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Dynamics of Phase Switch in the Intrinsic Josephson Junctions Made of Bi2212 with Perfectly-stoichiometric Cation Compositions

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Abstract. We study the phase switching dynamics in the intrinsic Josephson junctions (IJJs) of $Bi_2Sr_2CaCu_2O_y$ (Bi2212) cuprate superconductors, focusing on the effect of stoichiometry of cation composition. The current-voltage characteristics for the IJJs with the cation composition approaching to be perfectly stoichiometric (Bi:Sr:Ca:Cu=2:2:1:2) show the highly-underdamped nature with a very small retrapping current. We found that the switching current distribution $P(I)$ for the IJJs with perfectly stoichiometric composition and less damage had double peaks or broadened. This suggests that the phase switched junction is not always specified in the case of IJJs with stoichiometric composition, since more than one junction with almost the same switching current is associated with the observed switching events. We obtained the magnitude of a critical current density J_c and an effective temperature T_{esc} for the phase escape composed of a single component, by analysing the bias current dependence of the switching rate $\Gamma(I)$. The results indicate that the perfectly-stoichiometric cation composition can greatly enhance the magnitude of J_c, although a crossover temperature to the macroscopic quantum tunnelling (MQT) for the higher-ordered phase switches is not influenced by the enhancement of J_c, in contrast to the conventional MQT theory.

1. Introduction

The intrinsic Josephson junctions (IJJs) of $Bi_2Sr_2CaCu_2O_y$ (Bi2212) cuprate superconductors have great advantage such as a perfectly smooth tunnel junction on an atomic scale and a high critical current density J_c, which remarkably increase a crossover temperature T_{cr} to the macroscopic quantum tunneling (MQT) state in the current-biased IJJs [1]. However, the underlying properties of IJJs have not been investigated in terms of nonstoichiometry of cation compositions, which is empirically known to induce disorder and constrict the magnitude of J_c and the superconducting transition temperature T_c [2]. For instance, the previous magnetization measurements for Bi2212 crystals with approaching the cation compositions to be stoichiometric suggested that the value of J_c in the vortex state rather than T_c was unexpectedly enhanced, implying the importance of the stoichiometric cation compositions for the enhancement of J_c and flux-pinning [3]. According to the conventional MQT theory [4], it is expected that T_{cr} is proportional to a square root of J_c in a Josephson junction. Thus, the control of cation stoichiometry in Bi2212 crystals is quite important to extract the excellent properties underlying the IJJs.

In this paper, we present a study on the phase switching properties in a small stack of IJJs with the cation compositions approaching to be perfectly stoichiometric (Bi:Sr:Ca:Cu=2:2:1:2). We found that the switching current distribution $P(I)$ often had double peaks or broadened. This suggests that more than one junction with almost the same switching current is associated with the observed switching events. We also tried to obtain the magnitude of J_c and an effective temperature T_{esc} for the data showing a sharp-single peak in $P(I)$. The results indicate that the perfectly-stoichiometric cation composition favors the great enhancement of J_c. This effect is expected to increase T_{cr}, as was predicted in the conventional MQT theory. However, the comparison between the previous results using the Bi2212-IJJs with slightly nonstoichiometric compositions [5,6] indicated that the value of T_{cr} for the higher-ordered phase switching events was not influenced by the increase of J_c, suggesting that the MQT rate for the higher-ordered switches was dominated by another contribution which was not included in the conventional theory.

2. Experiments and analyses

Bi2212 single crystals with the cation compositions approaching to be perfectly stoichiometric were grown by the floating zone method in 5% O_2 / Ar and annealed at 600 °C in air to be optimal doped. The cation composition was determined as Bi:Sr:Ca:Cu=2.0:2.0:1.0:2.0 by using the inductively-coupled-plasma (ICP) analyses. Other details of the crystal growth are described elsewhere [7]. The bridge-type Bi2212-IJJs were fabricated by using the focused ion beam (FIB) milling techniques [5]. The superconducting transition temperature T_c of the IJJs after the FIB fabrication was estimated as ~90 K by the zero resistance. This value is slightly larger than that for the previous IJJs [5] with slightly nonstoichiometric compositions (Bi:Sr:Ca:Cu=2.1:1.9:1.0:2.0).

