PHYSICAL REVIEW B VOLUME 51, NUMBER 6 1 FEBRUARY 1995-II

Fluctuation of vortices and the fluxon transition in $Bi_2Sr_2CaCu_2O_{8+y}$ single crystals

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(Received 15 July 1994; revised manuscript received 24 October 1994)

An anomalously broad foot structure is observed in the zero-field resistive transition for the *ab* plane of $Bi_2Sr_2CaCu_2O_{8+y}$ single crystals, which are found to have a high density of dislocations. However, this anomalous behavior is not apparent for resistive measurements along the *c* axis. The foot structure can be treated as a superposition of a long resistance tail and a dissipation peak, in which the long resistance tail obeys the theory of KT scaling behavior of resistivity. The dissipation peak is related to the fluxon transition in Josephson-coupled layered superconductors as detailed by Horovitz [Phys. Rev. Lett. **72**, 1569 (1994)].

I. INTRODUCTION

The recently discovered high-temperature superconductors (HTSC's) are strong type-II superconductors with an intrinsic multilayered structure.[1] Because of their extremely anisotropic structure and very weak coupling between the superconducting layers (CuO_2 planes), this multilayered system exhibits some features similar to a quasi-two-dimensional (2D) system, as observed in electronic transport,[2–4] thermal fluctuations,[5] vortex dynamics,[6,7] etc.

For a typical HTSC material, such as $Bi_2Sr_2CaCu_2O_x$ (BSCCO), a flux line parallel to the *c* axis is cut by superconducting layers into a series of vortex pancakes sitting in neighboring superconducting layers, and at high temperature (close to T_c) thermal fluctuations dissociate this series into independently moving pancakes.[8] The system exhibits a strong fluctuation of vortices like a two-dimensional (2D) system, and a Kosterlitz-Thouless (KT)-type transition.[9] Recently, Wan *et al.*[10] discovered that in Bi-2212 single crystals with decreasing temperature, the Josephson interaction couples the 2D CuO_2 bilayers at a temperature T_c^c, then, at a lower temperature designated as T_c^{ab}, the bilayers undergo a KT-type transition to a zero dissipation state. Between these two transition temperatures, a dissipation peak appears in the measurement of the zero-field resistive transition which was performed using a "flux transformer" electrode geometry. The observed peak is due to the competition between the interlayer Josephson coupling and the thermally excited vortices. However, this interpretation seems contradictory, as pointed out by Horovitz,[11] because at T_c^c the layers are not yet superconducting, and therefore, Josephson coupling cannot be manifested. In fact, a layered superconductor has two types of topological excitations:[12] (i) vortices, which are point singularities in each plane, and (ii) fluxons, which are lines parallel to the layers across which the relative phases of neighboring layers change by 2π. The observed transition at T_c^c may be due to the transition of the fluxons.[11] These fluxons result from the interplane Josephson interaction with an energy minimized if the centers of vortex phase on adjacent planes are aligned but raised by any vortex misalignment,[13–15] as may arise because of a transport current.

In this paper we report the results of the vortex and fluxon motion in Bi-2212 single crystals which have a high density of dislocations cutting the CuO_2 superconducting plane into segments. It is expected that the misalignment of the vortex pancakes in the present system is strong because the transport current cannot flow in the same plane and has to flow across and over the "step" along the *c* axis, leading to an irregular distribution of the current in the sample. It was found that the system exhibited an anomalously broad foot structure from 92.1 to 84 K in the zero-field resistive transition along the *ab* plane, $\rho_{ab}(T)$; however, this foot structure disappeared when the measurement was undertaken along the *c* axis, i.e., for $\rho_c(T)$ measurements. The more interesting feature of the foot structure is that it can be separated into two components: a long resistance tail and a dissipation peak. The significantly large difference between the temperatures of the mean-field transition and the vortex-related transition is consistent with the recent theory on the fluctuation of vortex lines in Josephson-coupled layered superconductors,[16] and a KT scaling behavior of resistivity is observed for the long resistance tail which suggests that some features of the motion of the vortex lines in Josephson-coupled layered superconductors is similar to that of 2D vortices. The additional dissipation peak can be explained by Horovitz's model[11] where the fluxon transition plays a significant role.

