Relationship between the Out-Of-Plane Resistance and the Subgap Resistance of Intrinsic Josephson Junctions in $Bi_2Sr_2CaCu_2O_{8+\delta}$

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We have experimentally demonstrated that the c-axis magnetoresistance peak effect is determined by the subgap resistance of intrinsic Josephson junctions in $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi2212). Given a Bi2212 single crystal, the effect may be predicted from the c-axis current-voltage (I-V) characteristics in *zero* magnetic field. At high magnetic field H, the I-V characteristics preserve their overall nonlinear shape at the transition temperature $T_c(H) \leq T_c(0)$ suggesting a smooth change of the vortex system with temperature. Observation of the gap feature below $T_c(0)$ at all $\mu_0 H \leq 7$ T means that the upper critical field is not attained at these fields. [S0031-9007(97)04867-9]

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For the most anisotropic cuprate superconductors, the temperature dependence of the out-of-plane (c-axis) resistance is very much different from the in-plane (a- or b-axis) dependence. Above the superconducting transition temperature $T_c(0)$, the in-plane resistance usually shows a linear increase with temperature. For the out-of-plane resistance, however, there is a large peak in the resistance, just above $T_c(0)$. Measurements of the c-axis magnetoresistance have revealed that the peak in resistance increased in magnitude with field and the zero resistance state moved to lower temperature [1].

Several models for the c-axis magnetoresistance peak effect were suggested [1–3]. An initial explanation of the peak by 1D (one dimensional) phase slippage [1] has not been able to explain the empirical “semiconducting” behavior of the normal state above the peak.

The fluctuation theory suggests a negative contribution to the c-axis conductivity associated with the fluctuation decrease of the quasiparticle density of states [2]. Far from the transition temperature the negative contribution may prevail over the paraconductivity [2]. This can explain a relatively small resistance increase, observed in several experiments [2]. However, the reported much larger increase in the c-axis resistance [4] is difficult to understand from fluctuations only [5].

The high-temperature superconducting (HTS) materials are composed of one or several superconducting Cu-O planes embedded in insulating, semiconducting, or semimetallic charge reservoirs. The most anisotropic HTS compounds may thus be modeled as stacks of Josephson junctions with superconducting electrodes of Cu-O planes, which are weakly coupled through the intermediate layers [6]. Several observations of the Josephson effects in $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi2212) and $Tl_2Ba_2Ca_2Cu_3O_{10+\delta}$ now strongly favor this model [7]. The c-axis conduction in Bi2212 is then a conduction of the series array of such intrinsic Josephson junctions (IJJ) [3]. The conduction of an unshunted Josephson junction consists of the quasiparticle, G_q, and the pair G_p conductances, which have the opposite temperature dependences. The competition between the two determines the position in temperature and the magnitude of the peak in the c-axis resistance [3]. The role of the magnetic field resides in suppression of G_p and shifting the equilibrium towards lower temperatures.

Although being conceptually simple, this model of the c-axis magnetoresistance peak effect has not so far been experimentally checked. In the experiments, where the Josephson effects are directly seen, there were no measurements in magnetic field [7]. Likewise, the c-axis transport experiments in the magnetic field [1,4,8–10] showed no clear evidence of the Josephson effects [11]. In fact, in the majority of similar works, the Josephson nature of the interlayer coupling is simply taken for granted and, to our knowledge, no unique experimental evidence has been given to relate these two phenomena.

In this Letter we report on a direct correlation between the c-axis tunneling properties and the magnetoresistance, strongly supporting the model proposed by Gray and Kim [3].

Experimentally, in contrast to all previous studies [1,4,8–10], we investigate only a few unit cell layers (5–15) of low-height mesas patterned on the surface of a Bi2212 single crystal. Details of the fabrication process are published elsewhere [12]. Several electrical contacts on top of the mesas allowed us to perform four-probe measurements.

The smallness of the single crystal volume under study significantly reduces the probability of having severe crystal lattice defects in it and allows us to observe what we think is the unmasked genuine properties of the material.

Figure 1 shows a typical I-V characteristic for one of the investigated samples with a mesa area of $20 \times 30\ \mu m^2$. There are nine branches seen in Fig. 1, each corresponding to one, two, etc., IJJ leaving the zero-voltage state as the current subsequently exceeds the

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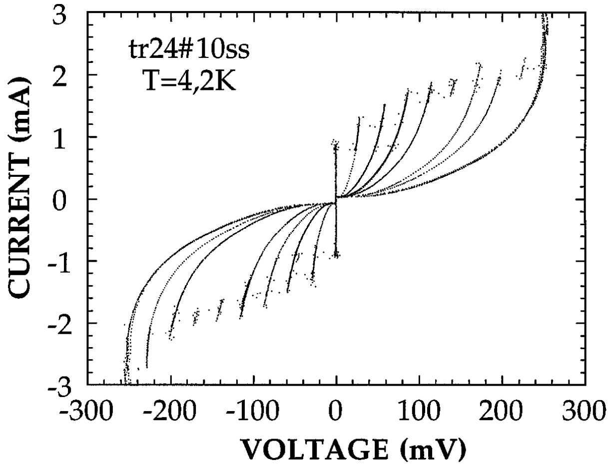

FIG. 1. Typical *I-V* characteristic of a series array of IJJ at 4.2 K in zero magnetic field.

