Study of microwave-induced phase switches from the finite voltage state in Bi$_2$Sr$_2$CaCu$_2$O$_y$ intrinsic Josephson junctions

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Abstract. We study the microwave-induced phase switches from the finite voltage state for the underdamped intrinsic Josephson junctions (IJJs) made of Bi$_2$Sr$_2$CaCu$_2$O$_y$ (Bi2212). We observe the resonant double-peak structure in the switching current distribution at low temperatures. This feature is successfully explained by a quantum mechanical model where the strong microwave field effectively suppresses the potential barrier for the phase escape from a potential well and the macroscopic quantum tunneling (MQT) is resonantly enhanced. The detailed analyses considering the effects of multiple phase retrapping processes after the phase escape strongly suggest that the intense microwave field suppresses the energy-level spacing in the potential well, by effectively decreasing the fluctuation-free critical current and the Josephson plasma frequency. This effect also reduces the number of photons required for the multiphoton transition between the ground and the first excited states, making it possible to observe the energy level quantization in the MQT state. The temperature dependence of the resonance peak emerging in the switching rate clearly demonstrates that the quantized energy state can be survived up to $\sim$10 K, which is much higher than a crossover temperature predicted by the conventional Caldeira-Leggett theory.

1. Introduction

The phase switching dynamics in the current-biased intrinsic Josephson junctions (IJJs) of high-$T_c$ cuprate superconductors have much attention, since the macroscopic quantum tunneling (MQT) in the phase switches from the zero voltage state was discovered in the underdamped IJJs made of Bi$_2$Sr$_2$CaCu$_2$O$_y$ (Bi2212) [1]. A gigantic critical current density and a perfectly smooth tunnel junction in IJJs benefit an increase of crossover temperature $T_{c_1}$ to the MQT region [2], expected to be much higher than a typical value of $T_{c_1}$ for the conventional Al- or Nb-based Josephson junctions (JJs). As well known, the current-voltage ($I$-$V$) curves of IJJs show a multiple-branched feature, suggesting that the neighboring superconducting layers involved into IJJs are strongly coupled with each other. Thus, it is quite important to investigate the phase switches from the finite voltage state as well as those from the zero voltage state in IJJs, toward the complete understanding of the complicated phase dynamics in IJJs.

In the phase switching events from the finite voltage state, such as the switch from the first to the second voltage state (2nd SW) and that from the second to the third voltage state (3rd SW) in the multiple branched $I$-$V$ curves, the influence of the phase running state before the occurrence of the phase switch should be carefully considered, in contrast to the phase switch from the zero to the first...
voltage state (1st SW). Recently, we discovered that the multiple phase retrapping (PR) processes, which were observed as a negative curvature in the switching rate $I(I)$ as a function of bias current, were systematically enhanced as the order of the phase switch was increased, even for the underdamped Bi2212-IJJs showing large hysteresis in the $I$-$V$ curve [3]. Our results clearly show that the switching current distribution $P(I)$ and $I(I)$ for the higher-ordered phase switches should be analyzed by considering the multiple PR processes, which have been discussed for the moderately damped JJJs [4, 5], in addition to the conventional thermally-activated (TA) escape processes from a potential well. Furthermore, we demonstrated that the resonant double-peak structure in $P(I)$ under the strong microwave irradiation was observed for the 2nd SW of Bi2212-IJJs below $T^*$ (~10 K) [6] and that it was successfully reproduced by a quantum-mechanical model proposed by Fistul et al [7]. These results strongly suggest that the MQT-like behavior in the 2nd SW of Bi2212-IJJs, observed as a clear saturation of the effective phase escape temperature $T_{esc}$ below $T^*$ [8, 9], essentially has the same origin as that for the MQT phenomena established in the 1st SW of Bi2212-IJJs [1, 10].

In this paper, we present the detailed analyses of $P(I)$ and $I(I)$, which were measured for the 2nd SW of Bi2212-IJJs under the microwave irradiation [6], by considering both the TA escape and the multiple PR processes for the principal peak in the double-peaked $P(I)$. It is shown that the strong microwave field suppresses the energy-level spacing between the quantized energy states in the potential well by effectively decreasing the fluctuation-free critical current $I_0$ and the Josephson plasma frequency $\omega_p$. This effect reduces the number of photons ($n=5$ to 3) required for the multiphoton transition between the ground state and the first excited state, making it possible to observe the energy level quantization (ELQ) through the multiphoton transition. We also discuss the temperature dependence of the resonance peak emerging in $I(I)$, providing clear evidence for the formation of ELQ surviving up to $T^*$.

