Observation of Macroscopic Quantum Tunneling in La$_{2-x}$Sr$_x$CuO$_4$ Intrinsic Josephson Juncions

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Abstract. We report on our success in (i) fabricating stacks of small intrinsic Josephson junctions using the high temperature superconductor La$_{2-x}$Sr$_x$CuO$_4$ ($x \approx 0.08$), and carrying out a reliable measurement of their switching current distributions. The standard deviation of the switching current converged below $\sim 5$ K, suggesting the occurrence of macroscopic quantum tunneling (MQT) below this temperature. It was also found that the distribution of switching current at MQT region is quite broader than that expected from the theory of conventional single Josephson junction model.

1. Introduction

The Josephson junction (JJ) is a treasure-house of quantum effects. The macroscopic quantum tunneling (MQT) from a meta-stable state formed within a tilted cosine potential of a current-biased JJ[1], as well as the energy level quantization (ELQ) within the potential well[2] are typical examples. These phenomena can be applied to a qubit implementation[3, 4], and have therefore lead over the years to intensive research activity. However, the temperature region where MQT and ELQ occur is extremely low ($\sim 100$ mK) in JJs artificially made of conventional superconductors, such as niobium or aluminum. This presents a major disadvantage for quantum computer applications.

In this respect, intrinsic Josephson junction stacks (IJJs)[5, 6], which are naturally built into the crystal structure of high temperature superconductor (HTSC), are promising candidates for qubit implementations due to their high Josephson plasma frequencies[7, 8]. The latter originates from the high critical current density which in turn reflects the atomic-scale flat structure. Kawabata et al. theoretically proposed that MQT can be observed in HTSC in spite of the presence of nodal quasi-particles which are characteristic to d-wave superconductor[9].

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Figure 1. (A): A scanning ion microscope image of intrinsic Josephson junction stacks (IJJs) of La$_{2-x}$Sr$_x$CuO$_4$ (LSCO). Two thin slits along the c direction (see arrows) are cut and slightly overlapped in the central part. The overlapped region acts as small intrinsic Josephson junction stacks (IJJs, white arrow). (B): A snapshot of the current-voltage characteristic at 0.7 K. The IJJs switches to a finite voltage state at the switching current $I_{SW}$ (red arrow), and shows a clear hysteresis in the returning quasi-particle curve.

Indeed, MQT was observed soon after in IJJs of Bi$_2$Sr$_2$CaCu$_2$O$_{8+δ}$ (BSCCO) by Inomata et al.[10], and in grain boundary biepitaxial JJ of YBa$_2$Cu$_3$O$_{7-δ}$ by Bauti et al.[11]. Moreover, interesting phenomena such as an $N^2$ enhancement of MQT rates ($N$ is the number of stacking IJJs) [12] have been also reported. MQT in IJJs has thus attracted much attentions in the past couple of years.

In IJJs of BSCCO, the crossover temperature $T^*$ below which MQT begins to occur is still considerably low ($\sim$ 1 K); access to such temperatures requires $^3$He or dilution refrigerator. La$_{2-x}$Sr$_x$CuO$_4$ (LSCO) has been known as a material having higher plasma frequency[7] than BSCCO. Hence the $T^*$ in IJJs of LSCO can be expected to be higher. Recently, we succeeded in fabricating small IJJs of LSCO which have a dimension comparable to the Josephson penetration depth $\lambda_J$[13]. In this report, we first describe the sample preparation procedures and the measurement techniques for obtaining the switching current distributions. Then we present the experimental results and discuss MQT in IJJs of LSCO.

2. Sample Preparation and Measurement of Switching Currents

Our bulk single crystal of LSCO was grown by the traveling solvent floating zone method[14]. The nominal concentration $x$ of Sr was 0.09. We fabricated micron-sized small IJJs by applying a focused ion beam etching in a small piece of the single crystal. Details of the fabrication process is described elsewhere[13]. A scanning ion microscope image of the small IJJs is presented in Fig. 1(A). The lateral size of the junction is about 1.1 $\times$ 1.3 $\mu$m$^2$, and the thickness is about 0.1 $\mu$m. The superconducting transition temperature was 21.5 K.

