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Proximity effect in BSCCO intrinsic Josephson junctions contacted with a normal metal layer

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Abstract

Superconductivity proximity effect is numerically evaluated based on McMillan's tunneling proximity model for a sandwich of a normal metal layer on top of the surface superconducting layer of intrinsic Josephson junctions in a $Bi_2Sr_2CaCu_2O_{8+\delta}$ (BSCCO) crystal. Due to the very thin thickness of 0.3 nm of the superconducting layer in IJJs, the surface layer is subject to influence of the proximity effect when the top layer is contacted with a normal metal layer. The effect manifests itself as a significant change in the characteristics of the IJJ surface Josephson junction. It is found that when the superconducting layer thickness is smaller than 0.6 nm, the pair potential reduces significantly, leading to an almost complete suppression of the critical Josephson current density for the surface junction. This result can partly explain the experimental results on the IJJ characteristics of a mesa type structure.

Keywords: Proximity effect, intrinsic Josephson junctions, critical Josephson current, high-T_c superconductors, Bi-2212

1. Introduction

The high-T_c superconductor $Bi_2Sr_2CaCu_2O_{8+\delta}$ (BSCCO or Bi-2212) is crystallographically equivalent to a stack of tunnel Josephson junctions [1, 2, 3], called intrinsic Josephson junctions (IJJs). Since the IJJs are a crystal structure itself, the junction interfaces are clean and atomically flat, giving rise to an almost ideal tunnel Josephson junction characteristics. The superconducting layers are double CuO_2 layers approximately 0.3 nm thick and very thin compared with conventional Josephson junctions. A compact stacked Josephson junctions composed of such thin superconducting layers are interesting subjects of coupled Josephson junctions systems [4].

When such a superconducting layer comes to close contact with a normal metal layer, on the other hand, the superconducting properties should suffer considerable influence from the presence of a normal metal layer. These changes in the properties manifest themselves in the surface IJJ characteristics and make effect on the phase dynamics of the finite size stacks of coupled Josephson junctions [5, 6]. Experimentally, a mesa structure fabricated on top of a cleaved crystal surface is commonly used to investigate the IJJ characteristics [7]. In these mesa structure, one electrode is fabricated on top of the mesa structure and the electrode layer

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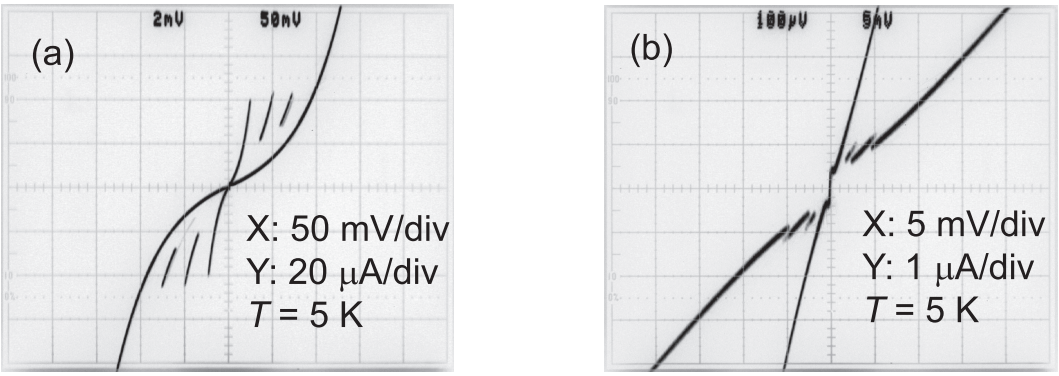

Fig. 1. (a) Oscilloscope images of the current-voltage characteristics for a small mesa structure of Bi-2212 IJJs fabricated on top of a crystal surface with the top Ag electrode thin film evaporated immediately after cleavage in vacuum. The mesa lateral size is 2 μm and the thickness is 6 nm. (b) An enlargement of the origin of the current-voltage characteristics.

is needed to attain close contact with the top superconducting layer in order to obtain a very low contact resistance. It was found by Zhao and his coworkers that evaporating an electrode metal layer in vacuum leads to a very low contact resistance [8, 9]. In such a case, a suppression of the maximum Josephson current is often observed [8, 9, 10]. In the present study, this suppression of the Josephson critical current is intended to be explained in terms of the proximity effect.

