Tunneling Characteristics for nm-Thick Mesas Consisting of a Few Intrinsic Josephson Junctions

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Abstract. Very thin mesa structures consisting of a few intrinsic Josephson junctions have been fabricated on single crystal surfaces of Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$. In the fabrication procedure, annealing is conducted after the mesa structure is formed by Ar ion milling. Or, the annealing is skipped and, instead, the electrodes to the mesas have been deposited in vacuum immediately after crystals are cleaved. We have attained both uniform current-voltage ($I$-$V$) characteristics and small contact resistances, which are usually difficult to obtain at the same time in the case of nm-thick mesa structures. For the mesas thus fabricated, it is found that the Josephson critical current $J_c$ of the top IJJ (the surface junction) is reduced significantly. The reduction of $J_c$ is more significant when the doping level of the crystal used is lower. We argue that this is due to the proximity effect of the surface junction, in which the top electrode is in close proximity with the Ag or Au film of a thickness of the order of 300 nm. For mesas obtained by this method, the switching probability distribution has been measured. It is found that when the mesa lateral size is larger than 2 $\mu$m the switching is unrepeatable and lacking systematic temperature dependence. It is also found that escape temperature $T_{esc}$ and the standard deviation $\sigma$ for the switching probability distribution exhibits a large deviation from the Kramers’ thermal activation theory. When the lateral size is no larger than 2 $\mu$m, the switching probability distribution results show coincidence with the theory in the temperature range from 1.3 K to 5 K. Below 0.5 K, the escape temperature tends to saturate and indicates a crossover near 0.5 K from the thermal activation to the macroscopic quantum tunneling.

1. Introduction

It is known that the layered crystal structure of some high-$T_c$ superconductors functions as a stack of tunnel Josephson junctions. This was actually demonstrated in single crystals of Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ [1, 2, 3]. These junctions are called intrinsic Josephson junctions (IJJs). A significant feature of the IJJs is, among others, the very flat and smooth junction interfaces.
Another characteristic feature of the IJJs is the very thin superconducting layers, i.e., the CuO$_2$ double layers, of which the thickness is only 0.3 nm. Because of the interface properties, the IJJs exhibit almost ideal current-voltage ($I-V$) characteristics. Based on these properties, the observation of the macroscopic quantum tunneling in IJJs is attracting increasingly extensive interest with a view of application to the qubits[4, 5, 6, 7, 8]. On the other hand, because of the very thin superconducting electrodes, IJJs are strongly coupled to produce cooperative behaviors, giving rise to interesting phenomena such as magnetoresistance oscillation[9] or a recent observation of THz radiation[10]. When the number of IJJs connected in series in a stack is reduced, it is possible to observe the $I-V$ characteristics in a wide voltage range, which provide us with a means to probe into the physics of high-$T_c$ superconductors[11, 12]. This is because self-heating is reduced significantly in mesas consisting of a small number of IJJs and the true $I-V$ characteristics are likely to be observable in these mesas if they are composed of a few IJJs.

The fabrication of IJJ stacks consisting of a few IJJs is usually difficult. This is because a stack of IJJs always contains a few junctions which exhibit irregular $I-V$ characteristics. These irregular characteristics are caused by irregular junction shapes which result from the fabrication process[13]. Usually, these irregularities are most likely to result from the surface roughness which is generated before the mesa structure is fabricated by Ar ion milling. This is because the crystal surface after the milling is just a replica of the surface of the Au/Ag film, which is deposited after the cleavage of the crystal. The surface roughness is caused by the annealing, which is usually necessary to reduce the contact resistance in the case of the three-terminal-configuration mesa structure. In the present case, we need to attain both the regular thin mesa structures and the low contact resistance at the same time, which were often contradictory.

To this end, we have adopted two methods. In one method, we have reversed the order of the part of the fabrication process, and the milling is performed before the annealing. In the other, we have adopted a method of evaporating Au or Ag immediately after cleavage of a crystal in vacuum. By both methods, we were able to obtain small mesa structures which consist of a few IJJs and exhibit uniform $I-V$ characteristics with low contact resistances. These small mesa structures were adopted for the measurements of the switching probability distribution and the crossover temperature to the macroscopic quantum tunneling (MQT)[8]. It is found that both the standard deviation of the switching probability distribution and the effective escape temperature becomes almost temperature independent below approximately 0.5 K, which we argue is very close to the crossover temperature to MQT.

