Probing the intrinsic Josephson coupling potential in $Bi_2Sr_2CaCu_2O_{8+\delta}$ superconductors by thermal activation

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We study thermal fluctuation phenomena in small Bi-2212 intrinsic Josephson junctions. Being able to measure switching currents of a single intrinsic junction, we observe that its statistics can be very well described by thermal activation from a periodic Josephson potential with the sinusoidal current-phase relation. This is a direct evidence for the dc-intrinsic Josephson effect and confirmation of the tunneling nature of interlayer transport in strongly anisotropic high-temperature superconductors. Furthermore, the fluctuation-free critical current, extracted from the analysis of switching current statistics, exhibits a temperature dependence typical for superconductor-insulator-superconductor tunnel junctions.

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The nature of interlayer transport in high-T_c superconductors (HTSC) has been a long standing question.[1] It is established that in extreme anisotropic Bi- and Tl-based HTSC intrinsic Josephson effect exists between superconducting CuO_2 planes.[2] Both dc- and ac-intrinsic Josephson effects were observed in $Bi_2Sr_2CaCu_2O_{8+x}$ (Bi-2212), in the form of flux quantization,[3–5] Fiske[3] and Shapiro[6] steps in current-voltage characteristics (IVC's), and the Josephson plasma resonance.[7] On the other hand, the role of blocking Bi-layers and the mechanism of interlayer transport in Bi-2212 is still unclear, partly due to difficulties in analyzing intrinsic Josephson data caused by stacking and strong electromagnetic coupling of intrinsic Josephson junctions (IJJ's).[8]

The type of Josephson coupling can be deduced from the dependence of the Josephson energy E_J on the phase difference φ, or, similarly, from the Josephson current-phase relationship $I_J(\varphi)=(2e/c\hbar)\partial E_J/\partial\varphi$, which varies from a sawtoothlike shape for metallic weak links to a sinusoidal shape for superconductor-insulator-superconductor (SIS) tunnel junctions.[9] The $E_J(\varphi)$ determines the junction electrodynamics, which is equivalent to motion of a particle in a "tilted washboard" potential, created by superposition of the periodic Josephson potential $E_J(\varphi)$ and the work done by the current source, $-(\hbar c/2e)I\varphi$. At a finite temperature, T, the particle can escape from the potential well as a result of thermal activation [see Fig. 3(a)]. This corresponds to switching of the junction from the superconducting to the resistive state. The rate of thermal escape,[10,11]

$$\Gamma_t(I) = a_t\frac{\omega_a}{2\pi}\exp\left[-\frac{\Delta U}{k_BT}\right], \quad (1)$$

is a sensitive probe of the $E_J(\varphi)$ both via the attempt frequency, ω_a, i.e., the frequency of oscillations at the bottom of the potential well, and, particularly, via strong exponential dependence of Γ_t on the potential barrier $\Delta U(\varphi)$. Thus, statistics of the switching current I_S carries direct information about the shape of $E_J(\varphi)$ and, therefore, about the type of Josephson coupling.

In this work we study the effect of thermal fluctuations in small Bi-2212 intrinsic Josephson junctions. Being able to measure switching currents of a *single* IJJ, we observe that its statistics can be very well described, without fitting parameters, by thermal activation from the tilted washboard potential with the sinusoidal current-phase relation. This is direct evidence for the dc-intrinsic Josephson effect and confirmation of the tunneling nature of interlayer transport in Bi-2212. We also demonstrate that thermal fluctuations dramatically affect properties of small IJJ's, resulting in strong suppression of the switching current and unusual temperature dependence in the whole T range. However, the fluctuation-free critical current I_{c0}, extracted from the analysis of switching current histograms, exhibits T dependence typical for SIS junctions, consistent with the tunneling nature of interlayer transport.

