High-\(T_c\) Josephson junction: towards improvement of \(I_cR_N\) product and realization of phase qubits

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Abstract. Josephson junction of high-\(T_c\) cuprate superconductor is studied in terms of (1) basic characteristics of junction to improve the \(I_cR_N\) product, and (2) a new candidate for quantum bits. Aiming to fabricate phase qubits, the switching current distribution of intrinsic Josephson junctions in Bi\(_2\)Sr\(_2\)CaCu\(_2\)O\(_y\) was investigated. The switching current distribution down to 40 K was consistent with the thermally activated escape process in the single junction, while a more complex feature appeared below 40 K, strongly suggesting the importance of the multi-junction effects.

1. Introduction

Josephson junction (JJ) of high-\(T_c\) superconductors (HTSCs) is potentially promising for various superconducting devices with high performance, because of a large superconductivity gap (equivalently, high critical temperature). One of important applications is a single-flux quantum (SFQ) device, since the operating speed of SFQ devices is inversely proportional to the so-called \(I_cR_N\) product (\(I_c\) is the critical current and \(R_N\) is the normal resistance of the junction, respectively), which is, in turn, proportional to the superconductivity gap ideally. Unfortunately, however, all of the reported values for the \(I_cR_N\) product for JJ of HTSCs was at most 1/10 of the ideal value. The reason for the very low \(I_cR_N\) product has not been clarified for more than 15 years[1].

Another fascinating application is the fabrication of quantum bits (qubits) using JJs of HTSCs, similar to the Josephson qubits which have recently been demonstrated using conventional JJs [2]. The large superconductivity gap of HTSCs also suggests the potential advantage that qubits can be operated at higher temperatures or for longer decoherence times. In particular, the phase qubits based on the current-biased JJs is the most promising for HTSCs, since the very recent experiments succeeded in observing the macroscopic quantum tunneling (MQT) for the grain boundary JJs of YBa\(_2\)Cu\(_3\)O\(_y\) [3] and the intrinsic JJs (IJJs) of Bi\(_2\)Sr\(_2\)CaCu\(_2\)O\(_y\) [4]. In fact, the latter suggested that MQT survived up to \(\sim\)0.8 K, which is one order of magnitude larger than a characteristic temperature in Nb JJs [5]. However, there still remain many things to be resolved toward the realization of phase qubits using JJs of HTSCs.
Figure 1. (a) Temperature dependence of the dc and microwave conductivity of LSCO (x=0.15) thin film. (b) Frequency dependence of the microwave conductivity of the same film.

To realize the high potential of HTSCs described above, the more fundamental understanding of JJs of HTSCs is essentially required. Thus, the following new features should be kept in mind in researches of JJ of HTSCs [6].

(1) Effect of the d-wave condensate: Since the wave function of condensate state mainly has the d-wave symmetry in HTSCs, the Josephson current, \( J_s \), changes the sign depending on the angle between the direction of \( J_s \) and the crystal axis of the d-wave superconductor. Thus, \( I_c R_N \) also behaves in a quite different manner from that in the Ambegaokar and Baratoff (AB) theory [7]. For instance, when \( J_s \) is in [001] direction, the magnitude and temperature dependence of \( I_c R_N(T) \) do not differ considerably from the results of the AB theory. On the other hand, when \( J_s \) is in [110] direction, \( I_c R_N \) was found to be proportional to \( R_1^1/2 \) because of the presence of the Andreev bound state, which enhances \( I_c R_N \) values at low temperatures. For some special angles such as \( \pm \pi/8 \), \( I_c R_N \) shows the nonmonotonous temperature dependence, including the disappearance of \( I_c R_N \) at a finite temperature. Thus, to get junctions with large \( I_c R_N \), precise control of the crystal axis during the fabrication procedure is essential.

(2) Effect of quasi-two dimensional nature: Electronic structure of HTSC is considered to be quasi-two dimensional (Q2D), corresponding to the layered structure. According to Ref. [6], if \( J_s \) flows perpendicular to the CuO\(_2\) plane, as is the case for IJJs, \( I_c R_N(T) \) behaves very similarly to that in conventional JJs. Thus, as far as Josephson effect is concerned, the Q2D nature does not bring any deficiencies.

(3) Doping dependence: One of the most pronounced aspect of HTSC is that the physical properties change largely as a function of carrier concentration. This has a significant meaning also for Josephson effect. Increasing carrier density also increases the coherence length. This can be mentioned as that the superconductivity phenomena change from Bose-Einstein condensation like to BCS condensation like. Excited quasiparticles and those interactions are expected to be very much different between these two extrema. Such a crossover has not been achieved in previous researches, and should be important both from basic and application points of view.

