Measurements of the switching current distribution in REBa$_2$Cu$_3$O$_y$ (RE = Eu, Er) intrinsic Josephson junctions

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Abstract. We have investigated the switching dynamics of current biased REBa$_2$Cu$_3$O$_y$ (RE123; RE = Eu, Er) intrinsic Josephson junctions (IJJs) with typical dimensions of ~1 x 1 x 0.1 µm$^3$. The heavily under-doped Re123 IJJs exhibited clear multiple-branches with hysteresis structure. The critical current density, $J_c$, of both IJJs was 15 – 17 kA/cm$^2$ at 4.2 K which was about ten times higher than that of Bi$_2$Sr$_2$CaCuO$_y$ (Bi2212) IJJs. From switching current measurements from the $V=0$ state to the $V≠0$ state of those IJJs, switching current distributions, $P(I)$, were found to be significantly broader than that expected from the escape model of a single Josephson junction. This is in contrast with the fact that $P(I)$ of Bi2212 IJJs have been well explained by the model. The $P(I)$ of Eu123 IJJs were found to be independent of temperature below 1.4 K, which indicated the crossover temperature to the quantum regime from the thermally activated regime.

1. Introduction
The intrinsic Josephson junctions, which consist of alternatively stacked superconducting and barrier layers in layered high-$T_c$ superconductors (HTS), is one of the promising candidate for quantum device application as so-called phase qubits based on macroscopic quantum tunneling (MQT). In the last few years, the MQT has been successfully observed in Bi2212 IJJs at relatively higher temperatures than that in conventional Josephson junctions of low $T_c$ superconductors [1-3]. While the crossover temperature between thermal and quantum escape of Josephson phase is proportional to the Josephson plasma frequency, $\omega_{p0}$ [4], and therefore IJJs with a large $\omega_{p0}$ of HTS with a large critical current density, $J_c$ is advantageous to observe MQT at high temperatures.

From the above view point, we have examined the switching dynamics of IJJs in RE123. Since RE123 IJJs has a large $J_c$, so that they have a significantly high $\omega_{p0}$ [5,6]. On the other hand, in order to observe the intrinsic Josephson junction properties in RE123, the carrier doping state should be controlled to under-doped region to enhance the electrical isolation of its barrier layers, because the barrier layers of RE123 are not insulating around the optimal doped region. In the present study, RE123 was tuned to heavily under-doped where the value of $\gamma = (m^*/m^*_{ab})^{1/2}$ was 30 – 40, which is still very small value than that of Bi2212.

Incidentally, the superconducting CuO$_2$ planes in the IJJs are thinner than the charge screening length, leading to a capacitive coupling between adjacent junctions [7-9]. The different value of the
capacitive coupling constant in high-$T_c$ superconductors causes the significant difference in their $I-V$ characteristics. It is known that the Bi2212 with a weak capacitive coupling constant commonly exhibit the multi branch structure \[10\], while collective switching instead of multiple-branch structure has been observed in $(La, Sr)_2CuO_4$ with a strong one \[11\]. However the capacitive coupling constant is roughly determined by the material, it is controllable by tuning the value of $\gamma$. By the precise control of the oxygen nonstoichiometry in RE123 IJJs, we successfully obtained two types of RE123 IJJs which exhibit single junction switching and two junctions switching in their $I-V$ characteristics. We reported on the investigation of switching dynamics in RE123 IJJs, and discussed the escape mechanism of these IJJs which could not be adopted to escape model of a single Josephson junction.

2. Experimental

Eu123 and Er123 single crystal whiskers were grown by Sb and Te-doping method \[12\], and two kinds of inline junctions with dimensions of $1 \times 1 \times 0.1 \mu m^3$ were fabricated from the whiskers using a focused Ga$^+$ ion beam. The details of the fabrication process are described in \[5,13\]. The overlap lengths through the c-axis of both the samples were 0.1 $\mu$m, which correspond to the total junction number of ~80. Post-annealing was then performed at $400^\circ$C under vacuum ($P_{O_2} < 10^{-2}$ Pa). The career doping state of RE123 IJJs was tuned to be heavily under-doped region where the $T_c$ was in the range of 30 – 35 K, the values of $\gamma$ were 30 – 40. The capacitance, $C$, of the junctions were estimated to be 140 fF for both samples using a dielectric constant of 15 \[14\]. The parameters of the samples were estimated from measurements at 4.2 K, and are summarized in Table I.

