Probing the intrinsic Josephson potential in Bi-2212 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 it’s 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 the first unambiguous confirmation of the tunnelling 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 \cite{1}. It is established that in extreme anisotropic Bi- and Ti-based HTSC intrinsic Josephson effects are observed in Bi$_2$Sr$_2$CaCu$_2$O$_{8+x}$ (Bi-2212), in the form of flux quantization \cite{3} and Shapiro \cite{4} steps in Current-Voltage characteristics (IVC’s) and the Josephson plasma resonance \cite{7}. On the other hand, the role of blocking Bi-layers and the nature of interlayer coupling in Bi-2212 is still unclear, partly due to difficulties in analysing intrinsic Josephson data caused by stacking and strong electromagnetic coupling of intrinsic Josephson junctions (IJJ’s) \cite{5}.

The type of Josephson coupling can be deduced from the dependence of the Josephson energy $E_J$ on the phase difference $\phi$, or, similarly, from the Josephson current-phase relationship $I_s(\phi) = \left(\frac{2e}{h}\right) \frac{\partial E_J}{\partial \phi}$, which varies from a saw-tooth like for metallic weak links to the sinusoidal for superconductor- insulator- superconductor (SIS) tunnel junctions \cite{2}. The $E_J(\phi)$ determines the junction electrodynamics, which is equivalent to motion of a particle in a "tilted wash-board" potential, created by superposition of the periodic Josephson potential $E_J(\phi)$ and the work done by the current source, $-(h/2e)I\phi$. At a finite temperature, $T$, the particle can escape from the potential well as a result of thermal fluctuations, see Fig. 3 a). This corresponds to switching of the junction from the superconducting to the resistive state. The rate of thermal escape \cite{6}, \cite{9},

$$\Gamma_I(I) = \frac{\omega_0}{2\pi} \exp \left[ -\frac{\Delta U}{k_B T} \right], \quad (1)$$

is a sensitive probe of the $E_J(\phi)$ both via the attempt frequency, $\omega_0$, \textit{i.e.}, the frequency of oscillations at the bottom of the potential well, and, particularly, via strong exponential dependence of $\Gamma_I$ on the potential barrier $\Delta U$. Thus, the switching current statistics carries direct information about the shape of $E_J(\phi)$ and, therefore, about the nature of Josephson coupling.

In this letter we study the effect of thermal fluctuations in small Bi-2212 intrinsic Josephson junctions. Being able to measure switching currents of a single IJJ in an electrically shielded environment, we observe that it’s statistics can be very well, and without fitting parameters, described by thermal activation from the tilted wash-board potential with the sinusoidal current-phase relation. This is a direct evidence for the dc-intrinsic Josephson effect and the first unambiguous confirmation of the tunnelling 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 $I_0$, extracted from the analysis of switching current histograms, exhibit $T$-dependence typical for SIS junctions, consistent with tunnelling nature of the interlayer coupling.

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 sub-micron multi-terminal IJJ’s. Fig. 1 shows a sketch of fabrication procedure. It involved self-alignment cross-bar photolithography, during which an insulating CaF$_2$ layer was formed using lift-off, see Fig. 1 a), and $\sim 3 \times 3 - 5 \times 5 \mu m^2$ mesas were formed in a self-aligned manner, Fig. 1 c), at the crossing between the narrow-long mesa, Fig. 1 a) and bar-like electrodes, Fig. 1 b). Finally, the sample was transferred into standard Focused Ion Beam (FIB) system (FEI Inc. FIB-200), and a smaller mesa was trimmed by cutting of a portion of the mesa, 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. Fig. 1 e) shows IVC’s of mesas before and after FIB trimming to sub-micron dimensions. Both IVC’s exhibit a knee at the sum-gap voltage, fol-
The increase in resistance after trimming is in agreement with reference [12], which is typical for SIS tunnel junctions. The probability to tunneling due to decrease of the potential barrier ∆E is proportional to the Josephson energy E_{J0} = ℏ/2eI_{c0}, made for the typical experimental conditions. It is seen that I_{max} decreases with E_{J0}, which in turn is proportional to the area of the junction. 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 T_{eff} 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 switching currents for all three mesas. Taking into account that there was no free fitting parameters (three points were fitted with three variables) and that \( T_{c,ff} = 10K \) and \( 12K \) are similar and only few degrees above the substrate temperature \( T \approx 6K \), we conclude that the observed decrease of the switching current density in smaller mesas is the result of enhanced thermal fluctuation caused by reduction of the Josephson coupling energy \( E_{J0} \) with junction area.

