Enhancement of macroscopic quantum tunneling in the higher-order phase switches of Bi2212 intrinsic Josephson junctions

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Abstract. The macroscopic quantum tunneling (MQT) in the current-biased intrinsic Josephson junctions (IJJs) of high-$T_c$ cuprates has attracted much attention for decades. Although the MQT for the phase switches from the zero to the first voltage state (1st SW) in the multiple-branched $I$-$V$ curves is well explained by the conventional theory, the occurrence of MQT for the higher order switches such as the switch from the 1st to 2nd voltage state (2nd SW) has been still debated. Here, we present an experimental study on the phase switches of small IJJs fabricated from underdoped Bi$_2$Sr$_2$(Ca,Y)Cu$_2$O$_y$. We observed the single photon transition between quantized energy levels in the 3rd phase switches at 59.15 GHz and 2 K. The comparison with the previous studies on the nearly optimal-doped Bi$_2$Sr$_2$CaCu$_2$O$_y$ clearly suggests a possibility that the MQT rate for the higher-order phase switches is commonly enhanced by the effective suppression of the energy barrier for the higher-order phase escape due to the phase-running state after the 1st SW, in spite of the large difference in a critical current density and $T_c$.

1. Introduction
Macroscopic quantum tunneling (MQT) in a superconducting Josephson junction (JJ) is one of interesting phenomena to study the quantum-mechanical behavior of a macroscopic degree of freedom [1]. MQT occurs in the stochastic switch from the zero voltage state to the finite voltage state in the current-biased JJ below a crossover temperature $T_c$ [2] and is closely related with the energy level quantization (ELQ) in a potential well to describe the dynamics of the superconducting phase difference across the junction [3]. In early studies on MQT and ELQ [2, 3] providing the fundamental of superconducting qubits in quantum information technology of the moment, the single tunnel junctions, which were artificially fabricated on conventional superconducting films, have often been investigated.

On the other hand, the intrinsic Josephson junctions (IJJs) of high-$T_c$ cuprate superconductors provide another type of JJs that are naturally stacked in the layered crystal structure and mutually connected in an atomic scale [4]. Compared with the artificial JJs fabricated with integrated circuit technology, IJJs have great advantage such as a high critical current density $j_c$, an almost perfectly smooth tunnel junction, and the negligible influence of dissipative quasiparticles lying in the node of $d$-wave superconducting gap to the MQT rate [5]. These remarkable properties benefit an increase of
$T_c$ to the quantum phase escape, as was successfully demonstrated in a small stack of IJJs made of Bi$_2$Sr$_2$CaCu$_2$O$_y$ (Bi2212) [6].

However, in contrast to the conventional JJs, the dynamics of the phase difference across each junction in IJJs is expected to be more complex, as suggested by the fact that the thickness of the superconducting layer and the distance between junctions in IJJs are much smaller than those of artificially-fabricated JJs. Actually, this fact gives a good explanation about the multiple-branched current-voltage ($I$-$V$) characteristics observed for stacked IJJs [7]. It seems that the small thickness of superconducting layers enhances the fluctuation of phase differences and that the small distance between JJs induces the strong correlation between the phase differences in IJJs. Thus, it is quite interesting to study MQT and ELQ in IJJs in the sense that the phase-running state in a phase-switched junction can affect the phase switching dynamics in another junction near by the junction.

Unfortunately, in the previous studies on MQT in IJJs [6,8], only the quantum phase escape from the zero to the first voltage state (1st SW) was well established by the conventional theory, while the occurrence of MQT in the higher-order phase switches, such as the switch from the first to the second voltage state (2nd SW) or that from the second to the third state (3rd SW), has still been unresolved [9-12]. Note that the conventional theory [1] was based on single JJs and has not considered the strong correlation between junctions. The only exception is the recent theories discussing about the strong electromagnetic coupling between JJs [13,14], which is considered to play an important role in the uniform switches where several junctions in IJJs are simultaneously switched from the zero voltage state [15].