II. EXPERIMENTAL

Our transport measurements were performed on two different types of Bi-2212 single crystals prepared by a traveling solvent floating-zone method using different growth conditions.[17] Here the nominal composition of the as-grown specimens was $Bi_2Sr_{1.9}CaCu_2O_x$. One crystal-growth condition resulted in "defect single crystals" which were extracted from an as-grown rod prepared using a microgrowth fluctuation condition. The microgrowth fluctuation at the front of the growing crystals, which were caused by an uneven mechanical movement, resulted in a high density of dislocations or antiphase boundaries in the *ab* planes in the as-grown crystals.[18,19] High-resolution transmission electron microscope (HRTEM) images revealed that these dislocations cut the CuO_2 planes into segments along the *a* axis of the single crystals (see schematic of such a structure in the inset of Fig. 1). The detailed HRTEM results for these crystals will be reported elsewhere. A second crystal-growth condition resulted in "perfect single crystals" which were extracted from an as-grown rod prepared using a stable growth condition. In this case, no growth dislocations which cut the CuO_2 planes into segments along the *a* axis were found by HRTEM. The resistive measurements were made using an ac four-terminal technique. The current and voltage contacts are evaporated silver strips on the surface of the crystals, which have contact resistances less than 1 Ω.

III. RESULTS AND DISCUSSION

The resistive transition of a defect single-crystal sample with the dimensions of $5.1\times1.2\times0.1$ mm^3 (denoted as sample *A*) is shown in Fig. 1. The resistivity ρ_{ab} was measured with all contacts on the same surface. For the ρ_c measurement, one of the current contacts and one of the voltage contacts were placed on the top surface with the others on the bottom surface. As already pointed out, for the layered compounds,[2] the current distribution is inhomogeneous along the *c* axis in the sample. The resistivity shown here is merely a nominal one, denoted as ρ_{ab} for the *ab*-plane resistivity, and ρ_c for the *c*-axis resistivity. It should be noted that ρ_{ab} has a similar temperature-dependent behavior to that of ρ_c, i.e., a semiconductive behavior before the superconducting transition. For comparison, the equivalent results of a dislocation-free sample of Bi-2212 single crystal (denoted as sample *B*), selected from another rod is shown in Fig. 1(b). This result exhibits a typical metallic behavior along the *ab* plane above the superconducting transition, in contrast to those samples containing dislocations. Moreover, even though the value of ρ_{ab} for sample *A* is approximately 300 times less than that of ρ_c, it is still two orders of magnitude greater than that for the dislocation-free sample. Considering the particular structure of sample *A*, it is assumed that the ρ_{ab} measurement

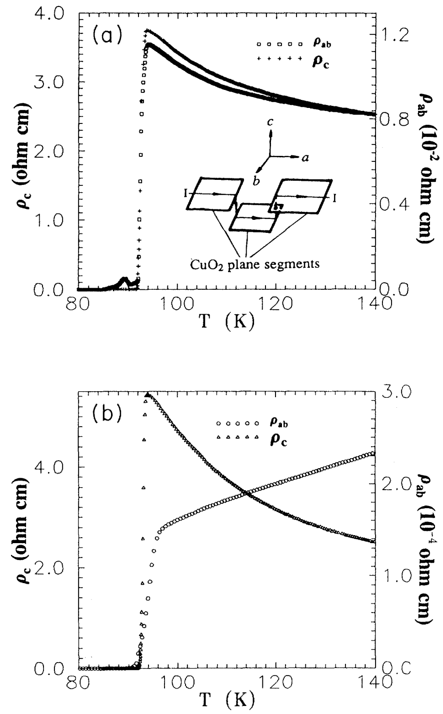

FIG. 1. (a) Resistive transition of a defect $Bi_2Sr_2CaCu_2O_{8+y}$ single crystal containing a high density of dislocations (sample *A*). Inset: a schematic of the structure of a defect single crystal and a current path. (b) Resistive transition of a dislocation-free $Bi_2Sr_2CaCu_2O_{8+y}$ single crystal (sample *B*).

is in essence a mixture of the resistivity along the *ab* plane and that along the *c* axis. This is because the CuO_2 planes are cut into a series of segments by the dislocations, and beside each of the dislocation lines, the CuO_2 planes shift along the *c* direction by about half a unit cell. Therefore, the transport current path must include both the in-plane and the out-of-plane components, as shown in the inset of Fig. 1.