2. Sample fabrication and contact resistances

In the fabrication of small mesas exhibiting both uniform $I-V$ characteristics and low contact resistances, we have adopted two methods: the post-annealing method and the cleavage-in-vacuum method. In the post-annealing method, single crystals of Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ (Bi2212) were cleaved in air and then Au/Ag films were evaporated on the cleaved surface as soon as possible. Then, the cleaved single crystals were glued on a sapphire substrate with polyimide or In metal. Then the mesa structure was fabricated by Ar ion milling before the Au/Ag films were annealed in flowing oxygen at 400°C for 10 s and then 350°C for 20 min. In this method, the self-align technique is no more applicable for the deposition of the insulating layer. Therefore, the lateral size of the junction is limited to be no smaller than ~10 $\mu$m in the present study, where the standard photolithography was employed.

The mesa structures were fabricated by the standard photolithography in the case of lateral mesa size of larger than 2 $\mu$m or by the electron-beam lithography in the case of 2 $\mu$m or less. In the case of post-annealing method, the contact area between the mesa and the electrode was smaller than the mesa area to attain reliable insulation between the electrode and the pedestal.
In the cleavage-in-vacuum method, which was originally adopted by Zhao et al. [14], the Au/Ag films were evaporated immediately after the Bi2212 single crystals were cleaved in vacuum of less than $\sim 2 \times 10^{-6}$ Torr. We noticed that the vacuum pressure does not seriously affect the magnitude of the contact resistance.

In the case of post-annealing method, we were able to obtain a contact resistivity of as low as $\rho_{\text{cont}} = 2 \times 10^{-6} \, \Omega\text{cm}^2$. It should be noted that we also obtained a few orders of magnitude larger $\rho_{\text{cont}}$ values quite occasionally. In the case of the cleavage-in-vacuum method, we were able to attain very low values for $\rho_{\text{cont}}$ with reproducibility. In particular, a value of as low as $\rho_{\text{cont}} = 1 \times 10^{-7} \, \Omega\text{cm}^2$ was attained in the case of the cleavage-in-vacuum. For the purpose of the present study, sufficiently low contact resistances were obtained by both methods.

### 3. Current-voltage characteristics

Typical current-voltage ($I - V$) characteristics observed for a mesa fabricated by the post-annealing method are shown in Fig. 2. It is clearly seen in these $I - V$ characteristics that the contact resistance is sufficiently small. It is also seen that the $I - V$ characteristics are uniform, showing almost equal spacing of resistive branches and the almost equal magnitude of the Josephson critical current $I_c$ for all the junction except for the one representing the zero-voltage Josephson critical current.

In Fig. 3, the $I - V$ characteristics are shown for different mesas fabricated by the cleavage-in-vacuum method. Clearly, it is seen that the $I_c$’s are homogeneous and the resistive branches are equally spaced, indicating that the IJJ’s in the mesas are homogenous.

### 4. Significantly small $J_c$

In Fig. 3, three typical $I - V$ characteristics are shown for three different mesas fabricated by the cleavage-in-vacuum method. It should be noted that the magnitude of $I_c$ is significantly reduced compared with $I_c$ values for the other branches. It is quite natural to ascribe this...
Figure 3. $I - V$ characteristics for mesas of different doping levels, showing various zero voltage $I_c$ magnitudes. (a) $I - V$ characteristics for a mesa of an underdoped level. (b) $I - V$ characteristics for a mesa of a slightly underdoped level. (c) $I - V$ characteristics for a mesa of a slightly overdoped level. All the mesas were fabricated by the cleavage-in-vacuum method. Sizes and scales are shown in the figures.

reduced $I_c$ to the surface junction of the mesa structure, because the surface junction is in close proximity with the normal metal electrode on top of the mesa structure. It is observed that the magnitude of $I_c$ varies from less than 1/10 to a nearly similar proportion of the those for the other branches. There is a clear tendency that the magnitude of $I_c$ for the surface junction decreases with decreasing doping level, which we judged from the temperature dependence of $R_c$. This phenomenon is obvious and significant when the contact resistance is very small. In the present case, the superconducting layer of the surface junction is the CuO$_2$ double layer itself and very thin with a thickness of only 0.3 nm, while the normal layer is approximately 300 nm located in close proximity with the superconducting layer. Then, the quasiparticle diffusion into the superconducting layer from the normal layer and the pair diffusion in the opposite direction cause the reduction in the superfluid density. This is a kind of proximity effect in a sense that is opposite to the usual proximity effect, in which the very thin normal metal is in close proximity with a thick superconductor. We argue that due to this proximity effect, the surface junction has a lower $I_c$ value, and consequently the mesas in the present study have two different levels for $I_c$.