Switching events were measured in a $^3$He refrigerator. Four lead wires were carefully fed into the sample space via high impedance stainless steel coaxial cables which have attenuation of 80 dB at 5 GHz, and thermally anchored at 4 K stage. Switching current distributions $P(I_{SW})$ were measured at 0.5 - 11 K. We used the time-of-flight method; namely, we determined the switching current from the time delay between the beginning of the linear bias current ramp applied to the sample and switching of the IJJs to the finite voltage state. The measurement is performed using a time interval analyzer which has a resolution of 100 ps. Similar measurement techniques have been also proposed and developed by other groups[16, 17, 18]. $10^4$ switching events were recorded at each temperature.
Figure 2. (a): Probability distributions of the switching currents \( P(I_{SW}) \) at 0.7 - 7 K. (b): Standard deviations of the \( I_{SW} \) (distribution width of \( P(I_{SW}) \)). Inset: Enlarged figure of \( P(I) \) at 1.0 K, and a theoretical curve based on the single Josephson junction (SJJ) model. The following parameters were used for the calculation: the relative dielectric constant \( \epsilon_r = 25 \), the distance between superconducting CuO\(_2\) layers \( d = 0.66 \) nm, the capacitance \( C = \frac{\epsilon_0 \epsilon_r S}{d} = 480 \) fF, and the ramp rate of bias current \( \frac{dI}{dt} = 55.0 \) mA/sec. \( I_c = 709 \mu A \) was obtained as a fitting parameter.

3. Current-Voltage Characteristics and Switching Current Distributions
The current-voltage (\( I - V \)) characteristic for the IJJs of LSCO is presented in Fig. 1B). All the junctions simultaneously switched to the voltage state. Layer-by-layer switchings (the so-called multi-branch structure [5, 10]) were never observed in the course of ramping up the current. A similar feature was already observed in IJJs of BSCCO by Jin et al., who referred to this behavior as a “uniform switching”. However, contrary to their results, multi-branches were seen in the returning quasi-particle curve in our IJJs (not shown; see Ref. [13]). This controversial but interesting behavior is yet to be understood.

Fig. 2(a) shows the probability distributions of switching currents \( P(I_{SW}) \) of the IJJs in the temperature range 0.7 - 7 K. The profile of \( P(I_{SW}) \) becomes sharp with decreasing temperature, and ceases to exhibit a temperature dependence below \( \sim 5 \) K. The standard deviation \( \sigma(T) \) which characterizes the width of \( P(I_{SW}) \) (namely the fluctuation of the switching events) is shown in Fig. 2(b). \( \sigma(T) \) converges below \( \sim 5 \) K while attaining a strong temperature dependence above \( \sim 5 \) K. Since the MQT rate does not depend on temperature (see Eq. 1 shown below), this result suggests that MQT process dominates below \( \sim 5 \) K and the \( T^* \) is about 5.5 K. This exceptionally high \( T^* \) is attributed to the LSCO’s extremely high Josephson plasma frequency [7]. These findings lead us to anticipate the feasibility of phase qubit above liquid helium.

4. Analysis using MQT Theory of Single Josephon Junction
Finally we discuss our experimental results using MQT theory which is well established in the conventional single Josephson junction (SJJ) [19]:

\[
\tau_{MQT}^{-1} = 12\omega_p \left( \frac{3U(x)}{2\pi\hbar\omega_p} \right)^{\frac{1}{2}} \exp \left( -\frac{36U(x)}{5\hbar\omega_p} \right),
\]
where $\tau_{\text{MQT}}^{-1}$ is MQT rate, $U(x) \approx \frac{4\sqrt{2} \hbar L}{3e} (1 - \gamma)^{3/2}$ is the potential height ($\gamma = I/I_c \leq 1$, $I_c$: fluctuation free critical current). In addition, $\omega_p = \omega_{p0}(1 - \gamma^{2})^{1/4}$ is the plasma frequency of the junction at the bias current $\gamma$. $\omega_{p0} = \sqrt{2eI_c/\bar{h}C}$ is the plasma frequency at zero bias, $C$ is the junction capacitance. The calculated result is shown in the inset of Fig. 2(b) with the data at 1.0 K. The values of used parameters are indicated in the caption of Fig. 2. The calculated distribution is considerably narrower than the experimental result. Similar results in IJJs of BSCCO and EuBa$_2$Cu$_3$O$_{7-\delta}$ were also reported elsewhere. At present, there is no satisfactory explanations which can theoretically account for the observed broadening of the current distribution in IJJs. The electromagnetic coupling between IJJs should affect MQT, and may be a relevant factor responsible for the deviation from the SJJ case.

5. Summary

In summary, we succeeded in measuring the switching current distributions of intrinsic Josephson junction stacks of La$_{2-x}$Sr$_x$CuO$_4$ ($x \approx 0.08$). Standard deviations of the switching currents converged below $\sim 5$ K. This result strongly suggests that MQT can be realized temperatures higher than were previously achieved. It was also found that the distribution of switching current at MQT region is quite broader than that expected by the MQT theory of a conventional single Josephson junction.

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