Macroscopic quantum tunneling and thermal activation in a small mesa structured Bi$_2$Sr$_2$CaCu$_2$O$_y$ intrinsic Josephson junctions

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Abstract. A nanometer-thick small mesa consisting of only two or three Bi$_2$Sr$_2$CaCu$_2$O$_y$ intrinsic Josephson junctions (IJJs) is studied through the switching current distribution measurements down to 0.4 K. Experimental results clearly show that the first switching events from the zero-voltage state for $1 \text{K} < T < 4 \text{K}$ are successfully described by a conventional thermal activation (TA) theory for a single Josephson junction, and that they become independent of temperature below $T^* \sim 0.7 \text{K}$. We observe the microwave-induced peak in the switching distribution at 0.4 K, which is induced by the microwave irradiation at 55 GHz. These results strongly suggest that the system crossovers to macroscopic quantum tunneling (MQT) regime below $T^*$, which is as high as the previously reported value for a stacked IJJs with several tens of junctions, in contrast to the recent result on a similar mesa-structured surface IJJ.

1. Introduction

Recently, the observation of macroscopic quantum tunneling (MQT) in the current-biased intrinsic Josephson junction (IJJ) in a Bi$_2$Sr$_2$CaCu$_2$O$_y$ (BSCCO) single crystal attracts great interest as a new candidate for the so-called phase qubit [1, 2]. However, the use of stacked IJJs with almost the same critical current, $I_c$, gives rise to a serious problem that one cannot certify that a switching event to the first resistive state always occurs at the same junction when a bias current is repeatedly ramped up to measure the switching current. In order to avoid the complication by using stacked IJJs, a surface IJJ formed at the top of a small mesa with 5 IJJs was proposed by Li et al [3], since $I_c$ of the surface was significantly smaller than that of inner IJJs in the stack. Their results showing MQT behavior only below $\sim 0.1 \text{K}$ seem to provide another problem that the property of the surface IJJ may be seriously influenced by a thick normal-metal electrode.

In order to settle this issue, we performed the switching current distribution measurements of a nanometer-thick small mesa with only two or three IJJs. We carefully distinguished the switched junction from the others by using a large difference between the first and the second switching currents. Experimental results showed that the first switching events from the zero-
voltage state for $1 \text{ K} < T < 4 \text{ K}$ were successfully described by a conventional thermal activation (TA) theory for a single Josephson junction, and that they became independent of temperature below $T^* \sim 0.7 \text{ K}$, suggesting a crossover to the MQT regime. We also observed the microwave-induced resonance due to a single photon absorption between quantized energy levels at the lowest temperature ($\sim 0.4 \text{ K}$), which were expected to appear in the MQT regime. These observations strongly suggest that the system crossovers to the MQT regime below $T^*$, which is as high as the previously reported value for a stacked IJJs with several tens of junctions [1, 2], in contrast to the recent result on a similar mesa-structured surface IJJ [3].

2. Experimental methods
A nanometer-thick small mesa with a few IJJs was fabricated on a single crystal of BSCCO by using electron-beam lithography and Ar-ion milling techniques. The lateral sizes of the mesa are $2 \times 2 \mu\text{m}^2$. The number of included junctions, $N$, was confirmed by the observation of $I – V$ characteristics, as shown in Fig. 1(a). Parameters of the fabricated small mesa with a few IJJs are listed in Table I. $T_c$ is determined by a temperature where the resistance of the fabricated mesa becomes zero. $I_c$ is estimated by fitting the measured switching current distribution to a conventional TA theory for a single Josephson junction, as described below.

The probability distribution of the switching current from the zero-voltage state to the first resistive branch was measured at temperatures between 0.4 K and 10 K in a $^3\text{He}$ cryostat by repeating 5000–10000 switching events. The bias current was slowly ramped up with a constant rate of 1 mA/s. Other details of the experimental setup including the methods to exclude high-frequency noise from the IJJ sample are described elsewhere [4].

| Sample | size ($\mu\text{m}^2$) | $N$ | $T_c$ (K) | $I_c$ ($\mu\text{A}$) |
|--------|----------------|----|--------|------------|
| M      | $2 \times 2$  | 2  | 74     | 10         |
| N      | $2 \times 2$  | 3  | 43     | 2.7        |
| R      | $2 \times 2$  | 3  | 50     | 6.3        |

3. Results and discussion
Figure 1(a) shows the typical $I – V$ characteristics of a small mesa with only two IJJs (sample M), measured at $T = 5 \text{ K}$. The voltage jump for the first switching is about 10 mV, which is larger than the previously reported value for a similar small mesa with 5 IJJs [3]. The large difference between the first and the second switching currents allows us to distinguish the corresponding switched junction from the others. These results suggest that the fabricated small mesa samples are sufficiently high quality to investigate the switching properties in TA and MQT regimes.

