μm^2. The IJJs with $S = 75\ \mu$m^2 was fabricated on a film grown on an MgO substrate with a step structure.

The samples were cooled in a liquid He bath and measured in a shielded room using a high sensitive oscilloscope and low-noise amplifier, and all measurements of electrical properties were carried out with a standard four terminal method.

III. Results and Discussion

The typical normalized current (I/I_c)-voltage (V) characteristics of fabricated IJJs with $S = 1$ and 2 μm^2 at 4.2 K are shown in Fig. 2. Both characteristics indicate clear hysteresis and a superconducting gap voltage V_{gap}, where V_{gap} was 25 and 30 mV, respectively. Furthermore, it can be seen that as S decreases, the characteristic resembles a superconductor (S)-insulator (I)-S like characteristic more. It indicates that IJJs with smaller S fabricated on our film can clearly show ideal c-axis electrical characteristics because the several micro crack parts on crystalline were excluded approximately by FIB etching.

Fig. 3 shows the normalized critical current $I_c(T)/I_c(4.2\ \mathrm{K})$ dependence on normalized temperature T/T_c obtained from direct observation of I-V characteristics of IJJs with various S. The curve of the Ambegaokar-Baratoff (A-B) relation for an S-I-S type Josephson junction in conventional superconductor is also plotted [11]. For $S = 75\ \mu$m^2, the curve seems to be closer to A-B relation. However, the behavior of curves are changed drastically when S is reduced to a few or submicron range. It may be thought that this behavior is due to the Josephson coupling energy $E_J = hJ_cS/4\pi e$ of small size IJJs being comparable with the thermal energy k_BT, where h is Planck's constant and k_B is Boltzmann's constant. Also, allows in Fig. 3 indicate the threshold temperature T_t, which corresponds to $E_J/k_B = T_t$ for each IJJs. It can be seen that as increase the temperature, the curves for IJJs with $S < 2\ \mu$m^2 drop to $E_J/k_BT_t = 1$, and show the tail structure with constant normalized I_c to the T_c. This result corresponds to the case of small size IJJs formed as mesa structures pointed out by Irie *et al.* [12], and demonstrates



(a) (b)

Fig. 4. I-V characteristics of the IJJs with junction area $S = 0.5\ \mu$m^2 on large (a) and low (b) bias region at 4.2 K.

that the behavior of small size IJJs is indeed sensitive to other energy factors due to its low E_J.

For submicron IJJs we also observed the individual I-V characteristic shown in Fig. 4. One can see that the 1st branch is extremely suppressed. Other branches indicate unsuppressed I_c although there are influences due to self-heating. Moreover this phenomenon was observed systematically when S was reduced under 2 μm^2. Fig. 5 shows the critical current I_c of the 1st and 2nd branches as a function of S. On reducing S to the submicron range, the I_c of the 1st branch decreases rapidly than that of 2nd branch. In the case of J_c, the distinct differences between 1st and 2nd branch can be seen (see the inset to Fig. 4). However, for the steep suppression of J_c of 2nd branch for a smallest IJJs, it may be caused from thermal fluctuation at 4.2 K same as above results.

There are some possible reasons for such conspicuous suppression. One of them is damage caused from FIB etching. When damage due to FIB etching is present, the I-V curve shows the branch structure with irregular I_c and V_{gap}. However, the I-V curve of fabricated IJJs did not show irregular I_c besides the 1st branch as seen in Fig. 4, although suppression due to self-heating was observed. Therefore the possibility of damage from the etching process is debatable.

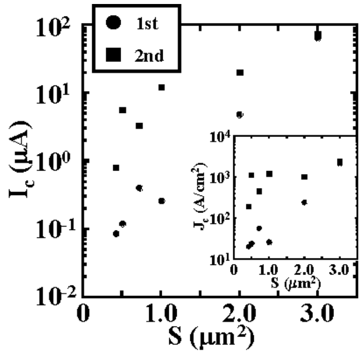


Fig. 5. Junction area S dependence of critical currents I_c estimated from 1st (circle) and 2nd (square) I_c of IJJs at 4.2 K. The inset shows S dependence of critical current density J_c for same junctions.