The IJJ's were fabricated by etching small mesa structures on top of Bi-2212 single crystals. We developed a simple procedure capable of fabricating deep submicron multiterminal IJJ's. Figure 1 shows a sketch of fabrication procedure. It involved self-alignment cross-bar photolithography, during which a window in the insulating CaF_2 layer was formed by lift-off and $\sim 3\times 3-6\times 6$ μm^2 mesas were formed at the crossing between the narrow-long mesa and barlike electrodes [see Figs. 1(a)–1(c)]. Finally, the sample was transferred into the standard focused ion beam (FIB) system and a smaller mesa was trimmed, as shown in [Fig. 1(d)]. Due to self-alignment at the previous stage, there is no parasitic area below the electrode and deep submicron mesas can be fabricated. Figure 1(e) shows IVC's of mesas before and after FIB trimming to submicron dimensions. Both IVC's exhibit a knee at the sum-gap voltage, followed by almost T-independent high-bias resistance,[12] which is typical for SIS tunnel junctions. The increase in resistance after trimming is in agreement with ~80-fold decrease in the mesa area.

Figure 2 shows IVC's, normalized by the mesa area, at $T\simeq 6$ K for the initial 6×3 μm^2 mesa and two smaller mesas obtained by cutting the initial mesa in two parts with the FIB. The multibranch structure of the IVC's is due to one-by-one switching of the IJJ's from the superconducting to the

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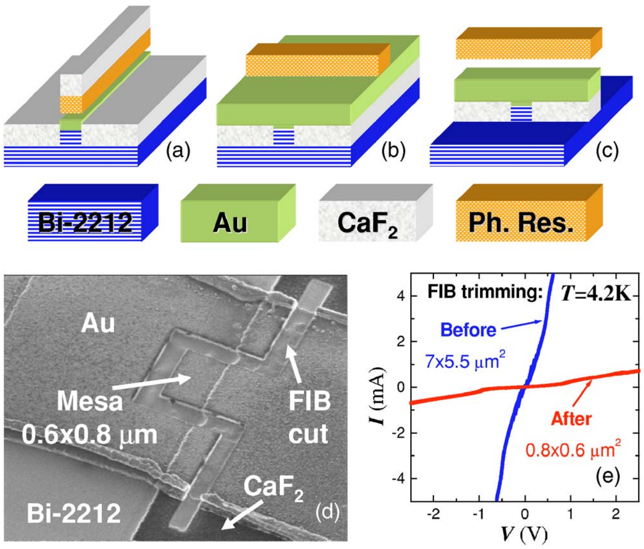

FIG. 1. (Color online) A sketch of sample fabrication: (a–c) Self-alignment cross-bar lithography, (d) secondary electron image of the sample after FIB trimming, and (e) I-V curves of mesas before and after FIB trimming.

resistive (quasiparticle) state. Naively, it could be expected that the normalized IVC's should collapse in one, since the critical current density is a material property, independent of the junction area. In reality, the measured switching current density decreases with the mesa area. To understand whether this is caused by deterioration of the IJJ's during FIB trimming and thermal cycling, we checked the scaling of quasiparticle branches in the IVC's. The thin solid lines in Fig. 2 represent multipleintegers of the fit to the first branch of the initial mesa. Quasiparticle branches of the initial mesa are perfectly periodic. However, the normalized quasiparticle branches of the trimmed mesas fall onto the same fitting curves. This implies that there is no visible deterioration of IJJ's during FIB trimming and thermal cycling. Therefore, the observed decrease of the switching current density in small mesas should be attributed to enhanced thermal activations due to decrease of the potential barrier ΔU, which is proportional to the Josephson energy $E_{J0}=(\hbar c/2e)I_{c0}$ and scales with the junction area.