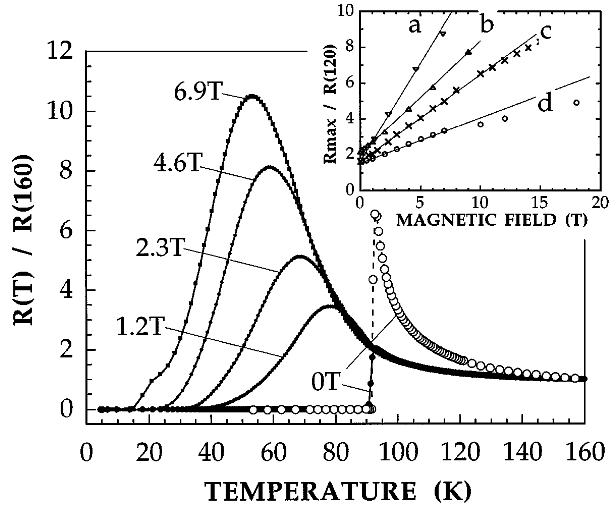

FIG. 2. The temperature dependence of the normalized resistance, $R(T)/R(160\ \mathrm{K})$, of the stack tr24#10ss with 9 IJJ (see Fig. 1) at different magnetic fields indicated for each curve (closed symbols and lines), and $R(T)/R(160\ \mathrm{K})$ for another sample in a zero magnetic field (open circles and dashed line). The latter demonstrates that $R(T)$ may have a large increase even in zero field. The inset shows the magnetic field dependence of the normalized maximal resistance, $R_{\max}/R(120\ \mathrm{K})$. (a) Our data; (b) data from Ref. [4]; (c) data from Ref. [10]; (d) data from Ref. [8]. Straight lines are guides for the eye.

critical currents for the first, second, etc., IJJ. From the number of junctions in series, we judge that the mesa is 135 Å high. The branches were traced in multiple sweeps of an ac bias current ($f_1 \sim 37$–47 Hz) with a 100% amplitude modulation ($f_2 \sim 3$–11 Hz).

The *I-V* characteristics are highly hysteretic, which is typical for Josephson tunnel junctions with large capacitances. The characteristic (gap) voltage, $v_g = 2\Delta_c/e$, for an individual IJJ is about 25 mV, which means that the c-axis superconducting energy gap parameter $\Delta_c \approx 12$ meV, about one half of the widely accepted value [13]. The reason for the reduced value of Δ_c may be a proximity induced superconductivity of the intermediate Bi-O layers [14]. Then, what is seen in the experiment is the tunneling in between adjacent Bi-O layers with a small induced superconducting gap, while in between Bi-O and Cu-O layers there is a strong proximity coupling. This model may also explain the temperature dependence of Δ_c as well [14].

The temperature dependence of the c-axis resistance $R(T)$ measured with an ac (37 Hz) bias current density of ≈ 1–$2\ \mathrm{A\,cm^{-2}}$ using a common lock-in technique is shown in Fig. 2 for different magnetic fields. In our measurements, with a maximum available field of 7 T, we have observed an enhancement in resistance of ~ 10 times; see the inset of Fig. 2, where the data extracted from similar experiments of Refs. [4,8,10] are plotted along with our data for comparison. We think the effect is larger for our samples mainly due to the smallness of the mesa sizes [11]. In favor of this speaks the fact that single crystals of the same origin [15] were used both in our experiments and in measurements of Ref. [10]; see curve c in the inset of Fig. 2.

To check the model of Gray and Kim [3] we directly determine the subgap resistance R_{sg} of the series array of IJJ from our *I-V* characteristics. We will define R_{sg} as the dynamic resistance $(\delta V/\delta I)_{V\to 0}$ of the last branch of the *I-V* characteristics corresponding to all IJJ in the quasiparticle state [16]. Then, we compare it with the c-axis resistance in magnetic field. From the model of Ref. [3] it follows that whatever the reason for the suppression of the pair conductance, the c-axis resistance of an ideal layered high-T_c single crystal is equal to the subgap resistance r_{sg} of an individual IJJ at zero bias voltage times the number of such junctions, $R_{sg} \approx N r_{sg}$. In a simplified picture, r_{sg} is determined by both the quasiparticle and shunting normal conductance G_n, $r_{sg} = (G_n + G_q)^{-1}$. At low enough temperature, G_q freezes out and the subgap resistance is dominated by the presumably temperature independent G_n. Thus, we expect the magnetoresistance peak effect to saturate at low temperatures (high magnetic fields).