Thus, we focus on the dynamics of the higher-order phase switches in IJJs. Recently, we reported a study on the microwave-induced resonance in the switching current distribution $P(I)$ for the 2nd SW, surviving up to roughly $\sim$$10$ K [16]. This strongly suggests that the macroscopic phase difference across the 2nd switched junction shows a quantum-mechanical behavior below $\sim$$10$ K. This temperature is also close to a temperature $T^*$, below which the MQT-like behavior for the 2nd SW appears, although it is much higher than both values of $T_c$ reported for the 1st SW [6,8] and predicted for the 2nd SW using the conventional theory. If a rapidly-oscillating supercurrent generating in the phase-running state after the 1st SW practically influences the phase dynamics in the 2nd switched junction through the strong correlation between junctions [17], the presence of the oscillating current is reminiscent of the strong irradiation of microwaves, which can enhance MQT rate through an effective suppression of the potential barrier for the phase escape [18]. This scenario seems to explain consistently our experimental results.

In this paper, we present a study on the higher-order phase switches in another stack of IJJs, fabricated from the underdoped Bi$_2$Sr$_2$CaCu$_2$O$_y$ ($\text{Y-doped Bi2212}$) with $T_c$ ~ 47 K, and compare it with the previous studies on the nearly optimal-doped Bi2212 with $T_c$ ~ 83-85 K [12,16]. We confirm that the MQT-like behavior and the microwave-induced resonance in $P(I)$ for the higher-order phase switches are commonly observed, independent of the carrier doping concentration. We also succeeded in detecting the single photon transition between quantized energy levels for the 3rd SW, which could be realized by the strong suppression of $j_c$ in Y-doped Bi2212. The comparison of $T^*$ for the 3rd to 5th SW in Y-doped Bi2212 and that for the 2nd to the 4th SW in the nearly optimal-doped Bi2212 clearly suggests that $T^*$ is not determined by $j_c$, in contrast to the conventional theory, rather it is roughly scaled with $T_c$. These results prove that the observed MQT-like behavior for the higher-order phase switches is not influenced by noise in our experimental setup and that it should be explained by a novel mechanism that has not been considered in the conventional theory.

2. Experiments and analyses

Y-doped Bi2212 single crystals were grown by the floating zone method and annealed in the same condition as the nearly optimal-doped Bi2212. We fabricated a small bridge-type IJJ device with a lateral size of $2.3 \times 1.9$ $\mu$m$^2$ by using the focused ion beam (FIB) milling techniques [12], as shown in the inset of Fig. 1(a). The switching current distribution $P(I)$ for the 3rd to the 5th SW was measured from 2 K to 24 K by applying a bias current with a constant rate $dI/dt$=$5$ mA/s under 5,000 or 10,000
switching events. The measured \( P(I) \) and the switching rate \( I(I) \) were analyzed by considering both the thermally-activated (TA) phase escape and the subsequent phase retrapping (PR) processes [17]. Other details on our experimental setup and analyses are described in our previous papers [10,12,16,17,19].

3. Results and discussion

Figure 1(a) shows the typical \( I-V \) characteristics of the bridge-type IJJs measured at 3 K, suggesting that the switching currents \( I_{SW} \) for the 1st and the 2nd SWs are strongly suppressed, compared to those for other SWs higher than the 3rd SW. This is presumably due to the damage given by FIB milling or the disorder derived by Y substitution for Ca. The recent transmission electron microscope (TEM) study reports that the thickness of the FIB damage in stacked IJJs made of Bi2212 can be reduced to about 30 nm by using Ga\(^+\) ion beam emitted at 50 pA and 30 kV [20]. Considering the fact that the bridge-type IJJs made of Bi2212 where the Ca site is not substituted by Y show much higher \( I_{SW} \) for the 1st and 2nd SWs [6,10,12], the observed strong suppression of \( I_{SW} \) for the 1st and 2nd SWs in Y-doped Bi2212 is probably attributed to strong disorders in the superconducting CuO\(_2\) bilayers where the Ca\(^{2+}\) ions sandwiched by two CuO planes is partly replaced by Y\(^{3+}\) ions.