The switching current distribution $P(I)$ was measured at several temperatures below 35 K, by applying a bias current with a constant rate dI/dt=10 or 30 mA/s under 10,000 switching events. The switching rate $\Gamma(I)$ was obtained from the measured $P(I)$ [8] and analyzed by considering both processes of the thermally-activated (TA) escape and the multiple phase-retrapping (PR) in a tilted washboard potential. Other details of the analyses of $\Gamma(I)$ is described elsewhere [6].

3. Results and discussion

Figures 1 and 2 show the I-V characteristics, which were measured at 3.15 K by using triangular ac voltage waveform with a repetition frequency of 23 Hz and a load resistor of 10 kΩ, for two devices of small IJJs with the perfectly-stoichiometric composition (ayf42 and ypf13, respectively). The lateral sizes of IJJs were 1.55×0.94 μm^2 and 1.22×1.15 μm^2, respectively. We observed one superconducting (zero-resistive) and four resistive branches in the I-V characteristics for both devices, as shown in Figs. 1 and 2. For the former device (ayf42), the switching current density for the first to the fourth switch (1st SW to 4th SW) was 3.5-7×10^3 A/cm^2 at 3.15 K, moderately larger than the previous results for the IJJs with slightly nonstoichiometric compositions [5]. On the other hand, the switching current density for the third switch (3rd SW) of the latter device (ypf13) was found to exceed 1.6×10^4 A/cm^2 at the same temperature. These results strongly suggest that the stoichiometric cation composition in Bi2212 crystals is quite important to extract the underlying properties of IJJs as well as the pinning properties in the vortex state. We also observed that the retrapping current density to the zero voltage state was less than 100 A/cm^2 for both devices, as small as the previous results for the IJJs with nonstoichiometric compositions. This suggests that the stoichiometric cation composition enhances a quality factor in IJJs, which keeps them in the highly underdamped region.

In addition, we observed that each resistive branch in the former device (ayf42) was almost equally spaced, showing a slightly larger voltage jump than that for the previous Bi2212-IJJs, while there were two branches closely apposed in the latter device (ypf13). The previous numerical study on the I-V characteristics in IJJs suggested that the voltage spacing between branches was strongly influenced by the strength of capacitive coupling between Josephson junctions or the existence of non-equivalent configuration in the voltage state of IJJs [9]. Although the observed features in the voltage spacing might be attributed to the stronger capacitive coupling in the IJJs with stoichiometric cation composition, we do not discuss it in this paper. In order to discuss such effects more quantitatively, the more precise control of the junction number included in IJJs (for instance, the same 4 junctions as the previous numerical simulations [9]) is required for a quantitative comparison with the numerical simulations.

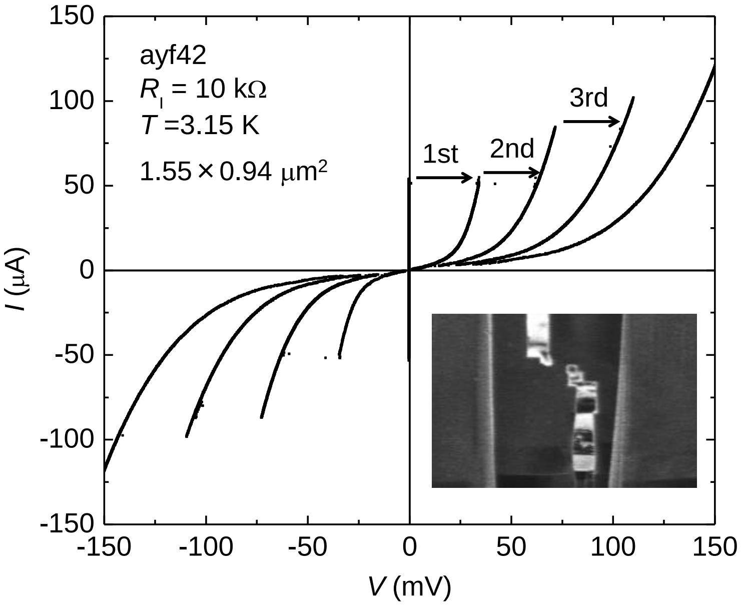

Figure 1. *I*-*V* characteristics of the bridge-type Bi2212-IJJs (ayf42) with the perfectly-stoichiometric composition, measured at 3.15 K. The inset shows an image of scanning ion microscope of the IJJ device.