The superconductivity proximity effect is usually known as a phenomenon in which a normal metal thin film in close contact with a superconductor exhibits superconductivity despite the fact that it alone shows no trace of superconductivity down to a very low temperature. The proximity effect to be dealt with in the present study is concerned with an opposite case. Namely, we are concerned with the case in which a very thin superconducting layer is contacted with a rather thick normal metal layer. In such a case, it occurs that the superconductivity of the thin film is weakened in the presence of a normal metal layer. In the present study, we try to numerically evaluate the Josephson critical current I_c based on McMillan's tunneling proximity model [11] for a Josephson junction in which one electrode is composed of a very thin superconducting layer, i. e., 0.3 nm CuO_2 double layer, backed by a normal metal layer. We have found that under some conditions I_c is significantly reduced, which is almost comparable with the experimental results.

2. Experimental background

Figure 1(a) shows an oscilloscope image of current-voltage (I-V) characteristics for a Bi-2212 IJJ mesa structure. It is clearly seen that the first zero-voltage branch current is almost completely suppressed compared with the other three branches. Figure 1(b) shows an enlarged image of the origin in Fig. 1(a). A suppressed I_c of a extremely small magnitude is observable. We presume that the suppression of I_c is caused by the proximity effect in the presense of a normal metal layer contacted with the top layer junction electrode. Such a suppressed zero-voltage branch was observed by Zhao *et al.* [8] and Zhu *et al.* [9] in their submicrometer mesa samples cleaved and electrode-evaporated in vacuum. There is no definite statement about the relationship between the suppressed I_c and the contact resistance, and they argue that the reduction in Ic is caused by the deficiency in the oxygen content in Bi-2212 which occurred during the cleavage in vacuum. As for the possibility of this different scenario, a relationship between both causes is discussed in Sec. 5.

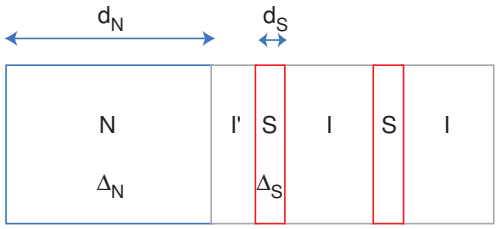

Fig. 2. Schematic illustration of a proximity sandwich in the present study. 'I'' indicates the BiO-SrO surface tunneling barrier layer, 'I' the $(BiO\text{-}SrO)_2$ IJJ tunneling barrier layer, N the normal metal layer, and S the superconducting 0.3 thick $(CuO_2)_2$ layer.

3. Calculation model

Numerical calculation was conducted based on McMillan's tunneling proximity model. Figure 2 shows the schematic illustration for the present proximity sandwich. As indicated in the figure, $\Delta_S(E)$ and $\Delta_N(E)$ denote the pair potentials at the superconductor side (S side) and that at the normal metal layer side (N side), respectively. In McMillan's tunneling model, the following equations hold.

$$\Delta_N(E) = \left(\Delta_N^{\mathrm{ph}} + \frac{\mathrm{i}\Gamma_N \Delta_S(E)}{[E^2 - \Delta_S^2(E)]^{1/2}}\right) \Bigg/ \left(1 + \frac{\mathrm{i}\Gamma_N}{[E^2 - \Delta_S^2(E)]^{1/2}}\right) \tag{1}$$

$$\Delta_N^{\mathrm{ph}} = \lambda_N \int_{\Delta}^{\Delta+\omega_{\mathrm{cN}}} \mathrm{Re}\left(\frac{\Delta_N(E)}{[E^2 - \Delta_N^2(E)]^{1/2}}\right) \tanh \frac{E}{2k_{\mathrm{B}}T} \mathrm{d}E, \tag{2}$$

where Γ_S and Γ_N are expressed as follows.