5. Switching probability distribution

Since the dynamics of a Josephson junction is equivalent to a point mass moving down a tilted washboard in which the coordinate is the phase and the mass is the capacitance of the junction. When the particle is inside a potential well, the phase is oscillating and once the particle escapes out of the potential then the particle continues to move down and the phase is rotating and the junction switches to the voltage state. The escape to the resistive state occurs either via thermally activated (TA) process or via macroscopic quantum tunneling (MQT). The switching probability to the resistivity is expressed by the following equation using the escape rate $\tau^{-1}$\textsuperscript{[15, 16]}

$$P(I) = \tau^{-1}(I) \left(\frac{dI}{dt}\right)^{-1} \left(1 - \int_0^I P(u)du\right).$$

The expression for $\tau^{-1}$ is different for both escape processes and for the TA escape process, it depends on temperature exponentially while it is temperature independent for the MQT process. The switching current distribution was measured by sweeping a current with a ramp of 1 mA/s and by accumulating $10^4$ switching events associated with the switching current magnitude. The details of the measurements were described elsewhere\textsuperscript{[8]}. 
We have measured the switching probability distribution for a number of IJJ mesas with different mesa lateral sizes. For large mesas in which the lateral size is larger than 2 \( \mu \)m, it was observed that the switching is unstable and probability distribution is unreproducible and even exhibits a double-peak structure [17]. When the Kramers thermal activation theory [15] is used to fit to the data, the effective escape temperature \( T_{\text{esc}} \) as a fitting parameter needs to have a pretty large value, sometimes exceeding 100K. Furthermore, the change with temperature is unsystematic and the data are forced to have a large scatter. We believe that this is due to the large junction size which is supposed to be larger than the Josephson penetration length \( \lambda_J \). In this case, the junction is no more capable of conveying homogeneous Josephson current and the switching becomes unstable to the fluctuation of external fields. In view of these preliminary experimental results, we adopted an IJJ mesa whose lateral length is 2 \( \mu \)m and the thickness is 3\text{~}\sim\text{~}4.5\text{~}nm, which corresponds to the IJJ number \( N \) of 2 or 3.

Figure 4 shows the \( I-V \) characteristics for the mesa, which was adopted in the low temperature measurements of switching probability down to 0.4 K. The magnitude of \( I_c \) observed in the switching probability measurements approximately 7 \( \mu \)A, which is significantly larger than that shown in Fig. 4. This is probably due to the elapsed time until the measurements were performed, during which the doping level increased in the surface junction. Figure 5 shows the switching probability density distribution at different temperatures, revealing temperature dependent \( I_c \) and the standard deviation \( \sigma \). The solid lines for 1.3 K, 2 K, and 3 K show the fits to the data by the Kramers thermal activation theory, indicating a good agreement. This implies that the switching probability density for the IJJ surface junction is explicable in terms of the TA theory.

The effective escape temperature \( T_{\text{esc}} \) obtained by the fitting is shown in Fig. 6, demonstrating the coincidence of \( T_{\text{esc}} \) with the bath temperature \( T \) in the temperature range from 1.3 to 5 K. At temperatures lower than 1 K, the values for \( T_{\text{esc}} \) deviates from \( T \) and tends to saturate below \( \sim 0.7 \) K. The same tendency is observed for the standard deviation \( \sigma(T) \) for the \( P(I) \) distribution [8]. When we estimate the MQT crossover temperature \( T_{\text{cr}} \) using the expression \( T_{\text{cr}} = \hbar \omega_p / 2 \pi k_B \), a value of \( T_{\text{cr}} = 0.37 \pm 0.02 \) K is obtained, if we employ values of \( \varepsilon_r = 5 \) and \( I_c = 10 \mu \)A[8]. This implies that the saturation of \( \sigma \) and \( T_{\text{esc}} \) below 0.7 K is indicative of a crossover to the MQT. Therefore, the present experimental result indicates that \( T_{\text{cr}} \) is a little below 0.5 K. The present evaluation of \( T_{\text{cr}} = 0.4 \sim 0.5 \) K is made on a surface IJJ on the top of the mesa structure, and the value is much higher than that obtained by Li et al.[7]. This implies that \( T_{\text{cr}} \) can be much higher even for a surface IJJ, which is in close proximity with a quasiparticle-populated normal metal.