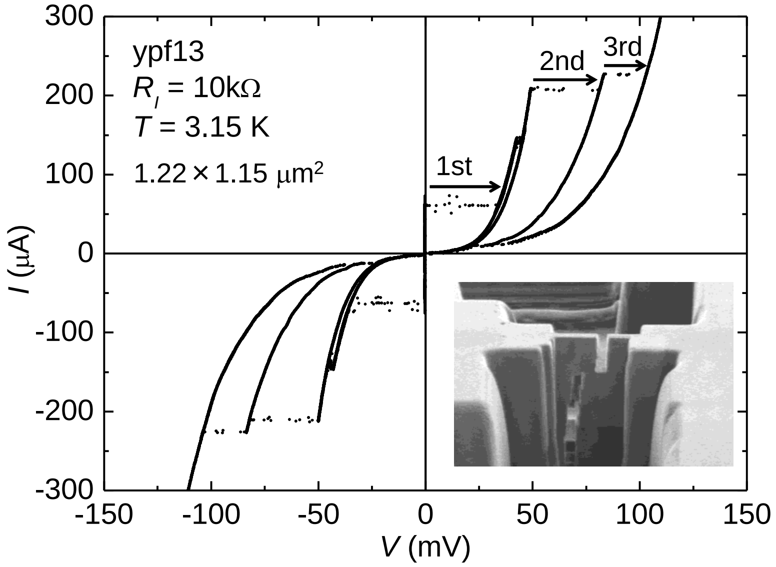

Figure 2. *I*-*V* characteristics of the bridge-type Bi2212-IJJs (ypf13) with the perfectly-stoichiometric composition, measured at 3.15 K. The inset shows an image of scanning ion microscope of the IJJ device.

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Next, we performed the measurements of $P(I)$ at several temperatures. Figures 3 and 4 show the bias current dependence of $P(I)$, measured at 3 K, for the 1st SW to 3rd SW of the two devices (ayf42 and ypf13, respectively). Surprisingly, we found that $P(I)$ had double peaks or broadened, suggesting that more than one junction with similar switching currents was associated with the observed phase switching events. In the previous measurements using IJJs with nonstoichiometric composition [6], we have observed that the existence of more than one junction with slightly different J_c influenced the bias current dependence of $P(I)$ and $\Gamma(I)$, although the contribution of such effects was much smaller than that observed in this work. We also found that there was no double-peak in $P(I)$ for other IJJs with a lower T_c, which were considered to be more damaged by the FIB fabrication, even if the cation composition was perfectly stoichiometric. These results imply that the microscopic disorders in the insulating layers of IJJs, which are produced by the nonstoichiometric composition or the slight damage in the FIB fabrication, strongly affect the sequence of phase switches in IJJs, since a junction with the weaker Josephson coupling in IJJs is switched to the voltage state at a smaller bias current. Thus, we consider that the phase switches measured in the IJJs with perfectly-stoichiometric composition and less damage tend to include the contributions from more than one junction, leading to the double-peaked or broadened structure in $P(I)$.

As for the broadened $P(I)$ observed in the 2nd SW of the latter device (ypf13), the contribution of large junction effects is also considered as another candidate [10,11]. However, as will be discussed below, we concluded that a large junction effect due to the decrease of the Josephson penetration depth followed by the enhancement of J_c was not so strong to influence the phase switching dynamics.