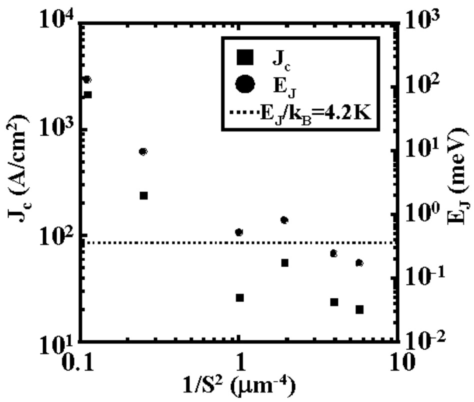


Fig. 6. $1/S^2$ ratio dependence of critical current density J_c and Josephson coupling energy E_J. J_c and E_J were estimated from 1st I_c of IJJs at 4.2 K. The dashed line indicates $E_J/k_B = 4.2$ K.

As another possibility, a reduction of J_c as S decreases may be explained by the charging effect on a Cooper-pair tunneling due to competition between the charging energy $E_c = e^2t/2\varepsilon_c\varepsilon_o S$ and E_J [6], [7], where $\varepsilon_c(= 5)$ is the dielectric constant for Bi-2212, ε_o is the vacuum dielectric constant and $t(= 1.2 \text{ nm})$ is the interlayer spacing. From the uncertainty relation between charge and phase difference on the Josephson junction, a suppression of J_c occurs when the quantum fluctuations of phase increase and the charge localization occurs as increase ratio E_c/E_J [13].

To investigate the influence of charging effect, in Fig. 6, the dependence of J_c and E_J on $1/S^2$, being equivalent to ratio E_c/E_J for our IJJs is plotted. We used the I_c value of the 1st branch from direct observation of the I-V characteristics of IJJs at 4.2 K to estimate J_c and E_J. One can see that a reduction of J_c was observed as $1/S^2$ increase. From $E_J - 1/S^2$ characteristic the relationship between E_J and k_BT may not be observed because there is no behavior to converge the line $E_J/k_B = 4.2$ K like a tail structure seen in I_c-T curve on Fig. 3, and evidently its behavior depends on only $1/S^2$. This means that observed reductions might be due to charging energy depended on S.

The IJJs can be regarded as an effective 1D array. It is known that a Cooper-pair in 1D arrays behaves as a charge soliton with a characteristic length (soliton length): $L_s = 2t(C/C_s)^{0.5}$, where C_s is the stray capacitance, $C_s \cong 10^{-19}$ F [4]. In the case of our submicron IJJs, we estimate $L_s \cong 100t - 500(= 0.12\text{–}0.6\ \mu\text{m})$ by using the above equation. From this estimate it follows that the "single" charge soliton moves over the IJJs as an isolated charge because the length of our IJJs is below 0.1 μm.

Hence, we think that the charge localization of Cooper-pair (CLCP) as increasing ratio E_c/E_J occurs at a single junction in IJJs because the single charge soliton conducts isolative through the IJJs as mentioned above. Then, phase fluctuations due to the uncertainty principle also occur for a single junction. As a result, the phase of other junctions without CLCP is not fluctuated, and a suppression of the Josephson current due to the charging effect is observed as a suppression of the 1st branch on the I-V characteristics.

In general, the junction should be connected to a high impedance circuit larger than the quantum resistance R_q to observe the charging effect more clearly [6], [7]. Also, it is known that a series Josephson junction array in the superconducting state can work as a high impedance circuit, and the total resistance of several tens of junctions with submicron junction area is much larger than R_q [14]. Using this characteristic, Delsing *et al.* observed charging effects more clearly in a 1D array [15]. Also, Watanabe *et al.* successfully observed charging effects for a single junction by the same approach [16]. In the case of IJJs, it may be said that the junction with suppressed Josephson current due to charging effects is connected to a high impedance circuit comprised of IJJs without suppression because IJJs can be regarded as a 1D array. IJJs are suitable structures for observation and applications of the charging effects.

IV. Conclusion

In summary, we have fabricated small IJJs on high quality c-axis oriented Bi-2212 LPE films using the 3D FIB etching method and investigated its properties. When S decreased to several μm^2, I_c-T curves are changed drastically due to its low E_J comparable with the k_BT. Moreover, for IJJs with $S < 2\ \mu$m^2, a suppressed I_c of the 1st branch was observed systematically. From estimates of ratio E_c/E_J and L_s, we think that it may be caused by charging effects on IJJs as a 1D Josephson junction array.

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