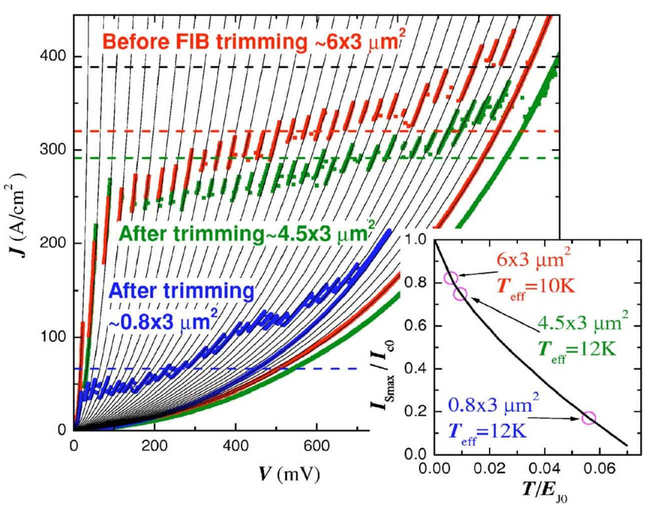

FIG. 2. (Color online) Current density vs voltage curves for a mesa before and after FIB cutting in two nonequal parts. The measured switching current density decreases with the size of the mesa. Solid lines are fits to quasiparticle branches, which are multiple integers of the first branch. Horizontal dashed lines show values of the fluctuation-free critical current density (the top line) and the most probable switching current densities for the three mesas, obtained from the fit shown in the inset. Inset: The solid line shows simulated dependence of the most probable switching current $I_{S\,max}$ vs T/E_{J0}, calculated for a classical thermal escape from a tilted washboard potential. Circles indicate the best fits for the three mesas.

For a quantitative analysis of the switching currents I_S in small mesas, we consider the effect of thermal activation from a tilted washboard potential. The switching probability is given by

$$P(I_S)=\frac{\Gamma(I_S)}{dI/dt}\left[1-\int_0^{I_S}P(I)dI\right]. \qquad (2)$$

Here dI/dt is the current sweeping rate. For moderately damped junctions the prefactor in Eq. (1) is $a_t=(1+1/4Q^2)^{1/2}-1/2Q$, where $Q=\omega_p RC$ is the quality factor.[11] In simulations we use the sinusoidal $I_J(\varphi)$, for which $\omega_a=\omega_p(1-(I/I_{c0})^2)^{1/4}$, where $\omega_p=(2eI_{c0}/\hbar cC)^{1/2}$ is the Josephson plasma frequency, and

$$\Delta U=2E_{J0}\left[\sqrt{1-\left(\frac{I}{I_{c0}}\right)^2}-\frac{I}{I_{c0}}\arccos\left(\frac{I}{I_{c0}}\right)\right]. \qquad (3)$$

The inset in Fig. 2 shows simulated dependence of the most probable switching current $I_{S\,max}$ as a function of the ratio T/E_{J0}, made for the typical experimental conditions. It is seen that $I_{S\,max}$ decreases with E_{J0}, which is proportional to the junction area. The circles in the inset show the fit to this universal dependence made using three fitting variables: the fluctuation-free critical current density J_{c0} (the same for all mesas), the effective noise temperature T_{eff} for the initial mesa, and for trimmed mesas (the same for both since they were measured in the same run). The horizontal dashed lines in Fig. 2 show J_{c0} (the top line) and the most probable switching current densities for the three mesas obtained from such a fit. Good agreement is seen between fitted and measured I_S for all three mesas. Taking into account that there were no free-fitting parameters (three points were fitted with three variables) and that $T_{eff}=10$ K and 12 K are similar and only few degrees above the substrate temperature $T\simeq 6$ K, we conclude that the observed decrease of the switching current density in smaller mesas is the result of enhanced thermal activation caused by reduction of E_{J0} with the junction area.

The thermal escape rate, Eq. (1) strongly depends on the shape of the washboard potential, $\Delta U(\varphi)$, which in turn depends on the current-phase relation $I_J(\varphi)$. Therefore, the probability distribution of the switching current $P(I)$ contains explicit information about the shape of Josephson potential $E_J(\varphi)$.[13] Since Fig. 2(b) indicates that the switching current density of small IJJ's is well described by thermal activation