For sample *A*, both ρ_c and ρ_{ab} exhibit a superconducting onset transition at about 93.5 K. However, the transition along the *c* axis is very sharp which shows a zero-resistance temperature at 91.4 K, whereas the transition along the *ab* plane exhibits a broad foot structure which extends to approximately 84.0 K, indicating that dissipation along the *c* axis and along the *ab* plane is quite different. This different dissipation behavior is similar to that observed in the *I-V* characteristic measurements[10] where the zero-resistance temperature along the *c* axis, T_c^c, is two degrees higher than that along the *ab* plane, T_c^{ab}; and between these two transition temperatures, a dissipation peak appears in the measurement of the zero-field resistive transition performed using a "flux transformer" electrode geometry. In the present system, there are two points worth noting: (i) the difference between the two transitions is 7.4 K, which is much larger than that observed by Wan *et al.*,[10] and (ii) besides a long resistance tail, a dissipation peak appears.

Figure 2 shows the *ab*-plane resistive transition of sam-

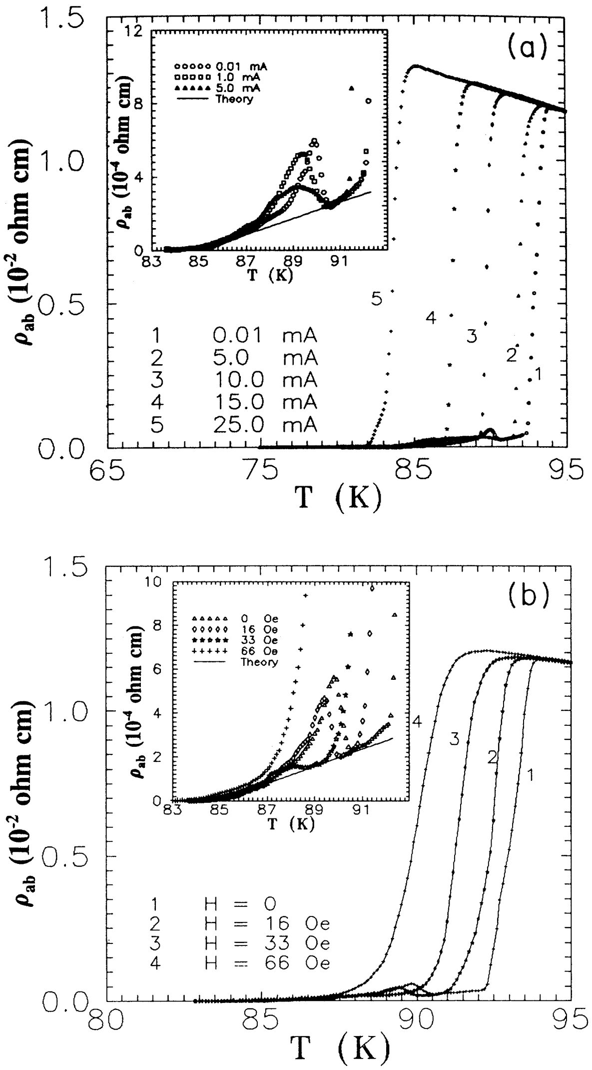

FIG. 2. Resistive transition of sample A along the *ab*-plane direction for (a) different test currents; and (b) different magnetic fields. Inset: Enlarged curves of the foot structure in the resistive transition.

ple A for a range of transport currents and magnetic fields. With increasing transport current or magnetic field, the superconducting transition shifts towards lower temperatures. As both the transport current and magnetic field are not too large, the main features of the long resistivity tails for the transitions in the different magnetic fields and transport currents are similar. However, the dissipation peak disappears gradually with increasing transport current or magnetic field.

It should be pointed out that the anomalous behavior reported above is common to those defect single-crystal samples containing dislocations. Figure 3 shows the results of another sample with the dimensions of $5.1\times1.1\times0.07$ mm^3 (denoted as sample C). The general features of the resistive transition are similar to those of sample A.