2. Experiments and analyses

Bi2212 single crystals were grown by the floating zone method and annealed to be optimal doped. The bridge-type Bi2212-IJJs shown in the inset of Fig. 1 were fabricated by using the focused ion beam (FIB) milling techniques [11]. The lateral sizes and the junction number of the IJJs were $1.2 \times 1.1$ µm$^2$ and 6, respectively. The superconducting transition temperature $T_c$ of the fabricated IJJs was estimated as ~85 K by the zero resistance. $P(I)$ for the 2nd SW was measured from 4.3 K to 30 K by applying a bias current with a constant rate $dI/dt = 3$ mA/s under 5,000 or 10,000 switching events. Other details are described in our previous paper [6].

The switching rate $I(I)$ was obtained from the measured $P(I)$ [12] and analyzed by considering both the TA escape and the subsequent PR processes. In the limit of $\Delta U/k_B T \gg 1$, $I(I)$ is expressed by [13]

$$I(I) = \Gamma_T (1 - W_R) \frac{\ln(1 - W_R)}{W_R}, \quad (1)$$

Here, $\Delta U$ is the potential barrier for an escape process, $\Gamma_T = (\omega/2\pi)\exp(-\Delta U/k_B T)$ is the TA escape rate, and $W_R$ is the PR probability that the phase particle escapes from a potential minimum and is retrapped in the next minimum.

The influence of PR processes to $I(I)$ is evaluated by using a characteristic ratio [3],

$$I_{PR} = \frac{I_{SW} - I_{SW}^{min}}{I_{SW}^{max} - I_{SW}^{min}} \quad (2)$$

Here $I_{PR}$ is a maximum current where the multiple PR processes occur after the phase escape from the potential well. $I_{SW}^{max}$ and $I_{SW}^{min}$ are maximum and minimum values of the measured switching current, respectively. Note that the PR processes are dominant in a whole range of the observed switching current if this ratio larger than unity, since $I_{PR}$ larger than $I_{SW}^{max}$ suggests that the measured phase switches are always influenced by the PR processes.
The quantized energy levels $E_n$ in the potential well for a quantum particle are numerically obtained by using the previous approach [14]. The numbers of photons required for the multiphoton transition between the ground state and the first excited state was estimated from such numerical calculations of $E_{01} \equiv E_1 - E_0$.

3. Results and discussion

Figure 1 shows the $I$-$V$ characteristics, which were measured at 4.3 K by using triangular ac voltage waveform and a load resistor of 10 kΩ. We observed that each resistive branch from the 1st to the 3rd almost equally spaced. Note that the switching current from the 1st SW to the 3rd SW is monotonically increased with increasing the order of switch, showing a contrast to the previous measurements reporting the anomalous switching order [15]. The McCumber parameters $\beta_C = 2eI_0CR_N^2/h$ was $\sim 60$ for the 1st SW, $\sim 110$ for the 2nd SW, and $\sim 160$ for the 3rd SW, respectively. $C$ ($\sim 60$ fF) and $R_N$ ($\sim 190$ Ω) are a capacitance and the normal-state resistance for a single junction in IJJs.

Figure 2 shows the plots of $P(I)$ for the 2nd SW under the microwave field at several temperatures. We observe that the principal peak in $P(I)$ located at a higher current region, is shifted to the resonant peak located at a lower current region, with increasing the microwave irradiation power. The double-peak structure in $P(I)$ is clearly observed at the intermediate irradiation power (−2.5 dBm) up to 10 K, while it is broadened at 20 K, as shown in Fig. 2.

The data set of $\Gamma(I)$, which was obtained from the measured $P(I)$ under the microwave field, was
analyzed by calculating Eq. (1) with the fitting parameters such as $T_{\text{esc}}$ and $I_{\text{c0}}$. Figure 3 shows the microwave power dependence of several parameters for the measurements at 4.3 K under the microwave irradiation at 40.5 GHz up to -2.3 dBm, at which the double-peak structure in $P(I)$ is not prominent yet. We found that $I_{\text{c0}}$ is strongly decreased by the microwave irradiation while $T_{\text{esc}}$ is slightly decreased, as shown in Figs. 3(a) and 3(c). In addition, as shown in Fig. 3(b), the ratio estimated by Eq. (2) becomes larger than unity with increasing the microwave power, suggesting that the PR processes are enhanced by the microwave irradiation. These results clearly show that the strong microwave irradiation decreases the effective depth of the potential well (in other words, effectively assists the phase escape events) and that a rapid oscillation of the tilted washboard potential induced by the microwave field intensely increases the PR process after the phase escape.