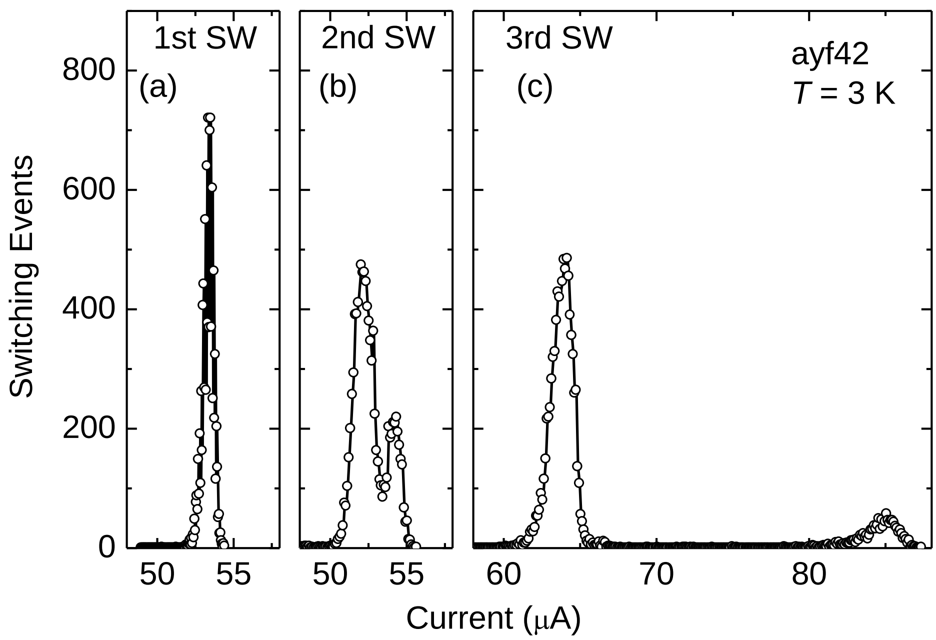

Figure 3. The switching current distribution for (a) for the first switches, (b) for the second switches, (c) for the third switches, which was measured at 3 K in the IJJs (ayf42).

Since our fitting model of $P(I)$ and $\Gamma(I)$ is based on the phase switches occurring in a *single* Josephson junction [6], we cannot analyse the measured $P(I)$ where more than one junction is associated with the phase switches unless the contribution from each junction is specified. Although the double peak structure observed in the 1st SW for the latter device (ypf13) seemed to be safely separated, this feature is found to be dependent on the value of dI/dt, suggesting a possibility that there are multiple components in each peak of the structure. Thus, in this work, we only analysed the data for the 1st SW of the former device (ayf42) and the 3rd SW of the latter device (ypf13), where only a single component seems to be included in $P(I)$.

Figures 5(a) and 5(b) show the fitting results of $\Gamma(I)$ for the 1st SW (ayf42) and the 3rd SW (ypf13), respectively. The deviation from the fitting curve, which is more prominent in $\Gamma(I)$ at higher bias current region and at lower temperatures in Fig. 5(a), is considered to be due to the small contribution from different junctions. The magnitude of J_c is 3.8×10^3 A/cm^2 for the 1st SW (ayf42) and 1.8×10^4 A/cm^2 for the 3rd SW (ypf13). The former value for the 1st SW (ayf42) is similar to that for the previous IJJs with nonstoichiometric composition, suggesting that the former device (ayf42) was slightly damaged by the FIB fabrication. On the other hand, the latter value of for the 3rd SW (ypf13) is much larger than the previous results [6], demonstrating that the stoichiometric composition with less damage can greatly enhance the magnitude of J_c in Bi2212-IJJs. We note that such an enhancement of J_c is not so seriously influenced to the estimation of the Josephson penetration depth, since it is inversely proportional to a square root of J_c. This leads to a conclusion that the Josephson penetration depth corresponding to J_c=1.8×10^4 A/cm^2 is roughly one-third or half of that for the Bi2212-IJJs measured previously. Thus, we can rule out a possibility that the phase dynamics in the IJJs with perfectly stoichiometric composition is dominated by the dynamics of fluxons in a large junction where the Josephson penetration depth is much smaller than a lateral size of the Josephson junction.