The $I-V$ characteristics of both the samples were measured using the four-terminal method in a $^3$He cryostat from room temperature to 0.6 K. To reduce the external noise, the samples were biased using an analog function generator at 0.015 A/s. The voltages across the sample and a reference resistance to monitor the current were amplified using low noise self-made amplifiers and measured using an oscilloscope. The switching current was measured using the “single-pulse-method”, where individual voltage pulses were discontinuously generated from the function generator in order to eliminate the self heating effect on the effective measurement, and at each temperature the switching current at which the junction switches from $V=0$ to a $V \neq 0$ state were recorded for 1000 – 8000 times.

### Table 1. Junction size, $T_c$, $J_c$, and $\beta_c$ at 4.2 K for the Eu123 and Er123 IJJs.

| Samples | Junction size [\mu m^3] | $T_c$ [K] | $J_c$ [Acm$^{-2}$] | $\beta_c$ ($= (4I_c/\pi I_r)^2$) |
|---------|------------------------|-----------|-------------------|---------------------------|
| Eu123   | 1.0 x 1.0 x 0.1         | 34.5      | 1.47 x 10$^4$     | 9                         |
| Er123   | 1.0 x 1.0 x 0.1         | 30        | 1.6 x 10$^4$      | 30                        |

3. Results and Discussions

The $I-V$ curves of Eu123 and Er123 IJJs exhibited clear multiple branches with hysteresis structure similar to those of other HTS IJJs; figure 1 (a) and (b) is a plot of the first switching from zero-voltage state of both IJJs. We can see transition to the first branch of approximately 7 mV in Eu123 IJJs, while Er123 IJJs exhibited transition to the second branch of ~13 mV. The collective switching in Er123 may occur as follows. When the initial junction turned to the resistive state, the critical current of neighbor junctions which were supposed to have slightly higher than the initial junction decreased by the sufficient heat diffusion and they also switched to the resistive state. Because the initial and the neighbor junctions switched at almost the same time, the collective switching seemed to occur. We thought that the collective switching in Er123 attributed to the slightly larger upper switching current,
$I_c$, than that of Eu123, which cause larger heating effect. In fact, the voltage transition of Eu123 also became to the collective switching of two-junctions at lower temperature where the $I_c$ value enlarged to $\sim 0.14$ mA.

**Figure 1.** $I$-$V$ curves of the first switching from zero voltage state of (a) the Eu123 IJJs and (b) the Er123 IJJs.

**Figure 2.** The $P(I)$ for (a) the Eu123 IJJs and (b) the Er123 IJJs measured at 1.0 – 6.0 K. The colored symbols represents the experimental data and the solid and dashed lines shows the modelled results of the equation (1) and (2) using effective energy barrier $U_{eff}$ instead of $U_0$. The inset shows the $P(I)$ for the Eu123 at 4.2 K with theoretical fitting using equation (1) using $U_0$.

The McCumber parameter $\beta_c \approx \left(\frac{4I_c}{\pi I_r}\right)^2$ [15], where $I_r$ is the return current, were estimated as 9 and 30 at 4.2 K for Eu123 and Er123, respectively, from the $I$-$V$ curves. From this it was found that both the samples were in the under-damped regime.

Figure 2 (a) and (b) shows a plot of $P(I)$ for the first switching of Eu123 and Er123 a function of the bias current $I$, measured below 6 K. The colored dots represent the experimental data. The peaks
were found to shift gradually to higher currents and become sharp with decreasing temperature. For Eu123 IJJs, the \( P(I) \) became independent of temperature below 1.4 K.

