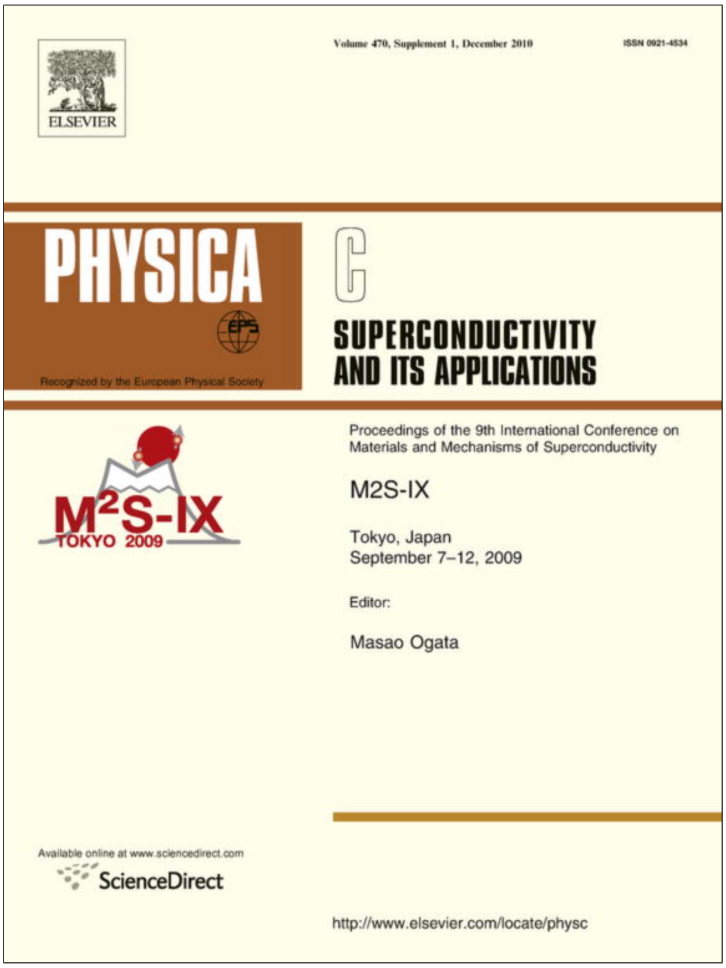
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Switching dynamics in a short and a long natural Josephson junction of $Bi_2Sr_2CaCu_2O_{8+\delta}$ single crystals

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ABSTRACT

We studied thermally activated and macroscopically quantum-tunneled switching from the zero-voltage state to a first resistive state in stacks of short and long Josephson junctions (JJs) naturally formed in $Bi_2Sr_2CaCu_2O_{8+\delta}$ single crystals. In the short (long) JJs the switching corresponds to an escape of a phase particle (a flexible phase line) from a potential well. The effective barrier height in the long JJs is reduced in proportion to the length of the junctions.

A pair of CuO_2 double layers separated by BiO and SrO insulating layers in $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi-2212) cuprate superconductors exhibit Josephson coupling below the superconducting transition temperature T_c. These natural Josephson junctions (JJs) constitute a stack of underdamped JJs connected in series along the c-axis with unsurpassed quality and homogeneity. Recently it has been confirmed that current-biased natural JJs retain the macroscopic quantum tunneling (MQT) of the phase difference across each JJ in spite of the dissipative low-energy excitation of quasiparticles near the nodes of the d-wave symmetry in the material down to the lowest temperatures [1–3]. The majority of studies on the phase MQT, however, have involved in short JJs whose lateral dimension L is smaller than the Josephson penetration depth $\lambda_J \approx 0.2$–$1.0\ \mu$m [4]. For $L > \lambda_J$, the JJ is no longer modeled as a point junction so that the phase dynamics is more complicated along with the possible introduction of Josephson vortices to the junction. Thus, studies on the phase MQT in natural JJs in a long junction limit are a subject of high interest [5]. Some results were reported on the thermal activation (TA) in the long JJ limit of conventional Nb-based JJs [6] and Bi-2212 natural JJs [7]. In this study, we investigated TA as well as MQT behavior of Bi-2212 natural JJs both in a short and a long junction limit.