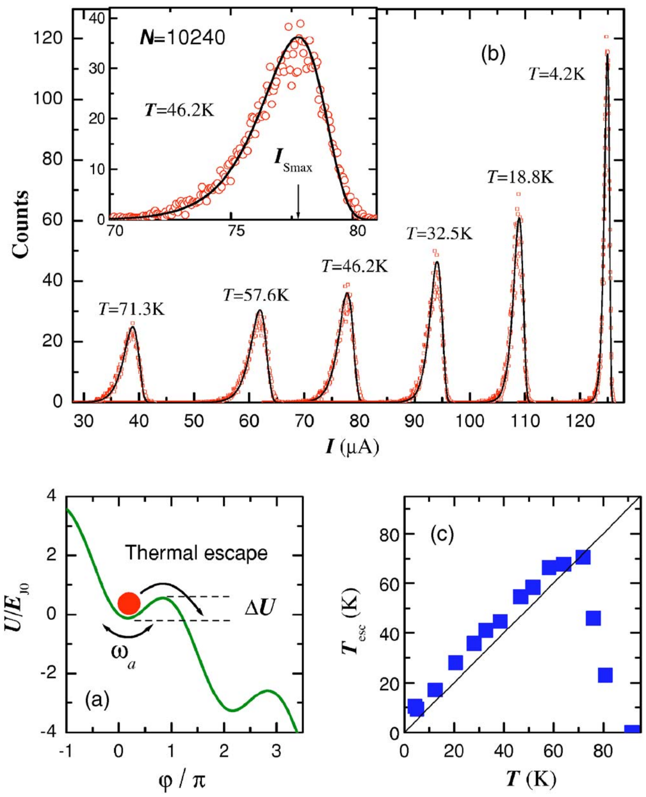

FIG. 3. (Color online) (a) The shape of tilted washboard potential for $I/I_{c0}=0.5$. (b) Switching current histograms of a single IJJ at different temperatures. Solid lines represent fits to classical thermal escape from the tilted washboard potential. The inset shows the quality of the fit for $T=46.2$ K. Dots and lines represent experimental data and fits, respectively. (c) The effective "escape temperature" vs temperature.

from the washboard potential, we should be able to probe the intrinsic Josephson potential by studying switching current statistics. Unfortunately, previous studies revealed that switching histograms of Bi-2212 mesas containing several IJJ's may be very complicated. It was reported that histograms of stacked IJJ's may contain multiple peaks[8,14] and appeared to be extremely broad,[8,14,15] up to ~10 times broader than expected. Such anomalous behavior was attributed to the presence of multiple metastable states (fluxon modes), which appear due to coupling of junctions in the stack.[8] The existence of metastable states results in a multiple valued critical current and dramatic enhancement of thermal fluctuations in stacked Josephson junctions. Note that such behavior is not specific to Bi-2212 mesas, but was also observed for low-T_c stacked Josephson junctions.[8]

In order to study the intrinsic Josephson potential we have to avoid metastable states. To solve this problem here, we have studied the switching of a *single* IJJ. The stable switching of a single junction can be obtained when there is a spread in critical currents between IJJ's in the mesa. Such a spread is often observed in mesas obtained by wet chemical etching (see Fig. 2) and is most probably caused by variation of the junction area due to undercut.

Figure 3 represents the switching statistics of a single IJJ in an optimally doped Bi-2212 mesa. This junction had ~20% smaller critical current than the rest of IJJ's in the mesa, which was sufficient for achieving stable biasing without switching the rest of IJJ's. Measurements were done in a shielded room using a sample-and-hold set up with the effective noise temperature ~100 mK.[16] Figure 3(b) shows switching histograms at different T, obtained from 10,240 switching events. The solid lines represent fits to classical thermal escape, Eqs. (1)–(3). The fits were made using following parameters: the experimental sweeping rate $dI/dt = 24.3$ mA/s, the specific capacitance $C=68.5\ fF/\mu\text{m}^2$, and the resistance, R, extracted from the high-bias resistivity $\rho_c = 25\ \Omega$ cm. Since $P(I_S)$ is only slightly dependent on C and R, those parameters were fixed during the fit to avoid ambiguity. The only remaining fitting parameter was the effective "escape" temperature T_{esc}, which in the absence of external noise should coincide with T, provided there are no second harmonics in $I_s(\varphi)$.[13] The obtained values of T_{esc} are plotted in Fig. 3(c). It is seen that for $T<72$ K, T_{esc} follows T. This confirms the validity of the fitting procedure and clearly demonstrates the sinusoidal $I_J(\varphi)$ in a wide T range. The accuracy with which the sinusoidal current-phase relationship is satisfied can be seen from the excellent quality of the fit, shown in detail in inset to Fig. 3(b). The upper limit of the second harmonics in $I_J(\varphi)$ is estimated to be $<10\%$, by adding the distortion (second harmonics) to the sinusoidal $I_J(\varphi)$, keeping T_{esc} fixed, until the calculated histogram deviated from the experimental by more than the data spread.