$$\Gamma_N = \frac{\hbar v_{FN}\alpha}{4B_N d_N}, \qquad \Gamma_S = \frac{\hbar v_{FS}\alpha}{4B_S d_S}, \tag{3}$$

The expressions for $\Delta_S(E)$ and Δ_S^{ph} are obtained by exchanging suffices S and N in the above equations. In the expressions, v_{FN} and v_{FS} are the Fermi velocities in N and S layers. α is the tunneling probability through the proximity interface between the S and N layers. $\lambda_{S,N}$ are the values self-consistently related to T_{c} through $T_{\mathrm{c}} = 1.13\hbar\omega_{cS} \exp(-1/\lambda_S)$ and Eq. (2) in the case of $d_S = 0$. In the present case, $\lambda_S = 0.446$ is chosen to represent a strong-coupling nature and in the absence of the normal layer $2\Delta(0)/k_{\mathrm{B}}T\mathrm{c}$ is approximately 4.3. B_{N} and B_{S} are functions of scattering time and nearly constant. The Josephson critical current is expressed by Nam's formula [12] by the following.

$$I_{\mathrm{c}}(T) = \frac{\hbar}{\pi e R_N} \mathrm{P} \int_{-\infty}^{\infty} \mathrm{d}E \int_{-\infty}^{\infty} \mathrm{d}E' \frac{p_L(E) p_R(E')}{E - E'} [f(E) - f(E')] \tag{4}$$

where, $f(E) = 1/[1 + \exp(E/k_{\mathrm{B}})]$ is the Fermi function, $p_{L,R}(E)$ are the pair density of states and $p_L(E) = \mathrm{Re}\, \Delta_{S,N}(E)/\sqrt{E^2 - \Delta_{S,N}(E)^2}$ for the S side of the proximity sandwich while $p_R(E)$ should be expressed by the BCS pair potential which is equivalent to Δ_S^{ph} with $\Gamma_S = 0$. In the numerical evaluation of I_{c}, Eqs. (1)-(4) are numerically solved self-consistently.

In the present study, we chose s-wave symmetry for the superconductor since it is sufficient for the present purpose to check the validity of the model in which we need to expect a much larger change in I_{c} than that caused by the difference between d-wave and s-wave symmetries.

4. Results

Figure 3 shows the pair density function $p_{S,N}(E)$ for the S side and N side of the proximity sandwich for $\alpha = 0.1$, $d_S = 6$ nm, $d_N = 6$ nm, and the other parameters listed in the figure caption. The values for the N layer are nearly compared with those for Ag. As a characteristics feature of a proximity sandwich represented by McMillan's model, the pair density becomes finite at the N side of the sandwich. The value of $\alpha = 0.1$ for the tunneling parameter is not a small value but nearly comparable to a value at the interface

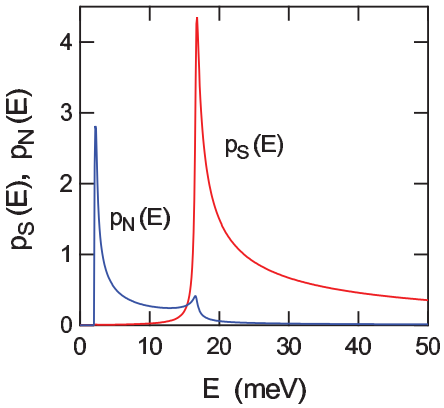

Fig. 3. Pair density of states for the S side of the proximity sandwich $p_S(E)$ and for the N side $p_N(E)$. The values for the calculations are $v_{FS} = 3.0 \times 10^7$ cm/s, $v_{FN} = 1.4 \times 10^8$ cm/s, $\lambda_S = 0.446$, $\lambda_N = 0.08$, $\omega_{cS} = 63.15$ meV, $\omega_{cN} = 18.53$ meV, $\alpha = 0.1$, $d_S = 6$ nm, $d_N = 6$ nm, $B_S = B_N = 2.0$, and $T = 0$.

