RESEARCH ARTICLE

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Characteristics of the Surface-Intrinsic Josephson Junction

Abstract During the fabrication of intrinsic Josephson junctions (IJJs) with $Bi_2Sr_2CaCu_2O_{8+\delta}$ (BSCCO) single crystals, the superconductivity of the surface Cu–O layer is degraded because of a deposited metal film on top of the stack. Thus, the characteristics of the surface junction consisting of the surface Cu–O double layers remarkably differ from those of the junctions deep in the stack, which will be referred to as ordinary IJJs. The electrical transport characteristics of the surface junction, such as I–V, I'_c–T, and R–T, show that the critical temperature T'_c of the surface junction is always lower than that of ordinary IJJs, and that the change of its critical current I'_c with temperature is different from that of ordinary IIJs. Furthermore, by shunting the surface junction resistively, we are able to observe the AC Josephson effect at 3-mm waveband.

Keywords Josephson junction, intrinsic junction, surface junction, high-temperature superconductor

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1 Introduction

High-T_c superconductors, such as $Bi_2Sr_2CaCu_2O_{8+\delta}$ (BSCCO), are intrinsically composed of layered structures. Superconducting (S) layers Cu–O are coupled through insulating (I) layers Bi–O and Sr–O, where each S-layer is 0.3 nm thick while each I-layer is 1.2 nm. Thus, a bilayer Cu–O structure can be regarded as two S-layers separated by an I-layer of 1.2 nm. Obviously, these layers form a Josephson junction. High-T_c superconductors mainly

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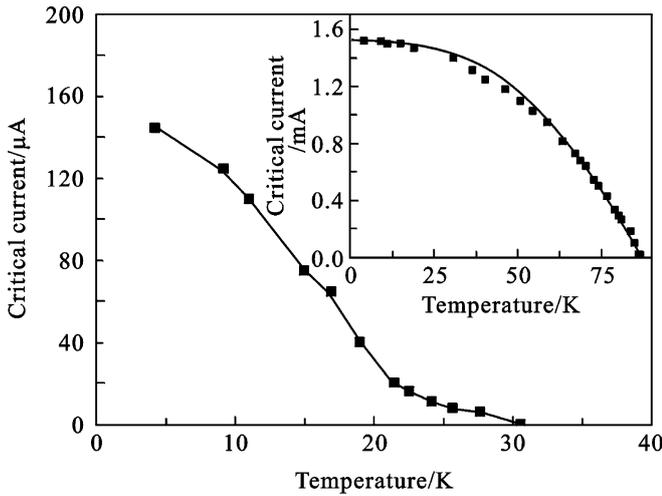Nanjing 210093, China
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consist of a stack of S-layers, which are weakly coupled with each other through the I-layers by the Josephson effect.

To look at the intrinsic Josephson effect, a stack of junctions of certain sizes should be cleaved from a bulk single crystal. During fabrication, metal (Au/Ag) is evaporated onto the surface of the stack to protect it from being contaminated in the following steps and to improve ohmic contacts between the sample and the electric leads. The superconductivity of surface Cu–O layers is degraded because of the existence of a metal layer. Thus, the characteristics of the surface junction consisting of the top two Cu–O layers are different from those of ordinary intrinsic Josephson junctions (IJJs) [1–3]. In this paper, we will analyze the I–V, I'_c–T, and R–T characteristics of the surface junction and discuss how we can successfully observe the AC Josephson effect of the surface junction by shunting it resistively.

2 Electrical transport characteristics of the surface junction

The critical temperature T'_c ($T'_c \approx 28$ K) of the surface junction is often lower than that ($T_c \approx 92$ K) of ordinary IJJs. Moreover, the critical current density of the latter is usually ten times higher than that of the former. When the temperature reaches T'_c, the critical current of the surface junction disappears. The Cu–O layer on top will be degraded from a superconductor to a normal metal, as well as the surface junction from S′–I–S to N–I–S.

Figure 1 is the temperature dependence of the critical current of the surface junction. As shown in the figure, there is a tail structure within the range of $1/2T'_c \leqslant T \leqslant T'_c$, which does not follow the Ambegaokar–Baratoff relationship for the SIS junction of s-wave or d-wave pairing symmetry [4,5]. So far, there has been no theoretical calculation for such abnormal phenomenon [1]. The inset shows the temperature dependence of the critical current of ordinary IJJs, with the solid line representing the characteristics of the SIS junction of the d-wave pairing

Fig. 1 Temperature dependence of the critical current of the surface junction. *Inset*: the I_c–T curve of ordinary IJJs

symmetry. Obviously, experimental data are quite consistent with the curve for the SIS junction of the d-wave pairing symmetry.