Based on these backgrounds, in this study, we focus on two types of JJs of HTSCs. One is the ramp-edge junction of La\(_{2-x}\)Sr\(_x\)CuO\(_4\) (LSCO) thin films to investigate the origin of low values of \( I_c R_N \). The other is the IJJ of Bi\(_2\)Sr\(_2\)CaCu\(_2\)O\(_y\) (BSCCO) single crystals to investigate
Figure 2. (a) Switching current distribution of IJJ of BSCCO for various temperatures (b) Probability of switching events at $T=70 \text{ K}$ (solid square), compared with theoretical calculation (open circle) (c) the similar comparison to (b) at $T=30 \text{ K}$

details of the escape rate of a zero-voltage state, aiming to fabricate phase qubit.

2. Experiment

The epitaxial LSCO thin films were grown on LaSrAlO$_4$ (LSAO) substrates by using the pulsed laser deposition technique [8]. LSCO thin films on LSAO substrates have the following advantages; (1) the crystallographic properties of films are of very high quality, since the lattice constant of LSAO is very close to that of LSCO. (2) the hole concentration can be widely controlled. The property of ramp-edge JJs, where the barrier is naturally formed at a ramp surface during an Ar-ion etching, have ever been investigated for YBa$_2$Cu$_3$O$_y$ thin films on MgO substrates [9]. Therefore, the systematic study of the ramp-edge JJs of LSCO films with a wide range of hole doping is expected to disclose the reason why $I_cR_N$ product is suppressed.

On the other hand, single crystals of BSCCO were grown by the floating-zone method. The small mesa structure (typically $20 \times 20 \mu m^2$) was fabricated on the top of BSCCO single crystal by Ar-ion etching. The structure and fabrication process of the IJJ device were similar to Ref.[10]. Total numbers of junctions, $N$, were estimated to be 20-30 typically, using an atomic-force microscope. Electrical properties, such as the $I-V$ characteristic, were measured by three-terminal method. In order to probe details of the tilted washboard potential in IJJs, the escape rate of the zero-voltage state in the underdamped JJs was investigated by the switching current measurement [11].

3. Results and discussion

Figs. 1(a) and 1(b) show the real part of microwave conductivity, $\sigma_1$, of LSCO film ($x=0.15$) as functions of temperature and frequency, respectively, which were measured by the microwave broadband technique [12]. As shown in Fig. 1, we confirmed that the LSCO film in the normal state was safely regarded as a good metal showing no frequency dependence in a broad frequency
region from dc to 10 GHz, as expected for the usual Drude conductivity. On the other hand, near \( T_c (\sim 31.9 \text{ K}) \), we observed the rapid divergence in \( \sigma_1(\omega) \) as \( \omega \to 0 \) and \( T \to T_c \), as shown in Fig. 1(b), suggesting that the contribution of the superconducting fluctuations to \( \sigma_1(\omega) \) were apparent. These results clearly show that the LSCO film is of sufficiently high quality to investigate the fundamental properties in the superconducting state. The fabrication of ramp-edge JJs of such LSCO films is now in progress.

The switching current distribution, \( P(I) \), for IJJs of nearly optimally doped BSCCO \((T_c \sim 90 \text{ K})\) was measured at several temperatures, as shown in Fig. 2(a). We tried to fit measured data to theoretical calculations based on the thermally activation theory [13]. We found that the temperature dependence of \( I_c \), which was obtained from the fitting, roughly agreed with that of the AB theory. Moreover, as shown in Fig. 2(b), we obtained the good fitting of \( P(I) \) to the thermally activation model with a single Josephson junction down to 40 K, while a large broadening or a multiple peak structure appeared in \( P(I) \) below 40 K, as shown in Fig 2(c). This behavior is similar to that reported in a current-biased hysteretic dc SQUID with two JJs [14], or in the previous study of IJJs in BSCCO [15]. Although details of this effect are still unknown at present, it is strongly suggested that the dynamics of IJJs of BSCCO should be understood by using a model which can appropriately describe the tilted washboard potential in \( N \) dimensional phase space, corresponding to a multi-junction system. Thus, it seems to be not so straightforward to establish the condition for observing MQT.

4. Conclusion
In order to overcome many unresolved issues on JJs of HTSCs, we proposed the systematic study of ramp-edge JJs of LSCO films, which can disclose the reason why \( I_c R_N \) product is suppressed. We also measured the switching current distribution of IJJ in BSCCO, to investigate details of the escape process of the zero-voltage state. The switching current distribution down to 40 K was found to be consistent with the thermally activated escape process in the single junction, while the large broadening or multi-peak structure appeared below 40 K, strongly suggesting the importance of the multi-junction effects. Although the very recent observation of MQT in IJJs by Inomata et al. [4] is very encouraging, it seems to be not so straightforward to establish the condition for observing MQT.

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6. References
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