Comparison between the first- and the second-junction switchings in a small stack of Bi$_2$Sr$_2$CaCu$_2$O$_y$ intrinsic Josephson junctions

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Abstract. We measured the switching current distributions of the first- and the second-junction switchings in a small stack of Bi$_2$Sr$_2$CaCu$_2$O$_y$ intrinsic Josephson junctions. Switching distribution for the first switching from the zero-voltage state became independent of temperature below 0.8 K suggesting the crossover from thermal activation to macroscopic quantum tunneling. On the other hand, switching distribution for the second switching from the first resistive state showed the similar temperature-independent behavior up to much higher temperature than the crossover temperature for the first switching. We argue that it cannot be explained in terms of self-heating owing to the dissipative currents after the first switching.

1. Introduction

High temperature cuprate superconductor such as Bi$_2$Sr$_2$CaCu$_2$O$_y$ (Bi2212) is extremely anisotropic layered compounds which exhibits a stack of the so-called intrinsic Josephson junctions (IJJs)[1]. IJJs have proved to be a rich source of physical interests and of attractive applications[2]. One of the great interests is the application for quantum bits (qubits). Many recent studies of superconducting qubits were performed using a single Josephson junction of conventional superconductors[3]. These qubits were, however, operated at extremely low temperatures below 0.1 K. Recently, macroscopic quantum tunneling (MQT) was observed up to $\sim$1 K in Bi2212 IJJs[4, 5]. These results show the possibility to operate the qubits at higher temperatures. However, some of the physical nature lying in the IJJs are still unclear, such as the enhancement of the MQT rate for the “uniform switching”[5]. Moreover, for the second switching in the multiple branches of the current-voltage characteristics, the recent study reported that the temperature-independent behavior observed below $\sim$ 8 K was not attributed to MQT but to the self-heating effect[6]. Hence the escape process of each junction switching should be investigated more carefully.

The current-biased single Josephson junction can be well described by a particle moving in a tilted cosine potential. In this model, the escape from the potential well corresponds to the voltage switching. At higher temperatures, the escape rate is explained by the thermal activation (TA) given by[7], $\tau^{-1}(I) = (\omega_p/2\pi)\exp(\Delta U/k_BT)$, where $\Delta U$ is the potential barrier, $\omega_p$ is the
The $I-V$ characteristics of the IJJs at 4.5 K. (b) Switching distributions for the first switching at several temperatures. (c) Similar distribution for the second switching.

current dependent plasma frequency, and $k_B$ is the Boltzmann constant. At lower temperatures, MQT is the dominant process where the escape rate becomes independent of temperature\cite{8}. The crossover temperature can be estimated by $T_{cr} \sim \hbar \omega_p/2\pi k_B$. In order to obtain the escape rate experimentally, we measured the switching current probability distribution, $P(I)$, which was acquired by measuring the junction switching currents repeatedly. $P(I)$ is related to the escape rate by, $P(I) = \tau^{-1}(I)(\frac{dI}{dt})(1 - \int_0^I P(u)du)$. Therefore, $P(I)$ can be calculated if the critical current, $I_c$, and the junction capacitance are provided. $I_c$ is determined as a fitting parameter.

In this paper, we compare the switching distribution between the first- and the second-junction switchings. The first switching shows the MQT behavior below 0.8K which is consistent with the estimated crossover temperature of the single Josephson junction model. On the other hand, the second switching shows the temperature-independent behavior up to much higher temperature than the estimated crossover temperature. We discuss that this behavior cannot be explained only by the self-heating effect, through the measurements of the switching distribution with various pulse widths.