The thermal escape rate, Eq. (1), strongly depends on the shape of the wash board potential, \( \Delta U(\varphi) \), which in turn depends on the current-phase relation \( J_s(\varphi) \). Therefore, the probability distribution of the switching current \( P(I) \) contains explicit information about the shape of Josephson potential \( E_J(\varphi) \). Since Fig. 2 b) indicates that the switching current density of small JJ’s is well described by thermal activation from the wash-board potential, we should be able to probe the intrinsic Josephson potential by studying switching current statistics. Unfortunately, previous studies of the switching current statistics in Bi-2212 mesas revealed that switching current histograms of mesas containing several stacked JJ’s may be very unusual. It was reported that histograms of stacked JJ’s may contain multiple peaks \[8,13\] and appeared to be extremely broad \[8,13,14\], up to \( \sim \)ten 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 switching of a single JJ. The stable switching of a single junction can be obtained when there is a spread in critical currents between JJ’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.

Fig. 3 represents the switching current statistics of a single JJ in an optimally doped Bi-2212 mesa. This junction had \( \sim 20\% \) smaller critical current than the rest of JJ’s in the mesa, which was sufficient for achieving stable biasing without switching the rest of JJ’s. Measurements were done in a shielded room environment using a sample-and-hold setup with the effective noise temperature \( \sim 100mK \) \[16\]. Fig. 3 b) shows switching current histograms obtained from 10240 switching events at
different $T$. The solid lines represent fits to classical thermal escape, Eqs. (1-3). The fit was made using following parameters: the experimental sweeping rate $dI/dt = 24.3 m A/s$, the specific capacitance $C = 68.5 f F/\mu m^2$, and the junction resistance, $R$, extracted from the high bias resistivity $\rho_e = 25 f cm$. Since the probability distribution 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 noise should coincide with $T$. The values of $T_{esc}$ obtained from the fit are plotted as a function of $T$ 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 current-phase relation and the cosinusoidal dependence of the intrinsic Josephson potential $E_J(\varphi)$. The remarkable accuracy with which the sinusoidal current-phase relationship is satisfied can be seen from the excellent quality of the fit, which is shown in detail in inset to Fig. 3 b). Such behavior is characteristic for high quality SIS tunnel junctions. This is the first unambiguous evidence for the tunnelling nature of interlayer transport in Bi-2212.

At high temperatures, $T > 75 K$, $T_{esc}$ starts to decrease and eventually vanishes close to $T_c \approx 93 K$. The surprising collapse of thermal fluctuations close to $T_c$ is associated with the change in the shape of switching histograms, which lose their characteristic asymmetric form and become symmetric and narrow. It is also associated with the decrease and collapse at $T \sim 80 K$ of the hysteresis in IVC, as seen from comparison of the most probable switching current, $I_{max}$, and the retrapping current $I_r$, shown in Fig. 4. We note that the switching current remains sharply defined and there is no indication for a phase-diffusion up to $\sim 90 K$. We believe that the collapse of $T_{esc}$ is caused by entering high dissipation regime close to $T_c$, in which the spread in switching currents is reduced by enhanced probability of retrapping of the rolling particle in the wash board potential. We emphasize that such unusual behavior is not unique for Bi-2212 IJJ’s but was also observed in low-$T_c$ superconductor- normal metal- superconductor junctions. Therefore, this phenomenon is not essential for the present work and will be discussed elsewhere.

Fig. 4 shows temperature dependence of the most probable switching current $I_{max}$ (circles), the retrapping current $I_r$ (rhombi), and $I_{0r}$, obtained from fitting switching current histograms (squares), for the same IJJ as in Fig. 3. It is seen that $I_{max}$ has an unusual linear dependence in the whole $T$-range. However, the $T-$dependence of $I_{0r}$ is quite normal and close to $T-$dependence of the superconducting gap $\Delta$ (triangles), which was obtained from the sum-gap knee in IVC’s at higher bias. For comparison, $T-$dependencies of the conventional BCS energy gap, $\Delta(BCS)$ and the Ambeokar-Baratoff value of the critical current $I_c(AB)$ for conventional SIS junctions are shown in Fig. 4 by solid and dashed lines, respectively. It is seen that $I_c(AB) \propto \Delta(BCS)$ at $T < T_c/2$. The experimental $\Delta(T)$ deviates somewhat from $I_{0r}(T)$ in the intermediate $T-$range. The deviation is likely a result of self-heating at the large sum-gap voltage $V = 2N\Delta/e$, where $N$ is the number of IJJ’s in the mesa. Such deviation is in agreement with both numerical simulations and in-situ measurement of self-heating in our mesa. Therefore, the unusual $T-$dependence of the switching current is solely due to thermal fluctuations, while $T-$dependence of the extracted fluctuation free critical current is consistent with the tunnelling nature of interlayer transport.

In conclusion, having studied the switching current statistics of a single Bi-2212 intrinsic Josephson junction, we observed that it can be very well, and without fitting parameters, described by thermal activation from a tilted wash-board potential with the sinusoidal current-phase relation. This is direct evidence for the dc-intrinsic Josephson effect and the first unambiguous confirmation of tunnelling nature of the interlayer transport in strongly anisotropic HTSC. 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 $I_{0r}$, extracted from the analysis of switching current histograms, exhibit a $T-$dependence typical for SIS tunnel junctions, also confirming tunnelling nature of the interlayer coupling.

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