Systematic Enhancements of Switching Rate in Intrinsic Josephson Junctions

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Abstract. We measure the switching probability distributions of the first and second switching in the stack of Bi₂Sr₂CaCu₂O₈⁺ and Bi₂Sr₂Ca₂Cu₃O₁₀⁺ intrinsic Josephson Junctions. The saturation temperature of the first switching in Bi₂212 is ~ 2 K. This temperature is almost same in Bi₂223. It is a little higher than crossover temperature estimated from thermal activation. On the other hand, in the second switching, the saturation temperature in Bi₂212 is ~ 10 K, while it is ~ 2 K in Bi₂223. Surprisingly, the high saturation temperature is observed only in Bi₂212, although the difference of the two materials is only the thickness of the superconducting layer. This result suggests that the high saturation temperature of the second switching in the stack of Bi₂Sr₂CaCu₂O₈⁺ is caused by capacitive coupling effects.

1. Introduction

High-Τc superconductors Bi₂Sr₂Caₙ₋₁CuₙO₄₊2n₊δ (BSCCO) are highly anisotropic and their transport properties along the c-axis are described as stacks of weakly coupled Josephson junctions with (CuO₂)ₙ layers being superconducting electrodes and Bi₂O₂ layers being barrier layers. These systems are referred as intrinsic Josephson junctions (IJJs) in contrast to artificially stacked multi-layered Josephson junctions. In IJJs, inductive (magnetic) coupling between stacked Josephson junction is essential because the separation between Josephson junctions are much shorter than the London penetration depth [1]. Furthermore, capacitive (charge) coupling is relevant because charge conservation within the superconducting layers does not hold due to the short Thomas-Fermi screening length ~ 1 nm being comparable to the interlayer separation [2]. These interactions emerges in phase dynamics in stacked IJJs observed as switching properties of connected IJJs in series.

The current-biased single Josephson Junction can be well described by the RCSJ (resistively and capacitively shunted junction) model, which depicts the phase dynamics as motion of a phase particle in a tilted washboard potential. The macroscopic quantum tunneling (MQT) is described as the quantum tunneling of the phase particle through the potential barrier due to Josephson plasma oscillation. The most sensitive measure for the phase dynamics is the switching probability distribution (SPD), the histogram of current where a Josephson junction switches from superconducting (R = 0) to resistive state (R ≠ 0). MQT in Bi₂212 IJJ has been observed as low-temperature saturation of the SPD width below 1 K, which is one order of magnitude higher than that of a single Josephson junction made by metallic superconductors like...
Nb/AlOx/Nb [3]. This raised crossover temperature between MQT and thermal activation (TA) has been explained by high critical current density \( j_c \) of Bi2212 IJJ. The crossover temperature can be estimated by \( \sim \hbar \omega_p/2\pi k_B \), where \( \omega_p \) is the current dependent plasma frequency which is roughly consistent with \( \sqrt{\varepsilon_c} \), and \( k_B \) is the Boltzmann constant.

More interestingly, it has been reported that the SPD width saturates around \( \sim 10 \) K for the second switching, where another IJJ included in the stack switches to resistive state subsequent to the first switching \([4, 5]\). The origin of the further enhancement is possibly attributed to interaction between adjacent IJJs, which can be described by coupled phase particles in a tilted washboard potentials. However, heating artifact cannot be excluded from the possible origins of the enhancement.

In this paper, we present systematic difference on the first and second switchings of the stack of Bi2212 and Bi2223 single crystal with the sizes of 1 \( \times \) 1 \( \mu \)m\(^2\) by using electron-beam lithography and Ar-ion milling. The details of mesa-fabrication are described elsewhere \([6]\). The mesa structure has advantages against the Z-type bridge structures in the following reasons. Heating in the IJJs is removed by the thick Ag electrode covering the top of the IJJs. The first switching definitely takes place at the topmost IJJ among the stacked IJJs because the critical current of the topmost IJJ is suppressed due to the proximity effect. The second switching is presumably induced in the adjacent IJJ, the second topmost IJJ in the mesa, when the inter-IJJ is taken into consideration.

Switching probability distributions were measured with following system. First, send a start signal to the counter and the constant current source. Second, the ramp current flows to the IJJs from the zero-voltage to the first or second resistive state. A stop signal is sent when the junction switches. The counter measures the elapsed time from the start signal to the stop signal. Switching current is calculated by multiplying the measured time and the ramp rate of the bias current. To reduce external noise, we used optical fibers which separates the constant current source and IJJs from the AC supply. We prepared home-made constant current source driven by DC stabilized voltage source to avoid external noise and the influence of changing resistance by switching. This current source consists of integrating circuit and voltage controlled current source.