Although the decrease of $\Delta U$ with the microwave power shows a good agreement with the concept proposed by Fistul et al [7] where $\Delta U$ is effectively suppressed by the strong microwave field, the observed decrease of $\Delta U$ is very weak, as shown in Fig. 3(e), compared to the strong decrease of $I_{\text{c0}}$. Such a moderate decrease of $\Delta U$ is qualitatively explained by the fact that the normalized switching current $I_{\text{sw}}/I_{\text{c0}}$ is also decreased with the microwave power, as shown in Fig. 3(d), since $\Delta U$ is increased with decreasing $I_{\text{sw}}/I_{\text{c0}}$ while it is decreased with decreasing $I_{\text{c0}}$ [12]. However, the decrease of both $I_{\text{c0}}$ and $I_{\text{sw}}/I_{\text{c0}}$ leads to a depression of $\omega_{0}$ and $E_{01}$, as shown in Fig. 3(f). The numbers of photons for the multiphoton transition is consequently reduced from 5 down to 3 with the microwave power. This effect seems to increase the probability to detect the quantum phase escape from the first excited state through the multiphoton transition. Our results obtained by the detailed analyses clearly demonstrate that the microwave field strongly affects the phase switching dynamics occurring in IJJs and that it can effectively change the energy level spacing in the quantized potential well.

Finally, we investigate the temperature-dependent properties of the resonant peak observed in $\Gamma(I)$ under the microwave irradiation. Figure 4 shows the enhancement of the switching rate $\Delta \Gamma(I) \equiv \Gamma(P_{\text{mw}}, I) \Gamma(0, I)$ at several temperatures, where $\Gamma(0, I)$ and $\Gamma(P_{\text{mw}}, I)$ are the switching rate without and with the microwave irradiation, respectively. In these plots, we use the microwave
irradiation power at which a positional shift from the principal peak to the excited peak in $P(I)$ is clearly observed, and the magnitude of $\Delta I(I)$ is appropriately normalized. Below 10 K where the MQT-like behavior appears in the temperature dependence of $T_{\text{esc}}$ [6], we observe a clear resonance peak in $\Delta I(I)$ which can be fitted to the Lorentzian curve with the quality factor $Q$ (=2.5 at 4.3 K and 1.7 at 10 K). On the other hand, above 16 K, the peak is not observed, as shown in Figs. 4(d)-4(f). Such a temperature-dependent feature in $\Delta I(I)$ is characteristic for the crossover from the MQT regime to the classical TA regime in a current-biased JJ [16]. Thus, our results provide clear evidence that we successfully detect the three-photon transition between the energy level spacing $E_{01}$ in the 2nd SW of IJJs, which survives up to $T^*$ (~10 K).

4. Conclusion
We present the detailed analyses of the switching current distribution $P(I)$ and the switching rate $I(I)$ for the 2nd SW of Bi2212-IJJs under the microwave irradiation, by considering both the TA escape and the multiple PR process in the phase-running state before the detection of the phase switching event. The strong microwave irradiation is found to assist the phase escape by effectively decreasing the fluctuation-free critical current $I_{c0}$ and to enhance the PR process after the phase escape by rapidly oscillating the tilted washboard potential. We confirmed that the potential barrier $\Delta U$ for the phase escape is decreased with increasing the microwave irradiation power, supporting the previous proposal by Fistul et al [7].
Figure 4. Enhancement of the switching rate $\Delta \Gamma(I)$ for the 2nd SW at (a) 4.3 K, (b) 7 K, (c) 10 K, (d) 16 K, (e) 20 K, and (f) 30 K, respectively. Solid lines are the Lorentzian fits.

The intense microwave field also suppresses the Josephson plasma frequency $\omega_p$ and the energy-level spacing $E_{01}$ due to the strong decrease of both $I_{c0}$ and $I_{sw}/I_{c0}$, giving a large reduction in the number of photons required for the multiphoton transition between the quantized energy levels. We observe the clear resonance peak in the enhancement of the switching rate $\Delta \Gamma(I)$ for the 2nd SW, which can be fitted to the Lorentzian curves with $Q \sim 1.7-2.5$ by assuming the three-photon transition. The temperature dependence of $\Delta \Gamma(I)$ strongly suggests that the microwave-induced resonance in $\Delta \Gamma(I)$ has the quantum-mechanical origin and survives up to $T^\ast \sim 10$ K. These results strongly support the occurrence of the MQT state below $T^\ast$ in the 2nd SW of Bi$_2$2212-IJJs, together with the recent report on the microwave power dependence of $I_{sw}$ giving maxima of $P(I)$ [6]. Thus, the dissipation of quasiparticle tunneling in the finite voltage state seems to be too small to prevent the occurrence of the MQT state in the higher-ordered phase switches, as was previously predicted for the 1st SW in IJJs [17,18]. The influence of the phase-running state before the occurrence of the phase switch from the finite voltage state is rather the generation of ac Josephson current, as discussed in Ref. [3]. This feature is suggested to be unique to the phase switching phenomenon from the voltage state in the IJJ systems with the superconducting single and double layers such as Bi$_2$Sr$_2$CuO$_{6+\delta}$ (Bi2201) [19] and Bi2212, showing a sharp contrast to IJJs made of Bi$_2$Sr$_2$Ca$_2$Cu$_3$O$_{10+\delta}$ (Bi2223) with the superconducting triple layers [20].