Bi-2212 single crystals grown by the self-flux method was fabricated, by adopting the double-side cleaving technique [8,9] along with e-beam lithography and thermal evaporation, into a stack of natural JJs sandwiched between two, top and bottom, gold electrodes. The sample dimensions of the short and the long stack were $2.2 \times 2.7\ \mu m^2$ and $1.0 \times 15.0\ \mu m^2$, respectively. Samples were mounted on a cold finger that was thermally anchored to the mixing chamber of a dilution fridge (Oxford Model AST). All measurement wires were RC- and π-filtered near the mixing chamber with the cutoff frequency of 50 kHz and 10 MHz, respectively. Since both stacks of short and long junctions contained 31 and 29 underdamped JJs, respectively, each stack reveals hysteretic multiple resistive states, corresponding to the number of junctions. In this study only the switching events were traced from a zero-voltage state to a first resistive branch, i.e., to a state with one resistive junction, with the voltage threshold of switching set to be 1 mV. Here, the contact resistance (220 Ω (1 Ω) for the short (long) junction) was subtracted from the sample resistance of the two-probe measurement configuration (see the inset of Fig. 1a).

Since the phase difference in a short JJ is spatially uniform its dynamics [10] is described in terms of a fictitious phase particle trapped in the washboard potential $U(\phi) = -E_J(\gamma\phi + \cos\phi)$, where ϕ is the phase difference across a JJ, $E_J(= \hbar I_c/2e)$ is the Josephson coupling energy and $\gamma = I/I_c$ is the bias current normalized by the critical current I_c. The potential barrier ΔU that a phase particle should overcome to escape from a potential well depends on γ as $\Delta U = U_0\left[\sqrt{1-\gamma^2} - \gamma \arccos(\gamma)\right]$, where U_0 is the zero-bias barrier height. $U_0 = 2E_J$ for a short JJ. At the bottom of the potential well the particle oscillates at the attempt frequency of $\omega_p = \omega_{p0}(1-\gamma^2)^{1/4}$, where $\omega_{p0} = (2eI_c/\hbar C)^{1/2}$ is the plasma frequency and C is the junction capacitance. At sufficiently high temperature T a phase particle undergoes the thermally activated escaping out of the potential barrier with the rate [11], $\Gamma_{TA} = \frac{\omega_p}{2\pi}\exp\left(-\frac{\Delta U}{k_B T}\right)$. As the TA is exponentially reduced with lowering T the temperature-independent MQT escaping rate exceeds the TA escaping rate at T below the crossover temperature [12]

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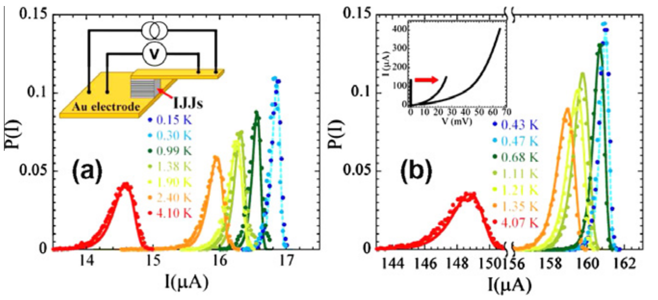

Fig. 1. The switching current distribution (solid circles) (a) of the short junction with the ramping rate of bias current $\dot{I} = 32.4$ mA/s and (b) of the long junction with $\dot{I} = 149.8$ mA/s, showing the best fit to the predictions of the thermal activation (solid lines) and the macroscopic quantum tunneling (dotted line). Inset of (a): sample configuration. Inset of (b): hysteretic quasiparticle-tunneling current–voltage curves for the long JJ, showing only the first three lowest-voltage branches among 29.

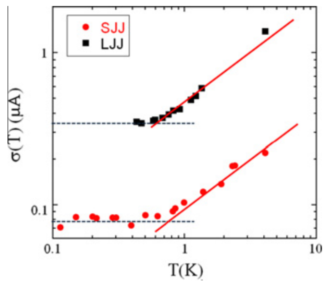

Fig. 2. Temperature dependence of the standard deviation $\sigma(I)$ of the switching current distribution $P(I)$ for the short (solid circle) and the long (solid square) stack of junctions.

$T_{cr} = \hbar\omega_p/2\pi k_B$. The MQT escaping rate is expressed as [13] $\Gamma_{\rm MQT} = \frac{\omega_p}{2\pi}\left(\frac{864\pi\Delta U}{\hbar\omega_p}\right)^{1/2}\exp\left(-\frac{36}{5}\frac{\Delta U}{\hbar\omega_p}\right)$.

The probability distribution of the switching current, $P(I)$, was measured as the bias current was ramped up at a constant rate $\dot{I}$. $P(I)$ is closely related to the escaping rate $\Gamma(I)$ as [11] $P(I) = \frac{\Gamma(I)}{\dot{I}}\left(1 - \int_0^I P(I')\,dI'\right)$.