The escape rate \( \Gamma_T \) from the \( V = 0 \) state of the single Josephson junction (SJJ) in the low damping regime can be analyzed in terms of activation model, which is given by [16,17]:

\[
\Gamma_T = \frac{\omega_0}{2\pi} \exp\left(-\frac{U_0}{k_B T}\right)
\]  

(1)

where \( U_{eff} \) is the barrier energy of the meta stable state. The meta stable state is found to decrease for an increasing bias current: that is, \( U_0(I) = h/2e[2\sin^{-1}(I/I_c0) + 2(I_c0^2-I^2)^{1/2} - \pi I] \). Here \( I \) and \( I_c0 \) are the bias and the critical current in the absence of fluctuations, respectively. \( \omega_0 \) is the bias depending plasma frequency, and \( \Phi_0 \) is the magnetic flux quantum. At temperatures below a crossover temperature, \( T^* \sim \hbar \omega_0/2\pi k_B \), the escape is dominated by quantum tunneling through the barrier. In the MQT process, the escape rate \( \Gamma_{MQT} \) is given by [18]

\[
\Gamma_{MQT} = 12\omega_0 \left( \frac{3U_0}{2\pi\hbar\omega_0} \right)^{1/2} \exp\left(-\frac{36U_0}{5\hbar\omega_0}\right)
\]  

(2)

The \( P(I) \) of the RE123 IJJs were fitted using this SJJ model, which is usually used for Bi2212 IJJs. The inset of figure 2 (a) shows the typical fit to the data using equation (1). As clearly seen, we found that the SJJ model could not explain the behavior of the \( P(I) \) in RE123 IJJs. This is in contrast with the fact that \( P(I) \) of Bi2212 IJJs have been well explained by the model [1-3].

However, \( P(I) \) were found to be significantly broader than that expected from the escape model, we eventually could fit our data with equation (1) by assuming the effective energy barrier \( U_{eff} \) instead of \( U_0 \); \( U_{eff} = a \times U_0 \), where \( a \) is the constant fixing the energy barrier \( U_0 \). Excellent fit were obtained when we supposed that the effective energy barrier \( U_{eff} \) were considerably smaller than \( U_0 \). The values of \( a \) were 0.2 for Eu123 IJJs and 0.15 for Er123 IJJs. The solid lines and dashed lines in figure 2 (a)(b) represent the fitting based on equation (1) and (2) using the \( U_{eff} \) in place of \( U_0 \). The zero-noise critical current estimated from the fitting were \( I_c0 = 167 \pm 2 \) \( \mu A \) and \( 187 \pm 1 \) \( \mu A \) for Eu123 and Er123, respectively.

There are some possibilities considered as reasons that model worked well by using \( U_{eff} \). One is the case that the IJJs contained magnetic flux. It is reported that if the cross-sectional dimension of IJJs is longer than the Josephson penetration depth, \( \lambda_J \), the switching dynamics of the junctions may be determined by the motion of vortex in the IJJs even in zero magnetic field [19,20]. The first switching in the \( I-V \) curve corresponds to escape of vortex from a pinning potential in one junction which has the minimum critical current in IJJs. In this case, the absolute value of energy potential is determined by the pinning strength which is variable value, and the energy barrier for the escape scales as \( (1-1/I_c0)^{3/2} \) close to \( I_c0 \) just as the Josephson phase escape in a small junction [21]. This explanation seems feasible for our experimental result, however to insert a fluxon into our IJJs seems impossible that self-fields generated by the bias currents in the IJJs were negligibly small <1 Oe compared to the \( H_{c1} \) of HTS which is larger than 100 Oe.

Another one is the possibility that effective energy barrier did not actually decrease in our samples, but escape rate were enhanced by multi junction effect. The model adopted our result was considering only a single junction, whereas IJJs were regarded as a multi junction system. It may well be that the escape rate in strongly coupled IJJs such as in RE123 is different from that in a single junction. To confirm the reason of enhanced escape rate in RE123 IJJs, an escape model for multi-stack junctions is required instead of the SJJ model.
Figure 3. The standard deviation of $P(I)$, $\sigma = \langle (I - \langle I \rangle)^2 \rangle^{1/2}$ for Eu123 and Er123 IJJs as a function of temperature. The dashed line indicates that $\sigma \propto T^{2/3}$.