At high temperatures, $T>75$ K, T_{esc} starts to decrease and eventually vanishes close to $T_c \simeq 93$ K. The surprising collapse of thermal activation is associated with the change in the shape and width of switching histograms.[16] It is also associated with the decrease of the hysteresis in IVC's, as

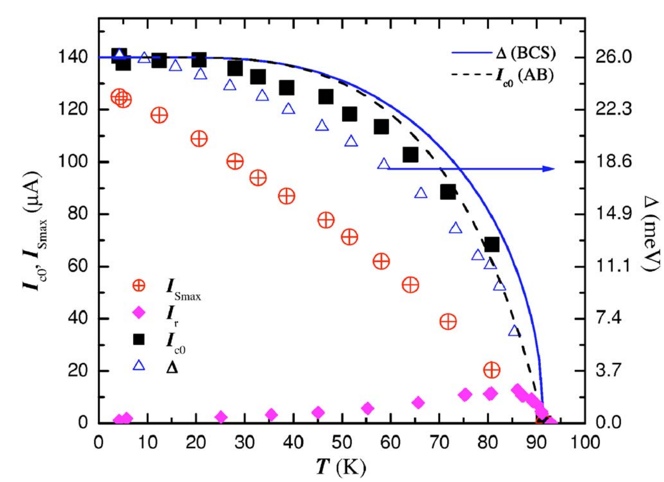

FIG. 4. (Color online) Temperature dependencies of the most probable switching current $I_{S\,max}$ (circles), the retrapping current I_r (rhombs), the extracted fluctuation-free critical current I_{c0} (squares), and the superconducting gap △ (triangles) for the same IJJ as in Fig. 3. It is seen that $I_{S\,max}$ has unusual linear dependence in the whole T range. However, $I_{c0}(T)$ is normal, close to $\Delta(T)$, and consistent with tunneling nature of the interlayer transport. For comparison, T dependencies of the energy gap $\Delta(BCS)$ and the critical current $I_{c0}(AB)$ for conventional SIS junctions are shown by solid and dashed lines, respectively.

seen from comparison of the switching current and the retrapping current, I_r, in Fig. 4. We note that the switching current remains sharply defined and there is no indication for a phase diffusion[17] up to ~ 90 K. We believe that the collapse of T_{esc} is caused by entering a high dissipation regime, where retrapping back to the superconducting state becomes significant. Such a paradoxical collapse is not unique for IJJ's but was also observed in low-T_c moderately damped junctions. Therefore, this phenomenon is not essential for the present work and is discussed elsewhere.[16]

Figure 4 shows temperature dependence of the most probable switching current $I_{S\,max}$ (circles), the retrapping current I_r (rhombs), and I_{c0}, obtained from fitting switching current histograms (squares), for the same IJJ as in Fig. 3. It is seen that $I_{S\,max}$ has an unusual linear dependence in the whole T range.[16] However, the T dependence of I_{c0} is quite normal and close to T dependence of the superconducting gap Δ (triangles), which was obtained from the sum-gap knee in IVC's at higher bias.[12] For comparison, T dependencies of the conventional BCS energy gap, $\Delta(BCS)$, and the Ambeokar-Baratoff value of the critical current $I_{c0}(AB)$ for conventional SIS junctions are shown in Fig. 4 by solid and dashed lines, respectively. It is seen that $I_{c0}(AB) \propto \Delta(BCS)$ at $T < T_c/2$.[18] The experimental $\Delta(T)$ deviates somewhat from $I_{c0}(T)$ in the intermediate T range. The deviation is likely a result of self-heating at the large sum-gap voltage. Such deviation is in agreement with both numerical simulations and *in situ* measurement of self-heating in our mesas.[19]