On the other hand, a long JJ can be considered as a lateral series of inductively coupled $n(= L/\lambda_J)$ short JJs of length λ_J for each, with a nontrivial spatial variation of the phase difference. Thus, its dynamics is described in terms of a flexible phase line (rather than a phase particle) that consists of $n(= L/\lambda_J)$ linked phase particles. The thermally activated escape of a phase line has been studied both theoretically and experimentally [6]. For $L > \pi\lambda_J$, the escape of a phase line occurs in an energetically favorable way: creating 2π phase kink rather than activating entire phase line out of the potential barrier concurrently. Accordingly, U_0 in a long JJ is reduced from $U_0^{\rm SJJ}(= 2E_J)$ for a short JJ by a factor $n/4$ as $U_0^{\rm LJJ} = U_0^{\rm SJJ}/(n/4)$. The corresponding attempt frequency ω_p is also modified for a long JJ, although the modification is not significant so that ω_p exhibits the same asymptotic behavior as for a short JJ near the critical current, $\gamma \rightarrow 1$ [6].

We study the stochastic escaping process in our stacks by measuring the switching current distribution $P(I)$ at various temperatures. When the bias current during ramping reached the switching current a sudden jump of sample voltage (see the inset of Fig. 1b) triggered the 18-bit data acquisition board (NI-6281) to register the value of switching current. The process was repeated 9000–10,000 times to obtain $P(I)$. For the short JJ, as shown in Fig. 1a, $P(I)$ gets narrower and shifts to a higher current as T is lowered. Solid lines are the best fits of $P(I)$ to the TA prediction at T in the range of 0.99–4.10 K with the fitting parameters of $I_c = 17.8 \pm 0.2$ μA and $C = 30.7$ fF, where we use $U_0^{\rm SJJ}$ as U_0. The value of C is smaller than the estimated junction capacitance of $C = \varepsilon_r\varepsilon_0 S/d = 350$ fF, where $\varepsilon_r \approx 10$ [14] is the relative permittivity, ε_0 the vacuum permittivity, d (=1.5 nm) the junction repetition spacing and S the junction area. It may be due to the reduction of active junction area caused during the sample preparation. However, $\omega_{p0}/2\pi$ (=211.2 GHz), which is independent of the junction area, has the value comparable to the ones reported previously [1,2]. Also the MQT prediction with $U_0^{\rm SJJ}$ well fits the $P(I)$ data in the lower temperature range with the same parameters determined from the TA fit. For the long JJ of Fig. 1b, $P(I)$ at 0.68–4.07 K well fits the TA prediction using $U_0^{\rm LJJ}$ as U_0 and $L = 15$ μm. The best-fit parameters are $I_c = 166.7 \pm 0.6$ μA and $C = 885$ fF as estimated from $C = \varepsilon_r\varepsilon_0 S/d$ and $\lambda_J = 0.75$ μm which again gives reasonable criteria for the short and long JJ, $\pi\lambda_J = 2.4$ μm. Estimated plasma frequency with I_c and C is $\omega_{p0}/2\pi = 120.4$ GHz. Again, the MQT fitting, with the same parameters obtained from the TA fitting, shows a good agreement with the observed results.

Fig. 2 represents the temperature dependence of the standard deviation $\sigma(T)$ of $P(I)$ for the two samples. Both show similar saturation behavior with lowering T. In the TA regime of $T > T_{cr}$, $\sigma(T)$ is proportional to $T^{2/3}$ [1] (solid line). For $T < T_{cr}$, $\sigma(T)$ becomes saturated as the temperature-independent MQT escaping predominates. T_{cr} turns out to be 0.75 K and 0.58 K for the short and long JJ, respectively. Considering bias dependence of ω_p, $T_{cr}(= \hbar\omega_p/2\pi k_B)$ is estimated to be 0.79–0.94 K (0.46–0.49 K) for the short (long) JJ, which are close to the experimental results.

In this study, by measuring the stochastic switching current distribution $P(I)$, we confirm that the behavior of natural JJs in a short junction limit is well described by a phase particle trapped in a washboard potential, showing both the TA and MQT escaping. In the long natural JJs, data are successfully analyzed in terms of the same form of the escaping rate as for short JJs but with simply reducing the potential barrier height in proportion to the junction length in both TA and MQT regimes. However, the details of the phase line dynamics in the long JJs due to, for instance, the energy level quantization (ELQ) in the quantum well need to be further investigated.

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