6. Influence of the junction size

In the present case, \( J_c = 250 \) A/cm\(^2\) for the surface junction in the sample employed in the switching experiments. This value is clearly smaller than usual values for \( J_c \) in IJJJs of nearly optimally doped Bi\(_2\)Sr\(_2\)CaCu\(_2\)O\(_{8+\delta}\). In the stacked Josephson junction model, the Josephson
penetration depth $\lambda$ is expressed as $[18, 19]$ 

\[
\frac{1}{\lambda_J^2} = \frac{2e\mu_0 J_c}{h} \left( t + 2\lambda \coth \frac{d}{\lambda} \right),
\]

where $d = 0.3$ nm is the thickness of the superconducting layer, $t = 1.2$ nm is the thickness of the insulating layer, $\lambda = \lambda_{ab}/(d + t)[20]$, and $\lambda_{ab} = 170$ nm is the magnetic penetration depth in the $ab$ plane for the Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ system$[21]$. When $d, t \ll \lambda$, Eq. (2) becomes $\lambda_J^2 = hd/4e\mu_0 J_c \lambda^2$. Since $J_c = 250$ A/cm$^2$ for the surface junction, Eq. (2) leads to a value of $\lambda_J = 3.68$ µm, which is much larger than the junction size shown in Fig. 4. Even for the second junction, where $J_c = 600$ A/cm$^2$, we obtain a value of $\lambda_J = 2.38$ µm. Therefore, the present junction employed in the switching probability distribution measurements is a small junction and the Josephson current within the junction is regarded as sufficiently homogenous.

For a value of $J_c = 1000$ A/cm$^2$ for typical IJJJs, Eq. (2) provides an estimate of $\lambda_J = 1.84$ µm. From this, it is known that larger than 2 µm IJJ mesas on a side, the Josephson current is no more homogenous and the switching to the voltage state is unstable to the environmental fluctuation, which is the case in the preliminary experiments for larger IJJ mesas.

7. Influence of heating and nonequilibrium effect

In the present experiment, it is a matter of important concern how much temperature rise is caused by the self-injection of quasiparticle current into the IJJJs. According to the numerical calculation based on the Fourier’s law$[22]$, it is known that the temperature rise $\Delta T$ for a 2 µm
square 15 nm thick mesa reaches the stationary value within a few μs and its magnitude is approximately 1.8 K at an injection current of 200 μA or a current density of $2 \times 10^4$ A/cm$^2$ at 10 K. It is also known from the numerical analysis that $\Delta T$ is nearly equal to that of Au layer on top of the mesa, and $\Delta T$ is determined by the temperature rise of Au electrode surrounding the mesa with a thermal diffusion length $L$. In the present case, the current density is $2.5 \times 10^2$ A/cm$^2$, a value much lower than the above, so that we expect a temperature rise of $\Delta T = 2.8 \times 10^{-5}$ K at 10 K because the power dissipation is proportional to $J^2$ and the resistance is 1/10.

The specific heat of Au decreases from $2.2 \times 10^{-3}$ J/gK to $6 \times 10^{-6}$ J/gK at 1 K, and its thermal conductivity decreases from 2800 W/mK at 10 K to 700 W/mK at 1 K. All these changes cause an increase in $\Delta T$. Since the thermal diffusion length is $L = \sqrt{\kappa t/c_p \rho}$, where $\kappa$ is the thermal conductivity, $c_p$ is the specific heat, and $\rho$ is the density, and only a Au circle plate with a radius $L$ is heated by the time of $t$, then $\Delta T$ is expected roughly to be inversely proportional to $\kappa$, from the variation of which we obtain an estimate of $\Delta T = 2.0 \times 10^{-4}$ K at 1 K. Although this is simply a very rough estimate, we can infer that the temperature rise due to the injection of current is much smaller than 0.1 K. It is clear, however, that we need to elaborate on a more accurate numerical analysis in order to know the precise effect of the self-heating. However, it may be safely concluded that the temperature rise due to self-injection of quasiparticle current is much less than 0.1 K as far as the phonon temperature is concerned.

As for the nonequilibrium effect due to self-injection of quasiparticle current, there is no definite estimate for the time being because we need to know the pair recombination time for the Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ system, which has yet to be known. At present, it is anticipated that the $d$-wave superconducting order parameter makes the present system have a tendency to be less influenced by the quasiparticle injection as far as its magnitude is not large.

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