On the other hand, the resistive branches higher than the 2nd branch are almost equally spaced and have relatively large switching currents, suggesting that the intrinsic junctions other than the weakest and next weakest junctions among IJJs are not degraded by Y substitution. Thus, \( P(I) \) and \( I(I) \) for the 3rd to the 5th SW were measured at several temperatures up to 24 K. Figures 1(b) and 1(c) show \( P(I) \) and \( I(I) \) for the 4th SW, respectively. They were successfully fitted to numerical results by a single junction model considering both the TA escape and the multiple PR process, as shown by solid lines in Figs. 1(b) and 1(c). We confirmed that the influence of PR events after a TA escape, which produced a negative curvature in logarithmic plots of \( I(I) \), was more prominent with increasing the order of phase

Figure 1. (a) \( I-V \) characteristic of the bridge-type Y-doped Bi2212-IJJs measured at 3 K. The inset shows an image of scanning ion microscope of the IJJ device. (b) (Color online) \( P(I) \) for the 4th SW as a function of bias current. Solid circles and solid lines are experimental results and numerical calculations, respectively. (c) (Color online) \( I(I) \) for the 4th SW as a function of bias current. Solid circles and solid lines are the same as (b).
switches from the 3rd SW to 5th SW. This trend is also confirmed by our previous study on the higher order phase switches for Bi2212-IJJs [17].

The microwave-induced resonance in \( P(I) \) for the 3rd SW was observed at 59.15 GHz and 2 K, as shown in Fig. 2(a). Note that there is almost no change in \( P(I) \) located at near 7 \( \mu \)A, corresponding to the primary peak of \( P(I) \), with increasing the irradiation power of microwaves up to a power at which the resonant double-peak structure appears in \( P(I) \). This behavior shows a sharp contrast to the recent results on the resonant phase escape due to the three-photon absorption for the 2nd SW in Bi2212-IJJs [16]. We estimated the energy-level separation between the first excited state and the ground state in a potential well corresponding to the 3rd SW, by using fitting parameters to \( P(I) \) and \( I(T) \) under the microwaves and a calculation approach proposed by Kopietz and Chakravarty [21]. The result supported that the observed resonance agreed with the single-photon absorption. For IJJs made of the nearly optimal-doped Bi2212, it has been quite difficult to observe the single-photon transition between quantized energy levels, because of the Josephson plasma frequency \( \omega_p/2\pi \) higher than 100 GHz [10,15,16]. However, for the IJJs made of Y-doped Bi2212 with \( T_c \sim 47 \) K, we obtained the strongly suppressed \( j_c \) (~ 200 A/cm²), which was about an order of magnitude smaller than that for the nearly optimal-doped Bi2212. This leads to the first observation of single-photon transition in the higher-order phase switches.

Figure 2(b) shows the microwave power dependence of \( I_{SW} \) giving maxima of \( P(I) \) at the same temperature and microwave frequency as those in Fig. 2(a). A solid line represents a numerical fit to the quantum-mechanical model given by the following equation [16],

\[
\frac{I_{SW}}{I_{c0}} = 1 - \frac{4e^4 (P_{mw}/k)}{C^2\hbar^2} \frac{1}{\omega_p^2 (\omega_p - \omega)^2 + (\omega/2Q)^2}
\]  

Here, \( I_{c0} \) is a fluctuation-free critical current, \( C \) is a capacitance for single-junction in IJJs, \( P_{mw} \) is the applied power of microwaves, \( k \) is a coupling coefficient which combines \( P_{mw} \) with the ac current induced by microwaves, \( Q \) is a quality factor of the resonance. We found that the double-peak structure in \( P(I) \) is successfully explained by Eq. (1) with \( Q \sim 12 \), as shown in Fig. 2(b). Note that this value of \( Q \) is about twice larger than that for the three-photon absorption for the 2nd SW in the previous study [16], suggesting that the dissipation in the single-photon absorption is smaller than that in multiphoton absorption.

We also made sure that the double peak structure in \( P(I) \) for the 3rd SW was clearly observed up to 6 K and diminished at a temperature between 10 K and 16 K.

