Energy gap suppression and excess current in $Tl_2Ba_2CaCu_2O_8$ intrinsic Josephson junctions*

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Intrinsic Josephson junctions in misaligned $Tl_2Ba_2CaCu_2O_8$ thin film were fabricated on $LaAlO_3$ substrate. The temperature dependence of the critical current is investigated around liquid nitrogen temperature. In the current voltage characteristic, large voltage jump and lack of resistive branch are observed, which shows good consistency with the intrinsic Josephson junctions. By analyzing the large gap voltage in the curve, great suppression of the energy gap is found. Through discussing the temperature dependence of the gap voltage in liquid nitrogen temperature, it is shown that this phenomenon can be caused by the non-equilibrium quasiparticle injection. The temperature influence on the excess current also confirms the non-equilibrium effect.

Keywords: intrinsic Josephson junctions, current voltage characteristics, energy gap, excess current

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1. Introduction

Intrinsic Josephson junctions (IJJs) in high-temperature superconductors are regarded as a stack of Josephson junctions in atomic scales, about 1.5 nm per junction.[1,2] One typical feature of the IJJs in the high-temperature cuprate superconductors (e.g., $Bi_2Sr_2CaCu_2O_8$) is multiple-branch structure in the current–voltage characteristic (IVC).[1–5] Another feature in IVC is a large back-bending structure with negative dynamic resistance.[6,7] This back-bending structure accompanies a gap structure at high bias current and the suppression of the energy gap often appears.

In this letter, we present our experimental results of IJJs fabricated with misaligned $Tl_2Ba_2CaCu_2O_8$ (Tl-2212) thin film. Current–voltage characteristics of the IJJs around liquid nitrogen temperature are shown. The temperature dependence of the IVCs and the suppression of the energy gap as well as the excess current are studied. Possible explanation is given.

2. Experiment details

The Tl-2212 thin film was grown epitaxially on 20° miscut $LaAlO_3$ (LAO) substrate by magnetron sputtering and post annealing.[8] Then, a microbridge was patterned on the Tl-2212 thin film by photolithography and Ar ion milling. Figure 1 shows the schematic structure of the microbridge. The size of the microbridge was 5 μm in length and 11 μm in width. The thickness of the thin film was 500 nm and the critical temperature (T_c) measured by a mutual-induction method was 104 K (as shown in Fig. 2). By means of a four-terminal method, the IVCs of the IJJs were measured. The sample was immersed in liquid nitrogen dewar and the measurement process was in an electromagnetic shielding environment.

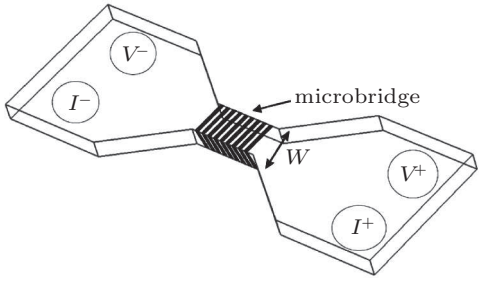


Fig. 1. Schematic structure of the microbridge. Here, W is the width and the black solid lines represent the superconducting layers.

3. Results and discussion

The inset of Fig. 2 shows the normalized temperature dependence of the critical current in liquid nitrogen temperature. Although the data is a little scattered, it presents a linear fitting. This linear relation conforms to the Ambegaokar–Baratoff (A–B) theory near T_c and shows that the IJJs are superconductor–insulator–superconductor (SIS) type.[9,10] Based on the SIS model, it is estimated that there are about 827 IJJs in the microbridge.[11,12]

The IVCs of the IJJs at different T are shown in Fig. 3. A supercurrent as large as 7.91 mA is observed at 77.6 K, corresponding to a critical current density of A/cm^2 along the c axis. By sweeping the bias current up and down, a large voltage jump appears (see the arrows) and shows a large hysteresis structure. The I_c and return current (I_r) can be clearly distinguished (see the labels). The inset shows the dependence of

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the Stewart–McCumber parameter β_c on the ratio I_r/I_c.[13] A decreasing β_c with increasing I_r/I_c can be seen, which indicates that at high temperature (close to T_c), there will be no hysteresis.[14] There is no branch structure and the IJJs act as a 'single' junction. This lack of branch has been observed in different geometric patterns and materials.[2,3,14,15] Two possible reasons are the high current density[3,14,15] and the influence of the substrate on the coupling of the IJJs.[16,17] Once the IJJs are biased, part of the emitting power from the IJJs will feed into the substrate and arouse resonance of the substrate. The resonance of the substrate will strengthen the interaction between the IJJs, and this system will tolerate the dispersion of the parameters of the IJJs.

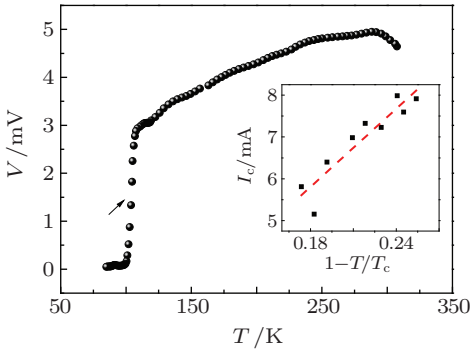


Fig. 2. (color online) Critical temperature (T_c) measured by a mutual induction method. The arrow is used to mark the transition temperature. The inset shows the normalized temperature dependence of the critical current (I_c) of the IJJs. The red dashed line represents a linear fitting of the data.