Figure 3 shows $R(T)$ for two samples together with the temperature dependences of the subgap resistances R_{sg}. It is clearly seen that within experimental accuracy $R(T \geq T^*) \approx R_{sg}(T)$. This demonstrates the one-to-one correlation between the two. Here T^* is the temperature corresponding to the maximum in $R(T)$. With decreasing temperature, R_{sg} continues to increase and tends to level off at low temperature in full accordance with the above-mentioned picture, reaching a value $\approx 50R(160\ \mathrm{K})$. A comparable increase of resistance in pulse measurements was also observed in Ref. [17]. The overall resistance of the stack, however, vanishes at the transition temperature $T_c(H)$, which was shown to be slightly higher than the irreversibility temperature [4,8].

We note that R_{sg} is almost magnetic field independent, which means that the upper limit of the peak effect can

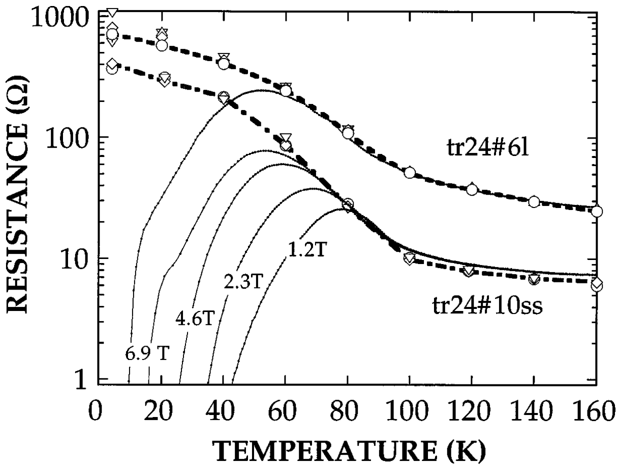

FIG. 3. Resistance of the stack R (thin lines) and the subgap resistance R_{sg} (open symbols and thick dotted lines) versus temperature for two samples at different magnetic fields. For the $R_{sg}(T)$ the different symbols correspond to different magnetic fields: (+) 0 T, (▽) −1.2 T, (△) −2.3 T, (◇) −4.6 T, and (○) −6.9 T. For clarity, there is only one $R(T)$ curve shown for the sample tr24#6l at 6.9 T.

be predicted directly from zero-field measurements of the I-V characteristics. The maximal magnetoresistance R_{max} cannot exceed R_{sg} at the temperature $T^*(H)$ corresponding to the peak position, and is expected to saturate at low T^* for high fields. This can also be seen in the inset of Fig. 2, where the data for higher fields have a tendency to saturate (curve d). For our samples we estimate the maximal effect at $\mu_0 H \sim 20$–30 T to be only a factor of 2 larger than presented here.

Closed symbols in Fig. 4 show the I-V characteristics of sample tr24#6l (mesa area 10×50 μm^2), at $\mu_0 H \approx 7$ T

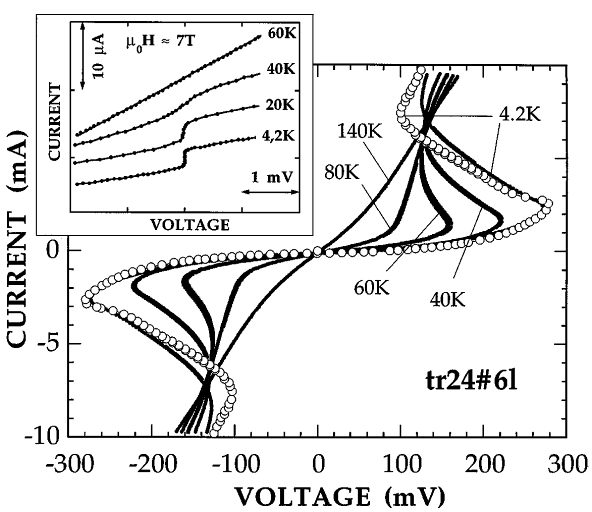

FIG. 4. The change of the I-V characteristics with temperature at $\mu_0 H \approx 7$ T and high current (closed symbols). The zero-field curve is shown for comparison (open symbols). (Inset) Low-bias parts of the I-V curves for the sample (shifted along the current axis for clarity).

and high bias current, when all IJJ in the stack are in the quasiparticle or normal tunneling state. The S-like shape of the I-V curves possibly witness to self-heating or nonequilibrium effects at high currents. Recently, Artemenko and Kobelkov have theoretically shown that a difference between densities of electron- and holelike quasiparticles due to a nonuniform current distribution in superconductors with anisotropic pairing may also result in a negative differential conductivity at high voltages [18].