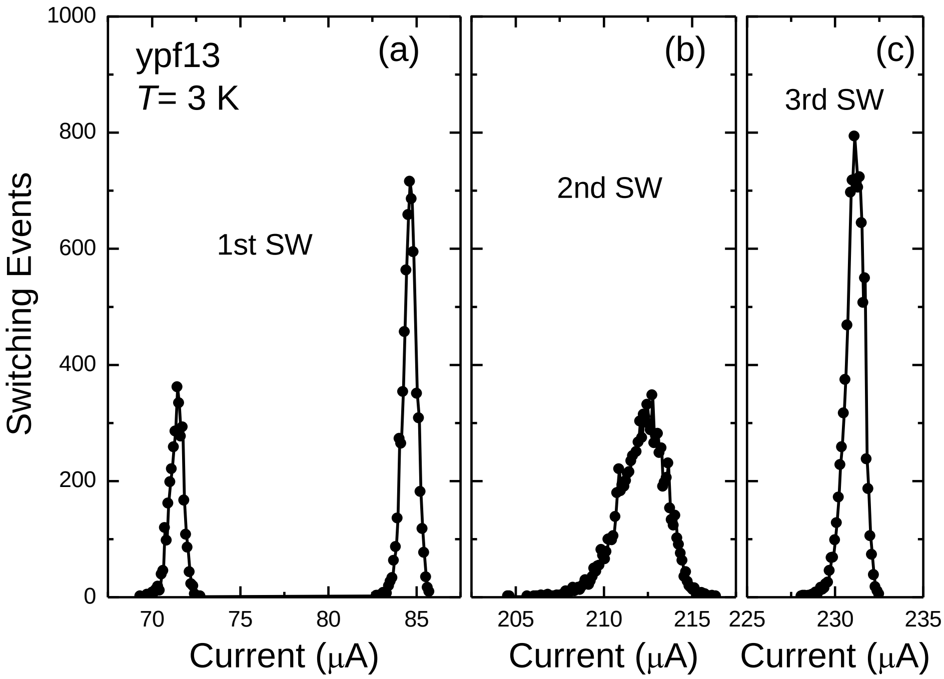

Figure 4. The switching current distribution for (a) for the first switches, (b) for the second switches, (c) for the third switches, which was measured at 3 K in the IJJs (ypf13).

Figure 5(c) shows the plots of the effective escape temperature T_{esc} in the phase switches versus the bath temperature T_{bath}. We found that T_{esc} for the 1st SW (ayf42) deviated from T_{bath} at 2 K while T_{esc} for the 3rd SW (ypf13) deviated from T_{bath} below 8 K, suggesting a sign of the crossover to the MQT state. According to the conventional theory of MQT phenomena [4], T_{cr} is expected to be proportional to a square root of J_c. Although the measurements at lower temperatures than 2 K are required for the confirmation of T_{cr} for the 1st SW (ayf42), the T-independent behavior of T_{esc} for the 3rd SW (ypf13), surviving up to 8 K, is clearly beyond the conventional prediction, since it only gives ~2.3 K as an estimate of T_{cr}. Such an unusual result has often been discussed in the higher-ordered phase switches in Bi2212-IJJs [5,6,12,13]. We found that the temperature (~8 K) below which T_{esc} for the 3rd SW was independent of T_{bath} was almost the same as the previously-reported value in the higher ordered SWs of the IJJs, in spite of a large difference in the estimates of J_c. This strongly suggests that the value of T_{cr} for the higher-ordered SWs is determined by a novel mechanism, which has not been included in the conventional theory but proposed in our previous paper [6]. Recently, we also obtained a similar result in a study of the dependence of T_{cr} for the higher-ordered SWs on the carrier concentration in the bridge-type IJJs made of Y-doped Bi2212 [14]. Thus, both results show a good agreement with each other.