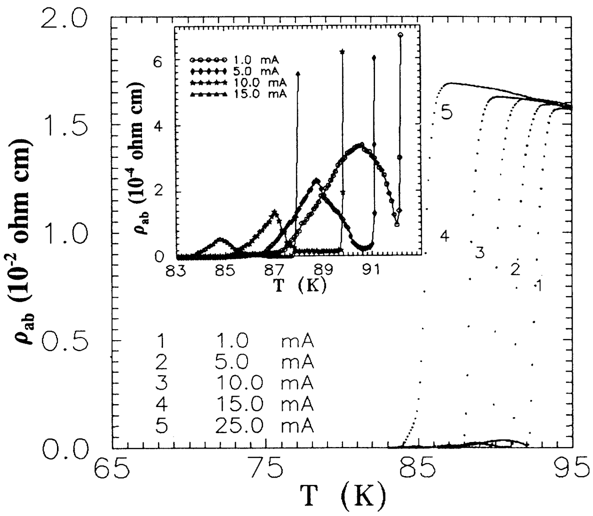

FIG. 3. Resistive transition of sample C along the *ab* plane for different transport currents. Inset: Enlarged curves of the foot structure in the resistive transition.

In our opinion, the origin of the long tail in the *ab*-plane resistive transition is very similar to that of vortex-pair excitations in the quasi-two-dimensional superconducting layers in Bi-2212. As is well known, the superconducting layers in Bi-2212 are spaced $d=15$ Å apart along the c axis[20] which is larger than the coherence length in the c direction, ξ_c, thus the interlayer coupling can be treated as a perturbation. In this case, the 2D fluctuation near the transition would be very strong, and the planes would show behavior analogous to the thermal fluctuations found in the thin films of conventional superconductors, where the dissipation is associated with the motion of thermally exited pairs of vortices with opposite circulation. Writing the vortex-pair interaction energy as $U(r)=(\phi_0^2 d/16\pi^2\lambda^2)\ln(r/\xi_{ab})$, where λ is the London penetration depth, ϕ_0 is the flux quantum, d is a layer thickness, ξ_{ab} is the *ab*-plane Ginzburg-Landau coherence length, and r is the distance between the vortex-pair, then a critical temperature T_K, which is associated with the KT transition, is given by

$$T_K=\phi_0^2 d/32\pi^2\lambda^2(T_K)\ . \tag{1}$$

At a temperature above T_K but below the mean-field transition temperature T_{c0}, thermally induced free vortices are present and dissipation resulting from thermally activated dissociation of vortex-antivortex pairs can be written as[21]

$$\rho/\rho_N=a\exp[-2(bt_{c0}/t)^{1/2}]\ , \tag{2}$$

where $t_{c0}=(T_{c0}/T_K-1)$, $t=(T/T_K-1)$, and a and b are nonuniversal constants.

In order to make a semiquantitative comparison of our experimental data with Eq. (2), we need to know the mean-field transition temperature T_{c0}. According to the Aslamosov-Larkin formula for the fluctuation conductivity in 2D,[22,23] $\rho^{-1}-\rho_N^{-1}=(e^2/16\hbar d)(T_{c0}-T)^{-1}$, and

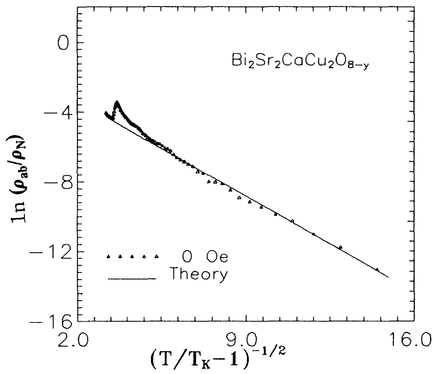

FIG. 4. Plot of $\ln(\rho_{ab}/\rho_N)$ vs $(T/T_K-1)^{-1/2}$ obtained from the resistive transition data for $H=0$.

by fitting the data above T_{c0} it is estimated that $T_{c0}=92.8$ K. In this fitting, the normal-state resistivity ρ_N is extrapolated from the data measured above 115 K.