In conclusion, we probed the interlayer coupling in optimally doped $Bi_2Sr_2CaCu_2O_{8+\delta}$ by studying thermal fluctuations in a *single* intrinsic Josephson junction. We have shown that the switching current statistics of the IJJ can be very well described, without fitting parameters, in terms of thermal activation from a tilted washboard potential with the sinusoidal current-phase relation. This is direct and clear evidences of the dc-intrinsic Josephson effect. The $I_J(\varphi)$ is purely sinusoidal in the wide T range, including $T \ll T_c$. Such behavior is characteristic only for high-quality (low-transparency) tunnel junctions, as opposed to superconductor-normal-metal-superconductor or constriction type Josephson junctions with high transparency of the interface, which have sawtooth like $I_J(\varphi)$, at least at low T (Ref. 9). Therefore, our observation confirms the tunneling nature of interlayer transport in Bi-2212. We demonstrated that thermal fluctuations dramatically affect properties of small IJJ's, resulting in strong suppression of the switching current density and unusual T dependence in the whole T range. However, fluctuation-free I_{c0}, extracted from the analysis of switching current histograms, exhibit a T dependence typical for SIS tunnel junctions, also consistent with the tunneling nature of interlayer transport in Bi-2212.

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[1] D. G. Clarke, S. P. Strong, and P. W. Anderson, Phys. Rev. Lett. **74**, 4499 (1995); W. Kim and J. P. Carbotte, Phys. Rev. B **63**, 054526 (2001).
[2] R. Kleiner *et al.*, Phys. Rev. Lett. **68**, 2394 (1992); R. Kleiner and P. Müller, Phys. Rev. B **49**, 1327 (1994).
[3] V. M. Krasnov *et al.*, Phys. Rev. B **59**, 8463 (1999).
[4] Yu. I. Latyshev *et al.*, Physica C **362**, 156 (2001).
[5] S. Ooi *et al.*, Phys. Rev. Lett. **89**, 247002 (2002).
[6] H. B. Wang *et al.*, Phys. Rev. Lett. **87**, 107002 (2001).
[7] M. B. Gaifullin *et al.*, Physica C **362**, 228 (2001).
[8] V. M. Krasnov *et al.*, Phys. Rev. B **61**, 766 (2000); **56**, 9106 (1997).
[9] A. A. Golubov *et al.*, Rev. Mod. Phys. **76**, 411 (2004).
[10] J. M. Martinis *et al.*, Phys. Rev. B **35**, 4682 (1987).
[11] H. Grabert *et al.*, Phys. Rev. B **36**, 1931 (1987).
[12] V. M. Krasnov *et al.*, Phys. Rev. Lett. **84**, 5860 (2000); **86**, 2657 (2001).
[13] T. Bauch *et al.*, Phys. Rev. Lett. **94**, 087003 (2005).
[14] N. Mros *et al.*, Phys. Rev. B **57**, R8135 (1998).
[15] P. A. Warburton *et al.*, J. Appl. Phys. **95**, 4941 (2004).
[16] V. M. Krasnov *et al.*, cond-mat/0503067.
[17] R. L. Kautz and J. M. Martinis, Phys. Rev. B **42**, 9903 (1990); A. Franz *et al.*, *ibid.* **69**, 014506 (2004).
[18] Deviations from $I_{c0}(AB)$ are expected for IJJ's due to d-wave symmetry of the order parameter in Bi–2212. Nevertheless, such comparison is still valid; see e.g., Y. Tanaka and S. Kashiwaya, Phys. Rev. B **56**, 892 (1997); R. A. Klemm *et al.*, *ibid.* **58**, 14203 (1998).
[19] V. M. Krasnov *et al.*, Phys. Rev. Lett. **94**, 077003 (2005); J. Appl. Phys. **89**, 5578 (2001); *ibid.* **93**, 1329 (2003); Physica C **372–376**, 103 (2002).