Effective temperature \( T_{\text{eff}} \) is a parameter representing fluctuation of the switching and is derived by fitting the TA model to the experimental data. The saturation temperature \( T_s \) is the highest temperature of the temperature independent region in the plot of \( T_{\text{eff}} \) versus bath temperature \( T_{\text{bath}} \) measured by temperature sensor.

3. Results and discussion

Figure 1 shows \( I-V \) characteristic and \( T_{\text{eff}} \) vs \( T_{\text{bath}} \) plots for the Bi2212 mesa. The critical current densities are found to be 2.0 kA/cm\(^2\) and 3.0 kA/cm\(^2\) for the first and second switchings, respectively. The saturation temperature \( T_s \) of the first switching in Bi2212 is \( \sim 2 \) K, which is slightly higher than the crossover temperature estimated from \( j_c \), which is \( \sim 0.72 \) K in Bi2212. Figure 2 represents the similar plots for the Bi2223 sample. In (a), \( j_c \) is found to be 0.7 kA/cm\(^2\) and 0.8 kA/cm\(^2\) for the first and second switchings, respectively. \( T_s \) of the first switching
is approximately 2 K, slightly higher than the estimated crossover temperature $\sim 0.54$ K. These results show that the first switching is roughly described by the single junction model and there exists no essential difference between Bi2212 and Bi2223.

The second switching indicates essential difference between Bi2212 and Bi2223. $T_s$ of the second switching in Bi2212 is $\sim 10$ K, one order of magnitude higher than $T_s$ of the first switching, as well as the previous reports [4, 5], and $T_{\text{eff}}$ starts to merge to the TA model at $T_{bath} = 10$ K. This is in sharp contrast to the result in Bi2223, in which $T_{\text{eff}}$ of the second switching is almost identical to $T_{\text{eff}}$ of the first switching except above 10 K, where the phase diffusion takes place for the first switching. Increase in $j_c$ of the second switching in Bi2212 is not sufficient to explain the enhancement of $T_s$ because the crossover temperature is given by $\sqrt{j_c}$ according to the single junction model. Moreover, the $T_s$ enhancement of the second switching in Bi2212 has been reported in stacks with uniform $j_c$ [5]. The possibility of the heating artifact is also excluded because the self heating and thermal properties are identical for the Bi2212 and Bi2223 mesas. Therefore, the present results clarify that the enhancement of $T_{\text{eff}}$ observed in Bi2212 is a result of coupling between IJJs. Switching of the second topmost IJJ of the stack is induced by the running state of the phase particle of the first topmost IJJ.

The enhancement of $T_s$ is observed only in Bi2212 although the difference between the two materials is nothing but the presence of a planar CuO$_2$ superconducting layer inserted between CuO pyramids. It is surprising that only 0.35 nm increase in the thickness of superconducting electrode completely depresses the enhancement of the second switching in the MQT state.
This drastic change within atomic length-scale suggests that the phase dynamics between two adjacent IJJs are coupled by the capacitive coupling. The enhancement of the second switching is the unique phenomenon in which the capacitive coupling plays dominant role as far as our knowledge.

4. Conclusion

We measured SPDs of the first and second switching in the stack of Bi2212 and Bi2223. The first switching shows the similar behavior in Bi2212 and Bi2223. However the second switching is strongly enhanced in Bi2212 in comparison with the first switching, whereas in Bi2223 the second switching is essentially same as the first switching. It is considered that the enhancement of the second switching is attributed to the capacitive coupling effect because of the drastic depression by the presence of the third CuO$_2$ layer.

Reference
[1] Sakai S, Bodin P and Pedersen N F 1991 J. Appl. Phys. 73 2411
[2] Koyama T, and Tachiki M 1996 Phys. Rev. B 54 16183
[3] Inomata K, Sato S, Nakajima K, Tanaka A, Takano Y, Wang H B, Nagao M, Hatano II and Kashiwaya S 2005 Phys. Rev. Lett. 95 107005
[4] Kashiwaya H, Matsumoto T, Shibata H, Kashiwaya S, Eisaki H, Ysohida Y, Kawabata S and Tanaka Y 2008 Phys. Soc. Jpn 77 104708
[5] Ota K, Hamada K, Takemura R, Ohmaki M, Machi T, Tanabe K, Suzuki M, Maeda A and Kitano H 2009 Phys. Rev. B 79 134505
[6] Kakeya I, Hamada K, Tachiki T, Watanabe T and Suzuki M 2009 Supercond. Sci. Technol. 22 114014