2. Experimental methods

In order to study IJJs, we fabricated a few hundreds of stacked IJJs on a narrow bridge Bi2212 single crystal with the lateral sizes of $1 \times 1 \mu$m and thickness of $\sim 300$ nm corresponding to $\sim 200$ junctions by using the focused ion beam technique. The switching current probability distribution, $P(I)$, for the first switching (or the second switching) was measured down to 0.42 K in a $^3$He cryostat. When the bias current was increased, the junction switched from zero voltage state (or the first resistive state) to the first resistive state (or the second resistive state). $P(I)$ can be obtained by measuring these switching currents repeatedly. We measured the switching currents for typically 5000~10000 times. Other details of the fabrication methods and of the experimental setup are described elsewhere\cite{9}.
3. Results and discussion

Figure 1(a) shows the $I$ – $V$ characteristics of IJJs. The clear hysteresis and the large voltage jumps, typically $\sim 25$ mV, assure the high quality of our junctions. The large difference between the first and the second switching currents and between the second and the third switching currents allowed us to distinguish the corresponding switched junction from the others. The measurement of $P(I)$ was performed for the first switching from the zero voltage state and for the second switching from the first resistive state. $P(I)$ of the first switching is shown in Fig. 1(b). Below 0.8 K, $P(I)$ of the first switching becomes temperature independent suggesting the crossover from TA to MQT. In order to see this behavior clearly, it is useful to calculate the standard deviation, $\sigma$, of $P(I)$ shown in Fig. 2(a). At higher temperatures, $\sigma$ decreases as temperature decreases which is well fitted by the TA theory, while it saturates below 0.8 K. The crossover temperature was estimated as 0.8 K by using the current dependent plasma frequency ($\omega_p = 650$ GHz), which shows a good agreement with our result. Thus, the escape process in the first switching can be well explained by the TA and the MQT processes in the single Josephson junction model.

$P(I)$ and $\sigma$ for the second switching are shown in Figs. 1(c) and 2(a), respectively. The behavior of the second switching is qualitatively similar to that of the first switching, that is, $\sigma$ decreases as the temperature decreases at higher temperatures while it saturates at low temperatures. However, the saturation temperature of the second switching, $\sim 8$ K, is much higher than that of the first switching and than that of the estimated crossover temperature, $\sim 1.3$ K, calculated by the critical current 22.3 $\mu$A and the junction capacitance in the same way as the first switching. The increase of the saturation temperature was previously reported and considered to be the self-heating effect which is assumed to occur from the dissipative current after the first switching[6]. In order to check the influence of the self-heating, we measured $P(I)$ of the second switching by applying the ramp current with different pulse widths.

Figure 2. (a) Temperature versus the standard deviation of $P(I)$ for the first and the second switching. The solid lines are the calculation using the TA theory. (b) The escape rate of the second switching measured by different pulse widths. The solid line is the calculation using the TA theory with $T = 10.20$ K.
Figure 2(b) shows the escape rate measured by each pulse width. It is clear that the escape rate is independent of the pulse width. In addition, the escape rate can be well fitted with only one temperature, 10.2 K, in the current range from 14 µA to 17 µA. The latter behavior also assures that the self-heating effect is negligibly small, since the amount of Joule heating depends on the magnitude of biased current. Our recent study of the comparison between the mesa-type sample and the narrow-bridge-type sample also suggests that the heating effect is negligibly small[9]. There are several candidates for explaining the unusual behavior in the second switching, such as the quasiparticle injection after the first switching or the MQT process for the second switching. Unfortunately, the origin for such unusual behaviors for the second switching remains unknown at present [9]. New experiments to resolve this issue are in progress.

4. Conclusion
We measured the switching current distributions of the first- and the second-junction switchings in a small stack of Bi2212 intrinsic Josephson junctions. Switching distribution of the first switching from the zero voltage state shows the MQT behavior below 0.8 K which is consistent with the estimated crossover temperature of the single Josephson junction model. On the other hand, switching distribution of the second switching from the first resistive state showed the temperature independent behavior up to much higher temperature than the estimated crossover temperature. Our experimental results strongly indicated that this unusual behavior could not be explained by the self-heating effect owing to the dissipative currents after the first switching.

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