Figure 2 shows the R–T characteristics of the intrinsic junction measured with a three-terminal method. The resistance of the junction slowly goes down as the temperature decreases from room temperature. The resistance drops sharply at $T_c = 92$ K and reaches its minimum at $T_{c0} = 79$ K. It rises again and, at $T_c' = 28$ K, reaches its maximum, which is 70% more than the normal resistance. Then it drops quickly again until the sample is in the superconducting state below $T_{c0}' = 18$ K. As shown in the curve, the cause of the first drop of the resistance is that all ordinary IJJs start going into the superconducting state while the surface junction is still in the normal state. Then there is the rising branch of resistance, indicating that the surface junction shows strong semiconducting characteristics. At sufficiently low temperatures (the critical temperature), the surface junction goes superconducting.
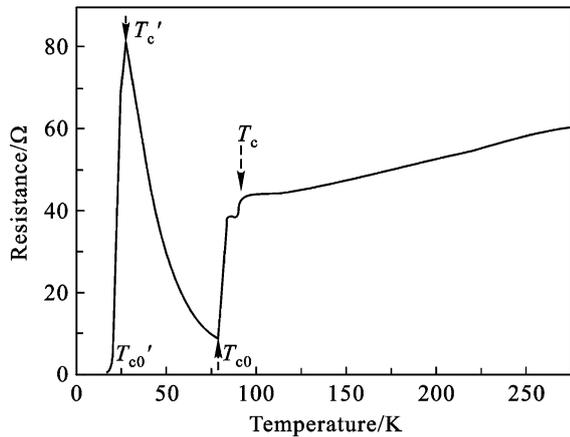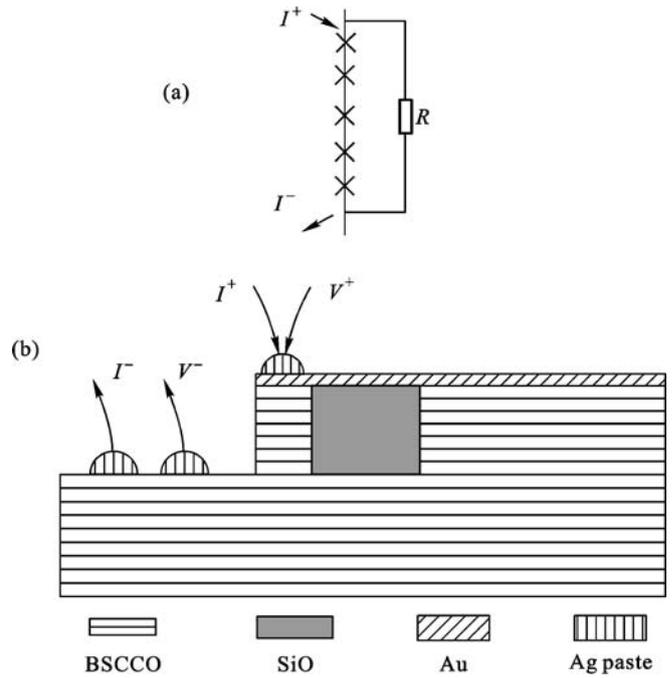

Fig. 3 (a) Equivalent circuit of shunted intrinsic junctions, (b) Schematic view of shunted intrinsic junctions

(a)

Fig. 2 The R–T curve of a stack of junctions measured with the three-terminal method
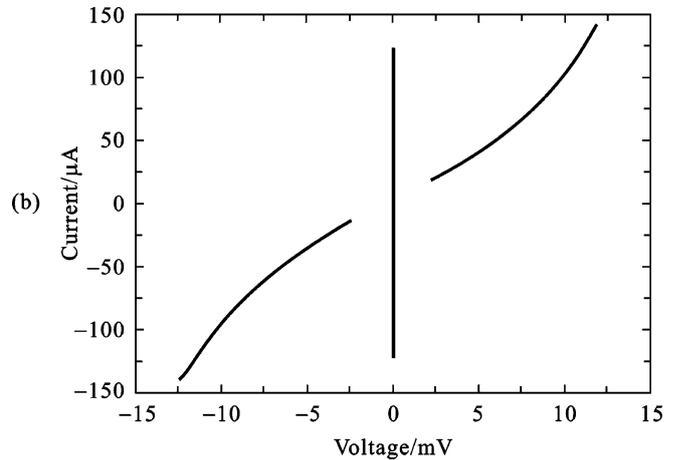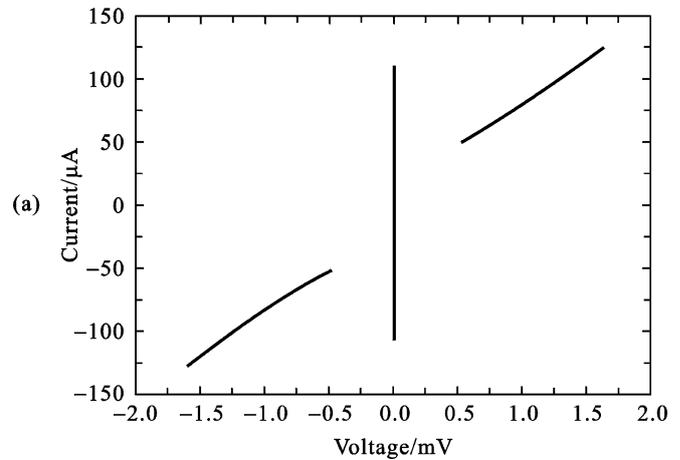