**Figure 2.** (a) (Color online) Density plots of the switching current versus the applied microwave power for the 3rd SW measured at 59.15 GHz and 2 K. (b) Microwave power dependence of the switching current giving maxima of \( P(I) \).
Finally, we estimated the effective escape temperature $T_{\text{esc}}$ for the 3rd to the 5th SW in the IJJs of Y-doped Bi2212 ($T_c \sim 47$ K) at measured temperatures, by using the fitting results of $P(I)$ and $I(T)$ to numerical calculations based on both of TA escape and multiple PR process. We compared the plots of $T_{\text{esc}}$ versus the bath temperature with those reported in the previous study [12] on other IJJs made of Bi2212 ($T_c \sim 83$ K), as shown in Fig. 3. Despite the fact that both samples have quite different $T_c$ and $j_c$, both plots shown in Fig. 3 indicate a common feature that the MQT-like behavior appears below $T^*$, corresponding to 0.1-0.2 times $T_c$. This proves that the observed MQT-like behavior is not limited by extrinsic noise in our experimental environment. Furthermore, the plots of $T_{\text{esc}}$ for the IJJs of Y-doped Bi2212 more clearly indicate a crossover from the classical to quantum phase escape. Note that the value of $T^*(\sim 6$ K) for the 3rd to 5th SWs in Y-doped Bi2212 are very close to a temperature where the microwave-induced resonance in $P(I)$ disappears. Thus, compared to our previous studies [12,16], the present results on the IJJs made of Y-doped Bi2212 more strongly suggest that MQT and ELQ for the higher-order phase switches in IJJs can occur and survive up to $T^*$, which is much higher than $T_{\text{cr}}$ estimated by the conventional theory. Interestingly, the experimental values of $T^*$ seem to be roughly scaled with $T_c$, although the conventional theory predicts that $T_{\text{cr}}$ is determined by the current-dependent Josephson plasma frequency proportional to $\sqrt{j_c}$. On the other hand, the energy level spacing in ELQ is successfully explained by the conventional theory, suggesting that the parabolic approximation of the potential well is still useful to describe the transition between quantized levels. Therefore, our results suggest that the bottom region in the potential well is not essentially changed even for the higher-order phase switches while the potential barrier for the phase escape is strongly suppressed by some novel mechanism which becomes important for the higher-order phase switches.

![Figure 3](image.png)

**Figure 3.** (a) (Color online) Plots of the effective escape temperature versus the bath temperature for the 3rd to 5th SW in IJJs made of Y-doped Bi2212. Both temperatures are normalized by $T_c$. A solid straight line represents that the effective escape temperature is equal to the bath temperature. (b) (Color online) Similar plots for the 2nd to 4th SW in IJJs made of nearly optimal-doped Bi2212.

4. Conclusion

We studied $P(I)$ and $I(T)$ for the higher-order phase switches in the IJJs made of underdoped Bi$_2$Sr$_2$Ca$_{y}$Y$_{0.3}$Cu$_2$O$_y$ and compared the experimental results with those measured previously in IJJs made of nearly optimal-doped Bi2212 [12,16,17,19]. We succeeded in observing the double-peak structure in $P(I)$ for the 3rd SW under the microwave irradiation, which was attributed to the single-photon transition between quantized energy levels. In spite of large differences in $T_c$ and $j_c$ between both the underdoped and optimal-doped IJJs, the distinctive properties suggesting the occurrence of MQT and ELQ in the higher-order phase switches were commonly observed below $T^*$. This confirms that our experimental results are not limited by extrinsic noise. Our results clearly show that the
observed ELQ associated with MQT is successfully explained by the conventional theory while $T^*$ is much higher than $T_c$, estimated by the conventional theory. This strongly suggests that the reason for disagreement between $T^*$ and $T_c$ probably originates in the large enhancement of MQT rate due to the strong suppression of the energy barrier for the phase escape. Since many of the previous studies concluded that MQT and ELQ for the 1st SW were consistently explained by the conventional theory, this situation is reminiscent of the quantum phase escape enhanced by the strong microwave irradiation proposed by Fistul et al [18], suggesting a possibility that a rapidly-oscillating current generating in the phase-running state suppresses the energy barrier for the higher-order phase switches.

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