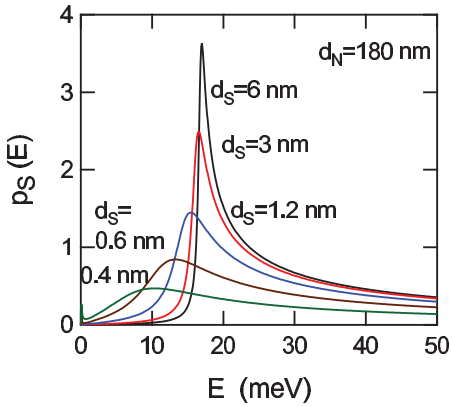

Fig. 4. The pair density of states at various superconducting layer thicknesses d_S nm. The values for the calculations are $d_N = 180$ nm, $\alpha = 0.1$, and the other parameters are the same in Fig. 3.

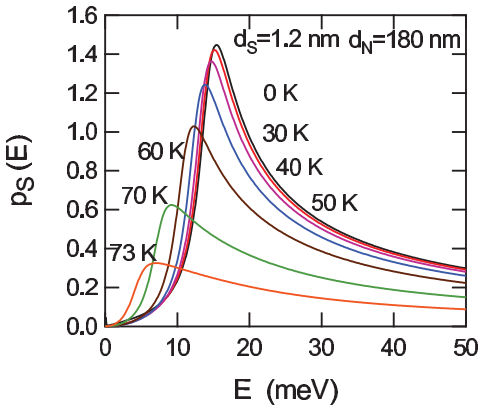

Fig. 5. The pair density of states at various temperatures T. The values for the calculations are $d_S = 1.2$ nm, $d_N = 180$ nm, $\alpha = 0.1$, and the other parameters are the same in Fig. 3.

between elemental metals [13]. Nevertheless, the sharp peak at nearly the original position indicates that the pair diffusion from the superconductor into the normal layer is not affluent. This arises from the fact that the value chosen for the Fermi velocity in the superconductor is small in the calculation, reflecting a large anisotropy in the Bi-2212 system and a low carrier density. The ratio of v_{FS}/v_{FN} implies approximately a value of 0.01 for the carrier density ratio when the effective masses are assumed to be the same. Since the anisotropy is ~100 for the Bi-2212 system, the above value for v_{FS} may be larger than the actual value. It is therefore more than expectation that the diffusion of pairs into the normal layer is pretty slim.

Figure 4 shows the pair density function $p_S(E)$ as a function of energy E at various values for the thichness of the superconducting layer d_S. It is seen that the pair density shifts toward lower energies with its peak lowered and broadened as d_S decreases, the magnitude of the pair density itself decreases as a result of diffusion of pair density into the N side. It is seen that $p(E)$ is pretty suppressed when d_S is less than 0.6 nm.

Figure 5 shows the temperature dependence of the pair density of states $p_S(E)$ at the S side of the proximity sandwich. The temperature dependence is determined self-consistently from Eq. (2) and its counterpart of the S layer depending on the values for λ_S and λ_N. In the present case, both values were preliminarily determined in the absence of proximity effect to give a T_c of 90 K and a superconducting order parameter magnitude of $4.3k_BT_c$. The curves of the pair density of states in Fig. 4 are the results of such

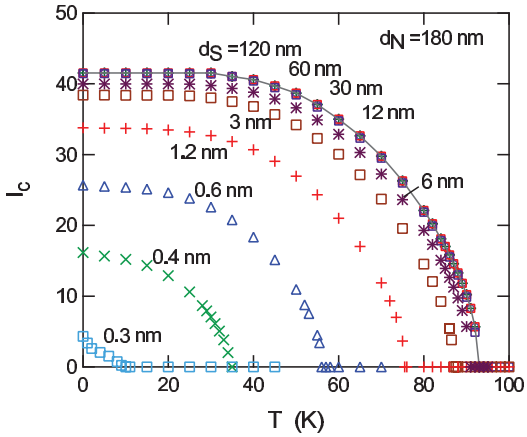

Fig. 6. Calculated results for the temperature dependence of I_c at various d_S values from 0.3 to 120 nm. The values for the parameters used are d_N = 180 nm, α = 0.09, and the other parameters are the same in Fig. 3. The Solid line depicts the case of d_S = 120 nm.

self-consistent results.