Figure 1(b) shows the switching current distributions, $P(I)$, at several temperatures for the first switching events. In the conventional TA theory for a single Josephson junction in the underdoped regime [5], $P(I)$ is given by $P(I) = \tau^{-1}(I)(dI/dt)(1 - \int_0^I P(u)du)$. Here, $\tau^{-1}(I)$ is an escape rate from the zero-voltage state to the finite voltage state, which is given by $\tau^{-1}(I) = (\omega_p/2\pi)\exp[\Delta U(I)/k_BT_{\text{esc}}]$, where $\omega_p$ is the current-dependent Josephson plasma frequency, $\Delta U(I)$ is the potential barrier in a tilted-washboard potential well, and $T_{\text{esc}}$ is an effective temperature at the escape event from the zero-voltage state, respectively. As shown in Fig. 1(b), we found that the experimental data (solid symbols) of $P(I)$ from 4 K down to 1.3 K...
were successfully fitted with the theoretical calculations (solid lines) in the TA regime using $I_c$ and $T_{\text{esc}}$, which was equal to the bath temperature.

Figure 2(a) shows the standard deviation, $\sigma(T)$, of $P(I)$ measured for samples M and N as a function of temperature. We observed that the behaviors of $\sigma(T)$ were divided into the following three temperature regions; (i) the lower temperature region (roughly below 1 K), where $\sigma(T)$ is almost independent of temperature, suggesting that the system crossovers to the MQT regime; (ii) the intermediate temperature region (roughly from 1 K to 4 K), where $\sigma(T)$ is proportional to $T^{2/3}$, suggesting that the system enters in the TA regime; (iii) the higher temperature region (roughly above 4 K), where $\sigma(T)$ is deviated from the behavior proportional to $T^{2/3}$, suggesting that the system crossovers to the phase-retrapping regime. Note that these behaviors qualitatively agree with the previously reported results by Li et al. [3]. However, the crossover temperature, $T^*$, which is experimentally estimated as a crossing point between the MQT behavior and the TA behavior, was found to be much higher than the value for the surface IJJ reported by Li et al [3]. Our results is rather similar to the values for the stacked IJJ with several tens of junctions [1, 2].

We also measured $P(I)$ under the microwave radiation in the frequency range between 40 GHz and 60 GHz at the lowest temperature ($\sim$0.4 K), as shown in Fig. 2(b). We observed that a resonant peak was developed in the lower current region of $P(I)$ with increasing the microwave power at 55 GHz, suggesting that the MQT process from the excited state was induced by the microwave radiation. Using the estimates of $I_c$ (=$6.3 \mu A$) and the junction capacitance, $C$ (=147.6 fF), the observed resonance peak corresponds to a single photon absorption rather than the previously reported multiphoton absorption [2].

These results strongly support that the observed MQT behaviors are common to the mesa structured IJJs with a few junctions and the stacked IJJs with several tens of junctions, suggesting that these phenomena are intrinsic to a single IJJ of BSCCO, independent of device structures.
Figure 2. (a) Temperature dependence of the standard deviation of $P(I)$ for the samples M and N. Solid lines are the theoretical calculations in the TA regime, which is proportional to $T^{2/3}$. Dashed lines are the guides to eyes for the MQT regime. (b) Probability distribution of switching current for the sample R under the microwave irradiation. Microwave power is measured at the output port of the microwave synthesized sweeper.

4. Conclusion
We studied the switching current distribution of the nanometer-thick small mesa consisting of only two or three IJJs. Our results clearly showed that the first switching events in the intermediate temperature region ($1 \text{ K} < T < 4 \text{ K}$) were successfully described by the conventional TA theory for a single Josephson junction. The crossover temperature, $T^*$, from the MQT regime to the TA regime was found to be as high as the values for the stacked IJJ with several tens of junctions, in contrast to the previous results on the similar mesa-structured surface IJJ. We also observed the microwave-induced peak in the switching distribution at 0.4 K, which was induced by the microwave irradiation at 55 GHz. Thus, we conclude that the observed MQT behaviors are intrinsic to the single IJJ of BSCCO, independent of device structures.

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