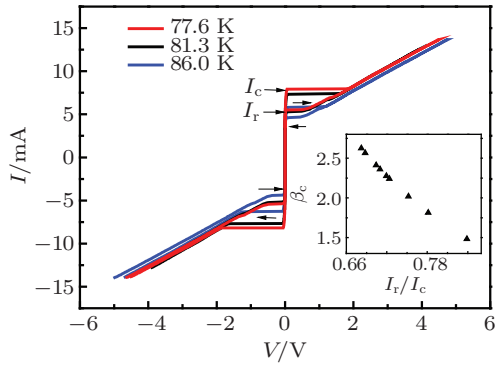


Fig. 3. (color online) Current–voltage characteristics (IVCs) of the IJJs at different temperatures. The arrows show the direction of voltage jump, the critical current (I_c), and return current (I_r). The inset shows the dependence of the Stewart–McCumber parameter β_c on the ratio I_r/I_c.

From the large jump voltage shown in Fig. 3, the gap voltage (V_J) per junction is obtained. It is about 2.2 mV at 77.6 K, which is much less than 11.8 mV in theory by a nine order polynomial.[18] From the relation $V_J = 2\Delta(T)/e$, where e is the electron charge, we find that the energy gap $\Delta(T)$ is suppressed. To obtain more information about the suppression of the energy gap, the dependence of V_J on temperature in liquid nitrogen temperature was measured, and is shown in Fig. 4. It shows that the experimental gap voltage (V_{gE}) and the theoretical gap voltage (V_{gT}) slightly decrease with increasing temperature. The V_{gE} is in the range of 1–2 mV, while V_{gT} varies between 10–12 mV. Obviously, the energy gap is suppressed. The inset shows the dependence of the ratio V_{gE}/V_{gT} on temperature. The value of only 0.1–0.2 illustrates great suppression of the energy gap under high current density injection.[19]

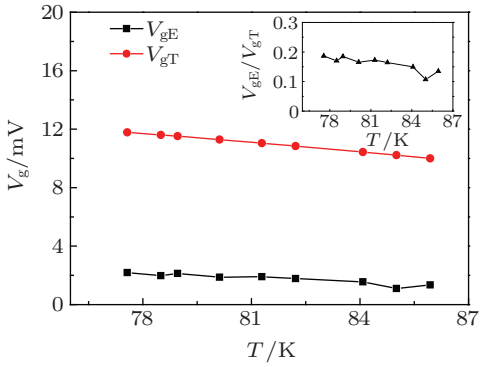


Fig. 4. (color online) Temperature dependence of gap voltage (V_g) per junction around liquid nitrogen temperature. The inset shows the temperature dependence of the ratio of V_{gE} to V_{gT}.

Other researchers have discussed the suppression of the energy gap and attributed it to Joule heating and non-equilibrium effects originating from high quasiparticle current density.[19,20] We also investigate this problem from the viewpoint of the effect of Joule heating or/and non-equilibrium. The magnitude of the c-axis relaxation length (δ_n^c), determining the effect of the quasiparticle current injection) is estimated to be about 16 nm for $Bi_2Sr_2CaCu_2O_{8+\delta}$,[19] which can also be used for Tl-2212 due to their similar crystal property. This value is much larger than the thickness of the superconducting layers (0.3 nm). Then, the quasiparticle current can easily pass through the superconducting layers and cause the non-equilibrium effect, as well as the suppression of the energy gap. The non-equilibrium process also affects the excess current. By extrapolating the linear part of the IVC, a current axis intercept, or excess current, is obtained. The excess current (I_e) is defined as $I_e = I - V/R$ at high voltage,[21] where R is the normal resistance of the IJJs. If the excess current originates from the non-equilibrium process, it will follow the same dependence of the I_c on temperature and saturate at lower temperature.[22] Figure 5 presents the experimental result at liquid nitrogen temperature, and shows the temperature dependence of I_e, which resembles that of I_c. The I_e saturates at a value of $0.5I_c$ (see the inset of Fig. 5). It confirms the effect of the non-equilibrium. On the other hand, considering the wide width of the microbridge and good contact interface between the IJJs and the substrate, Joule heating in IJJs can easily escape to the substrate and play a less important role in the great suppression of the energy gap.

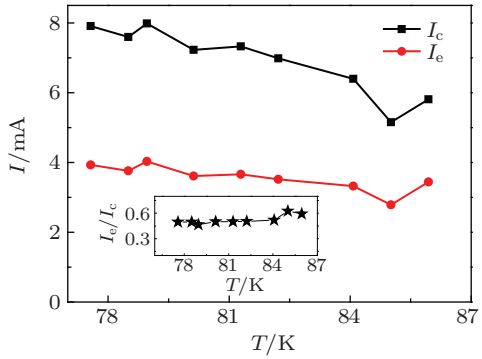


Fig. 5. (color online) Temperature dependence of the critical current (I_c) and the excess current (I_e) around liquid nitrogen temperature. The inset shows the ratio I_e/I_c as a function of temperature.

4. Conclusions

By fabricating IJJs in misaligned Tl-2212 thin film, we have investigated the dependence of IVCs on temperature at liquid temperature. The large voltage jump in the IVCs is discussed. By analyzing the suppression of the energy gap and the excess current, the non-equilibrium effect on the IJJs is explored. It is our further work to investigate the IVCs of the IJJs in a wider temperature range.

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