A remained problem in the MQT phenomena in the phase switch from the finite voltage state is that $T^\ast$ is much higher than $T_{cr}$ calculated by the conventional theory. At the present, there are two possible scenarios to resolve this issue. One is the contribution of ac Josephson current generated in the phase-running state, which can depress $\Delta U$ as like as the microwave irradiation. The other is the
fact that $I(I)$ for the 2nd SW is more enhanced than that for the 1st SW. Such an enhancement of $I(I)$ is very similar to the feature of $I(I)$ for the uniform phase switch, where several junctions involved into IJJs simultaneously switch from the zero voltage state [10]. Since the issue on the anomalously-enhanced MQT rate has extensively been discussed by several theoretical studies [21, 22], one of them is possible to resolve the problem remained in the phase switches from the voltage state.

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References
[1] Inomata K, Sato S, Nakajima K, Tanaka A, Takano Y, Wang H B, Nagao M, Hatano H and Kawabata S 2005 Phys. Rev. Lett. 95 107005
[2] Caldeira A O and Leggett A J 1981 Phys. Rev. Lett. 46 211
[3] Kitano H, Takahashi Y, Kakehi D, Yamaguchi H, Koizumi S and Ayukawa S 2016 J. Phys. Soc. Jpn. 85 054703
[4] Bae M H, Sahu M, Lee H J and Bezryadin A 2009 Phys. Rev. B 79 104509
[5] Kautz R L and Martinis J M, 1990 Phys. Rev. B 42 9903
[6] Takahashi Y, Kakehi D, Takekoshi S, Ishikawa K, Ayukawa S and Kitano H 2016 J. Phys. Soc. Jpn. 85 073702
[7] Fistul M V, Wallraff A and Ustinov A V 2003 Phys. Rev. B 68 060504
[8] Kashiwaya H, Matsumoto T, Shibata H, Kashiwaya S, Eisaki H, Yoshida Y, Kawabata S and Tanaka Y, 2008 J. Phys. Soc. Jpn. 77 104708
[9] 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
[10] Jin X Y, Koval Y, Lukashenko A, Ustinov A V, and Müller P 2006 Phys. Rev. Lett. 96 177003
[11] Kakehi D, Takahashi Y, Yamaguchi H, Koizumi S, Ayukawa S and Kitano H 2016 IEEE Trans. Appl. Supercond. 26 (3) 1800204
[12] Fulton T A and Dunkleberger L N 1974 Phys. Rev. B 9 4760
[13] Männik J, Li S, Qiu W, Chen W, Patel V, Han S and Lukens J E 2005 Phys. Rev. B 71 220509
[14] Kopietz P and Chakravarty S 1988 Phys. Rev. B 38 97
[15] For example, Warburton P A, Saleem S, Fenton J C, Korsah M and Gronvenor C R M 2009 Phys. Rev. Lett. 103, 217002
[16] Martinis J, Devoret M and Clarke J 1985 Phys. Rev. Lett. 55 1543
[17] Kawabata S, Kashiwaya S, Asano Y and Tanaka Y 2004 Phys. Rev. B 70 132505
[18] Yokoyama T, Kawabata S, Kato T and Tanaka Y 2007 Phys. Rev. B 76 134501
[19] Nomura Y, Mizuno T, Kambara H, Nakagawa Y and Kakeya I 2015 J. Phys. Soc. Jpn. 84 013704
[20] Nomura Y, Mizuno T, Kambara H, Nakagawa Y, Watanabe T, Kakeya I and Suzuki M 2014 J. Phys: Conference Series 507 012038
[21] Sevel’ev S, Rakhmanov A L and Nori F 2007 Phys. Rev. Lett. 98 077002; 2007 Erratum: 98 269901
[22] Koyama T and Machida M 2008 Physica C 468 695