Figure 3 shows the standard deviation of $P(I)$, $\sigma = \langle (I - \langle I \rangle)^2 \rangle^{1/2}$, for Eu123 and Er123 IJJs as a function of temperature. The $\sigma$ decreased almost proportional to $T^{2/3}$ in the temperature range of 1.5-5 K for Eu123 and Er123, which indicated that their escape process were dominated by thermal activation in these temperature range. Above 5 K, the deviation from $T^{2/3}$ dependence is observed in both IJJs, which may be due to the retrapping events in the under-damped phase diffusion regime [22]. The similar effects were also observed in Bi2212 IJJ [20,23]. Incidentally, the $\sigma$ of Eu123 IJJs saturated at 1.4 K, suggested that the escape process was dominated by MQT below 1.4 K. The crossover temperature of 1.4 K was higher than that of Bi2212, which would be attributed to the high plasma frequency $\sim$300 GHz at 4.2 K of Eu123 IJJs.

4. Conclusions
In summary, we have investigated the temperature dependence of $P(I)$ in heavily under-doped Eu123 and Er123 IJJJs, and found that the $P(I)$ of RE123 exhibited significant broadening deviations from the escape model of a SJJ in Eu123 IJJJs, deviation from $T^{2/3}$ dependence in $\sigma$ was observed above 5 K and below 1.4 K. One can be attributed to the retrapping events, and the other to the crossover of escape process from the thermally activated regime to the quantum regime. The crossover temperature of 1.4 K was higher than that of Bi2212, which is thought to be due to the high plasma frequency $\sim$300 GHz of Eu123 IJJJs. It can be said that the IJJs in a RE123 system exhibited good potential for the application in phase qubits based on MQT at high temperatures.

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] Jin X Y, Lisenfeld J, Koval Y, Lukashenko A, Ustinov A V, and Müller P 2006 Phys. Rev. Lett. 96 177003.
[3] Kashiwaya H, Matsumoto T, Shibata H, Kashiwaya S, Eisaki H, Yoshida Y, Kawabata S, and Tanaka Y cond-mat/0609615.
[4] Grabert H and Weiss U 1984 Phys. Rev. Lett. 53 1787.
[5] Kawae T, Nagao M, Takano Y, Wang H, Hatano T, Kim S J, and Yamashita T 2005 Supercond. Sci. Technol. 18 1159.
[6] Islam A T M N, Kawae T, Tachiki Y, Watauchi S, Takano Y, Hatano T, Yamashita T, and Tanaka I 2006 Supercond. Sci. Technol. 19 290.
[7] Koyama T and Tachiki M 1996 Phys. Rev. B 54 16183.
[8] Machida M, Koyama T, and Tachiki M 1998 Physica C 300 55.
[9] Machida M, Koyama T, and Tachiki M 1999 Phys. Rev. Lett 83 4618.
[10] Kleiner R, Steinmeyer F, Kunkel G, and Müller P 1992 Phys. Rev. Lett. 68 2394.
[11] Uematsu Y, Sasaki N, Mizugaki Y, Nakajima K, Yamashita T, Watauchi S, and Tanaka I 2001 Physica C 362 290.
[12] Nagao M, Yun K S, Nakane T, Wang H B, Takano Y, Hatano T, Yamashita T, Tachiki M, Maeda H, and Sato M 2005 Jpn. J. Appl. Phys. 44 L67.
[13] Kim S-J, Latyshev Y I, and Yamashita T 1999 Supercond. Sci. Technol. 12 729.
[14] Samara G A, Hammetter W F, and Venturini E L 1990 Phys. Rev. B 41 8974.
[15] Irie A, Hirai Y, and Oya G 1998 Apple. Phys. Lett. 72 2159.
[16] Kramers H A 1940 Physica 7, 284.
[17] Hänggi P, Talkner P, and Borkovec M 1990 Rev. Mod. Phys. 62 251.
[18] Caldeira A O, and Leggett A J 1981 Phys. Rev. Lett. 46 211.
[19] Mros N, Krasnov V M, Yurgens A, Winkler D, and Claeson T 1998 Phys. Rev. B 57 R8135.
[20] Kitano H, Ota K, and Maeda A 1999 Supercond. Sci. Technol. 20 S68.
[21] Kato T, and Imada M 1996 J. Phys. Soc. Jpn. 65 2963.
[22] Kivioja J M, Nieminen T E, Claudon J, Buisson O, Hekking F W J, and Pekola J P 2005 Phys. Rev. Lett. 94 247002.
[23] Krasnov V M, Bauch T, Intiso S, Hurfeld E, Akazaki T, Takayanagi H, and Delsing P 2005 Phys. Rev. Lett. 95 157002.