(b)

Fig. 4 (a) The I–V curve of a surface junction with shunting, (b) The I–V curve of a surface junction without shunting

3 AC Josephson effect of the surface junction

When high-frequency Josephson oscillation in a junction is locked to an applied external microwave, the so-called Shapiro steps appear in *I–V* characteristics. However, the Shapiro steps only can be observed when the frequency of the microwave is much higher than the plasma frequency of the junctions, that is,

$$f_{\mathrm{rf}} \gg f_{\mathrm{pl}}, \quad f_{\mathrm{pl}} = \sqrt{\frac{J_c d}{2\pi \Phi_0 \varepsilon_0 \varepsilon_r}}$$

where $\Phi_0 = \frac{\hbar}{2e}$ denotes the fluxon, J_c is the critical current density, f_{rf} is the frequency of the external microwave, f_{pl} is the plasma frequency of the junction, and d is the interlayer distance.

Although the critical current density J_c' of the surface junction is lower than that of ordinary IJJs, it is still very high. The experimentally measured J_c' is about several hundred milliamperes per squared centimeter, corresponding to a plasma frequency of about 100–200 GHz. Thus, at millimeter waveband, it is not easy to observe the Shapiro steps. To solve this problem, we can reduce critical current density and junction resistance, so that plasma oscillation can be attenuated quickly or plasma frequency can be drastically reduced.

We shunt the junction resistively to lower its resistance. Two mesas, of different sizes and isolated from each other by the SiO I-layer, are fabricated on the same BSCCO single crystal. Then they are connected by a metal lead so that the small one is effectively shunted by the big one, which plays the role of a resistor. Figure 3(a) is the equivalent circuit of shunted intrinsic junctions, while Fig. 3(b) is its schematic view. Au is used as electrode and metal lead.

Figures 4(a) and 4(b) show the *I–V* characteristics of the surface junction with and without shunting, respectively, with the contact resistance already subtracted. The hysteresis of the shunted mesa is obviously reduced. The voltage jump from the zero-voltage state to the nonzero voltage state is also changed from 10.9 to 1.2 mV. The critical current of the shunted junctions is 120 μA, and the critical current density is 350 A/cm², from which plasma frequency can be estimated to be 100 GHz. Figure 5 is the *I–V* curve of a shunted surface junction irradiated by a 99.3 GHz microwave. The first and second Shapiro steps can be observed in the curve, and the Josephson frequency–voltage relation *f/V* = 486.3 MHz/μV is well satisfied. The results show convincingly that the Shapiro steps from
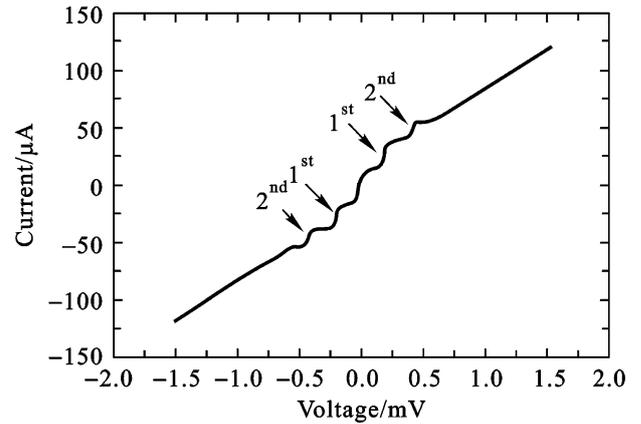

Fig. 5 The *I–V* curve of a shunted surface junction irradiated by a 99.3 GHz microwave

surface junctions can be observed at 3-mm waveband by resistive shunting.

4 Conclusions

The characteristics of a surface junction are very different from those of ordinary IJJs, including critical temperature, critical current, temperature dependence of critical current density, and junction resistance. In microwave response experiments, the plasma frequency of a surface junction is so high that we cannot directly observe the Shapiro steps. But with a shunted junction, these steps can be successfully observed at 3 mm waveband.

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