Figure 6 shows the temperature dependence of I_c for various values of d_S from 0.3 to 120 nm. The parameters in this case is $\alpha = 0.09$ and the other parameters are listed in the figure caption, which are almost the same as those in the previous calculations. It is clearly seen that I_c is totally suppressed when d_S is less than 0.3 nm. When d_S is thicker than 12 nm, the magnitude of I_c shows almost no change by the proximity effect. Similarly, when the normal metal layer is thicker than 60 nm, the numerical calculation results show no appreciable change relating to the change in d_N. Thus it becomes clear that the proximity effect can cause a significant reduction in the maximum Josephson current of the surface IJJ due to the proximity effect when $\alpha = 0.09$ or larger and $v_{FS} = 3 \times 10^7$ cm/s or larger.

5. Discussion

By the numerical calculation based on McMillan's tunneling model, it has become known that the Josephson critical current can be reduced to a considerable degree due to the proximity effect. By this point, we have assumed several values for the proximity parameters, of which important are the tunneling probability α and the Fermi velocity v_{FS} for the S layer. Since the degree of the proximity effect in McMillan's model is determined by the values for Γ_S and Γ_N, the degree of the influence is dominated by the value of α and v_{FS}/d_S. Namely, an increase of α exhibits the same effect as an increase in v_{FS} when the magnitude for Γ_S is the same. In the present study, we have adopted rather large values for α and v_{FS} as described in the preceding section. Actually, α can be much smaller than 0.1 and in this case, the present result is thought to be as an overestimation of the proximtiy effect.

In McMillan's tunneling proximity model, the diffusion of the pair density is mainly taken into account. This concept is effective in the case of a sandwich in which the Fermi velocity is nearly the same for both layers.

Another important point that must be reflected on is the d-wave symmetry of the order parameter in the BSCCO system. Since there is a node in the d-wave superconductor, diffusion of normal electrons into the superconducting layer is probable. The diffusion of normal electrons is not taken into account in the McMillan's model and therefore it is not reflected on the present result. The interdiffusion of normal electrons is particularly important in high-T_c superconductors, in which T_c and the critical Josephson current density J_c depends on the carrier density or doping level. Since the carrier type of high-T_c superconductors is the p-type, the diffusion of electron causes the superconducting layer to shift toward the underdoped side. This can be a cause of an extended proximity effect which results in a significant decrease in I_c. In turn, this implies that the proximity effect is largely mitigated when the doping level of the superconducting layer is in the overdoped region. Therefore, it also implies that the proximity effect becomes profound when the superconducting layer is in the underdoped range.

We cannot rule out the possibility of oxygen reduction from the top layer which causes underdoping in the superconductor. Zhao and his coworkers [8, 9] argue that evaporation of upper electrode metal in vacuum immediately after cleavage of a Bi-2212 crystal inevitably causes oxygen desorption to a greater or lesser degree depending on the evaporation rate. Since it is sufficiently likely that the excess oxygen atoms at the surface BiO layer can be desorbed during the evaporation process in vacuum, this causes the top CuO_2 layer to become more or less underdoped. When the top layer becomes underdoped, then the placement of a metal layer in close contact with the surface superconducting layer is sufficiently thought to bring about significant reduction in the Josephson critical current.

6. Conclusion

In order to explain the experimental result that I_c is significantly reduced for the surface junction in a stack of IJJs , we propose a model in which the proximity effect of the top normal layer in close contact with the junction is responsible for the phenomena. Numerical calculation based on McMillan's tunneling proximity model has revealed that the Josephson critical current I_c between the proximity sandwich and a single IJJ can be reduced to such a small level as observed experimentally under a limited condition. The condition is attained when the tunneling through a single BiO-SrO layer of 0.6 nm is sufficiently flourish or when the Fermi velocity of the superconductor in the normal direction is at least as large as 1/10 of a usual metal like Ag. The result also implies that oxygen reduction in vacuum should be taken into account and the reduced doping level enhances the proximity effect.

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