Whatever the reason of the negative dynamic conductance at $I \geq 3$ mA, a well pronounced feature is clearly seen at this current. We believe that it reflects the superconducting energy gap, which is then obviously nonzero at any magnetic field below $T_c(0)$. The zero-field I-V curve (open symbols) is also shown in Fig. 4 to demonstrate that the magnetic field has little effect on the gap [19].

This observation speaks against the attempt to deduce the upper critical field H_{c2} from c-axis magnetoresistance measurements [10]. The empirical temperature dependent "background," which was taken in Ref. [10] as the thermodynamical normal state is very likely to be just a quasiparticle state of the intrinsic tunnel junctions with their electrodes (Cu-O planes) still being superconducting.

The inset of Fig. 4 shows the zero bias region of I-V characteristics at different temperatures for $\mu_0 H \approx 7$ T, slightly above and below $T^* \approx 50$ K, and close to the transition temperature $T_c(7\text{ T}) \approx 15$ K. The closer to $T_c(H)$ from above the more nonlinear behavior is seen in the I-V characteristics starting from almost linear at $T \leq T_c(0)$. This change is smooth and does not have any feature at $T_c(H)$.

As is seen from a comparison of Figs. 4 and 1, the critical current I_c at $T = 4.2$ K is suppressed by about 2 orders of magnitude in $\mu_0 H \approx 7$ T. At $T = 20$ K the I-V characteristics tip out of vertical at zero bias indicating the presence of a nonzero c-axis resistance. The overall shape of the I-V curve at this temperature, however, stays unchanged and resembles the one at low temperature. At higher temperatures dissipation increases, and the nonlinearity of the I-V curves at zero bias gets smoothed. As the temperature for $T \geq T^*$ increases towards $T_c(0)$, the low-bias resistance of the stack asymptotically approaches R_{sg} (see Fig. 3), which may therefore be considered as an upper limit of resistance at a given magnetic field. The subgap conductance of a Josephson tunnel junction slightly increases with perpendicular magnetic field [20]. This may explain a small negative c-axis magnetoresistance, which is often observed at a constant temperature $T \geq T^*$ [9]; see also Fig. 2.

In a layered anisotropic superconductor, vortex lines consist of separate "pancakes," which interact with each other magnetically and via interlayer currents. In the case of high anisotropy, the interaction is relatively weak, and a random potential of pinning centers may cause a displacement of pancakes from their straight alignment. These displacements suppress the phase coherence between the layers even at $T = 0$ [21]. From the fact that both the in-plane and out-of-plane resistivities are characterized by the same value of thermal activation energy, it has been concluded that the dissipation in both directions has the same origin. In the case of strong disorder in the system it can be attributed to the diffusive motion of weakly pinned mobile pancakes [22]. Our experiments seem to be consistent with such a model. The large suppression of I_c in magnetic field may be due to the static-disorder-induced wandering of pancakes, while the temperature dependence of the I-V characteristics may qualitatively be attributed to the monotonic increase of the number of mobile pancakes with temperature.

Moreover, the fact that the I-V characteristics preserve their nonlinear shapes far beyond $T_c(H)$ implies the existence of Josephson coupling in the range $T_c(H) \leq T < T_c(0)$. This appears to be in agreement with recent microwave absorption resonance experiments [23]. The resonance has been attributed to Josephson plasma oscillations. It may serve as a probe of maximal interlayer Josephson coupling. The resonance was observed up to high temperatures close to $T_c(0)$ [23], which contradicts the theoretical suggestion that the Josephson coupling should be strongly suppressed by thermal fluctuations of pancakes above the decoupling temperature [24]. However, Koshelev showed theoretically that the Josephson energy should be finite at any temperature below $T_c(0)$ [25].

In summary, we have experimentally demonstrated that the c-axis magnetoresistance is highly correlated with the subgap resistance of intrinsic Josephson junctions in Bi2212. Given a single crystal, the effect of magnetic field may be predicted from the zero-field measurements of the c-axis I-V characteristics. The I-V characteristics at high field do not change their overall shape in a wide temperature range suggesting a smooth change of the vortex system even at a transition temperature $T_c(H) < T_c(0)$. The nonzero superconducting gap feature, which is seen below $T_c(0)$ at all magnetic fields $\leq$7 T suggests that $H_{c2}(T)$ is not reached in our experiments.

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