Switching dynamics in a short and a long natural Josephson junction of Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ single crystals

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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$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ 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.

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The switching current distribution (solid circles) (a) of the short junction with the ramping rate of bias current \( I = 32.4 \text{ mA/s} \) and (b) of the long junction with \( I = 149.8 \text{ mA/s} \), 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 activation (solid lines) and the macroscopic quantum tunneling (dotted line). 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 \( T = 0 \) in the range of 0.99–4.10 K with the fitting parameters of \( l_c = 17.8 \pm 0.2 \mu \text{m} \) and \( C = 30.7 \text{ fF} \), where we use \( l_c^0 \) as \( U_0 \). The value of \( C \) is smaller than the estimated junction capacitance of \( C = e \rho S/d = 350 \text{ fF} \), where \( e \approx 0.11 \) [14] is the relative permittivity, \( \rho \) the vacuum permittivity, \( d = (1.5 \text{ nm}) \) 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, \( \omega_p/2\pi \approx 211.2 \text{ GHz} \), which is independent of the junction area, has the value comparable to the ones reported previously [1]. Also the MQT prediction with \( U_0^0 \) 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 \( U_0^0 \) as \( U_0 \) and \( L = 15 \mu \text{m} \).

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.

The best-fit parameters are \( L = 166.7 \pm 0.6 \mu \text{m} \) and \( C = 885 \text{ fF} \) as estimated from \( C = e \rho_0 S/d \) and \( \lambda_I = 0.75 \mu \text{m} \) which again gives reasonable criteria for the short and long JJ, \( \lambda_J = 2.4 \mu \text{m} \). Estimated plasma frequencies \( \omega_p \) from the TA fitting, with the same parameters obtained from the TA fitting, shows a good agreement with the observed 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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References