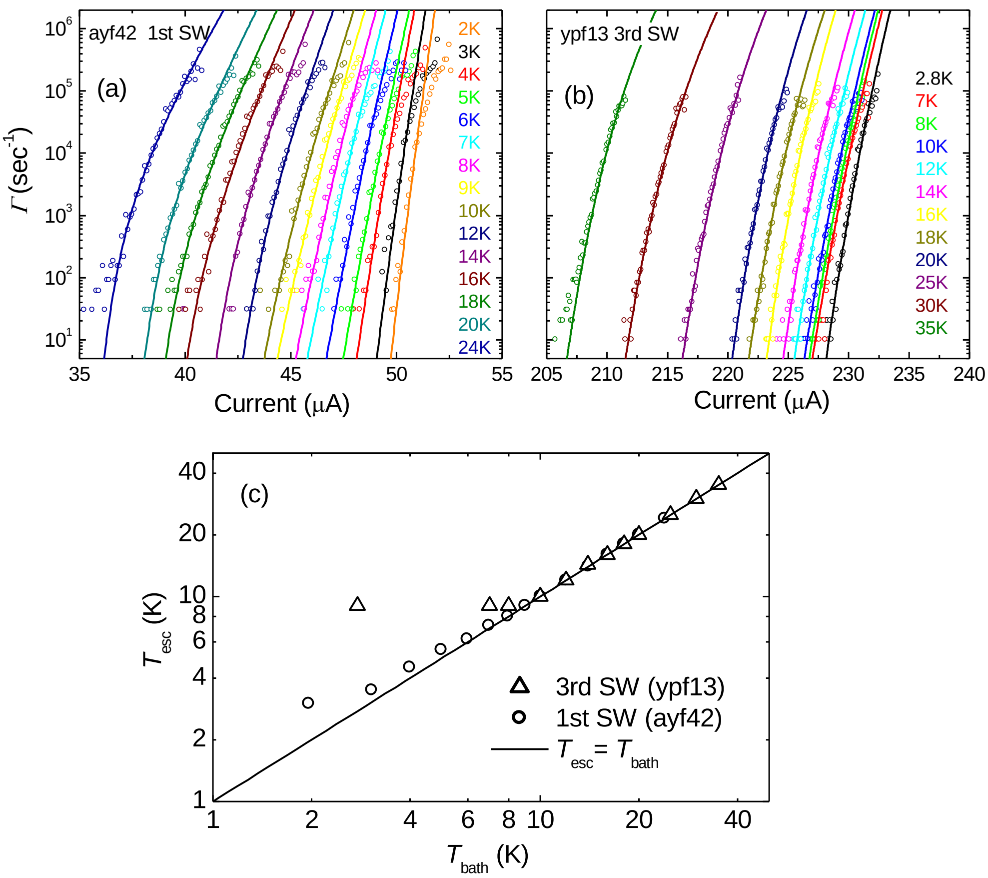

Figure 5. (Color online) The switching current distribution for (a) for the 1st SW in ayf42, (b) for the 3rd SW in ypf13. (c) Plots of the effective escape temperature T_{esc} versus the bath temperature T_{bath}.

4. Conclusion

We present the study on the measurements of *I-V* curves and $P(I)$ in the Bi2212-IJJs, focusing on the effect of stoichiometry of cation compositions. Our results clearly indicate that the switching current density in the IJJs with perfectly stoichiometric composition is greatly enhanced, keeping the retrapping current density very low. We also observed that $P(I)$ had double peaks and broadened, probably due to the multiple contributions from several junctions for the observed phase switches. Since such a feature made the fitting analyses of $P(I)$ and $\Gamma(I)$ more difficult, we obtained the magnitude of J_c and T_{esc} for the data where only a single component was contributed. The results show that the magnitude of J_c, which determines the strength of Josephson coupling in IJJs, can be greatly enhanced as the cation composition becomes perfectly stoichiometric, expecting an increase of T_{cr} to the MQT state. However, the temperature dependence of T_{esc} for the higher-ordered SWs was found to show almost the same behavior as that reported previously in the IJJs with nonstoichiometric compositions, in spite of a large difference in J_c. These results suggest that the excellent properties underlying IJJs such as J_c can be extracted by the precise control of the cation stoichiometry, while the crossover to the MQT state for the higher-ordered SWs is not influenced by the enhancement of J_c.

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