Figure 4 shows the comparison of the experimental data with Eq. (2), in which $\ln(\rho_{ab}/\rho_N)$ is plotted as a function of the reduced temperature $t=(T/T_K-1)$ using the data obtained at zero field. Good agreement between the theoretical and experimental results is obtained except for the region where the dissipation peak appears. As a first step, we ignore this discrepancy and will discuss its origin in later paragraphs. The KT transition temperature is fitted as $T_K=83.7$ K or $t_{c0}=0.11$, while a and b are fitted as 0.17 and 1.41, respectively. The value of b obtained here is very close to the 1.34 as reported by Martin *et al.*[9] for the perfect Bi-2212 single-crystal sample, but the value of a obtained here is much smaller than the 3.78 reported by them. We explain this discrepancy as follows: the ρ_{ab} measured in the present sample is, in fact, a mixture of the resistivity along the ab plane and along the c axis. Above the mean-field critical temperature T_{c0}, resistivity along the c direction provides a significant contribution to ρ_{ab}, which leads to a larger value of ρ_N than that for a perfect single-crystal sample. However, at temperature below T_{c0}, ρ_{ab} mainly results from the motion of thermally activated vortex pairs along the CuO_2 planes, for both perfect and dislocation-contained Bi-2212 single crystals. Another point we should note is that the KT transition has been observed in Bi-2212 single crystals by Martin *et al.*,[9] but the normalized KT transition temperature $t_K=T_K/T_{c0}=0.90$ in the present dislocation-contained crystals is much lower than the 0.98 found for the dislocation-free single crystals. This may be explained by the existence of some "weak" superconducting regions in the CuO_2 layers caused by dislocations. In the weak superconducting regions, the dynamics of the vortices is quite different from that within the perfect superconducting regions,[24] current-induced unbinding of the vortex-antivortex pairs is prone to be excited when compared to the situation in perfect superconducting layers. As a result, the KT transition temperature in this system is lowered. Another possible reason is the modification of the interaction between the vortices in different superconducting layers. As is well known, the Bi-2212 compound is not a perfect 2D system, the interlayer interaction must be taken into account. As calculated by Horovitz,[25] and by Scheidl and Hackenbroich,[26] the vortices in a given layer interact with the "bath" of thermally activated vortex-antivortex pairs in other layers which modifies the KT transition by shifting the transition temperature from T_K to T_k', with $T_K'<T_k<T_{c0}$. If the transport current path crosses through the adjacent superconducting layers, as shown in the inset of Fig. 1 for the dislocation-contained crystals, the density of the vortex-antivortex pairs in the bath will be increased by the current-induced excitation, and consequently the tridimensional screening effect of the logarithmic interaction is enhanced. The KT transition temperature may therefore be decreased further. In dislocation-free Bi-2212 crystals, the current decays exponentially with distance along c axis, the current-induced pairs in the bath is negligible. Strictly speaking, the KT transition observed here is different from that in conventional 2D systems. In addition, our result is close to that obtained from the recent calculation of Bulaevskii, Ledvij, and Kogan.[16] As considered in their paper, the HTSC Bi-2212 is not a perfect 2D system, interlayer Josephson coupling does exist in this layered system and for the case of weak Josephson coupling,[27] the energy of a vortex-pair increases linearly with the distance between the vortex pair, while the entropy of a 2D vortex changes logarithmically. Under these circumstances, thermally induced spontaneous creation of free 2D vortices (in the low concentration limit) is virtually impossible. However, after taking into account the contribution of thermal distortions of the vortex line to the free energy, Bulaevskii, Ledvij, and Kogan[16] found that for the Bi- and Tl-based layered HTSC systems, a superconducting transition associated with the vortex lines exists. Above this transition, the thermally induced vortex and antivortex lines gives rise to dissipative properties similar to those of a 2D superconductor above T_K. At this temperature, the resistivity and lower critical field become zero. This transition temperature lies noticeably below the mean-field transition. Our system has a more dramatic vortex misalignment induced by the dislocations, therefore, the thermal distortion of the vortices would be stronger. Thus, T_K is much lower than T_{c0} in our system, which is consistent with the Bulaevskii model. Based on the results and analyses detailed above we believe that the origin of the long resistance tail observed in our experiments is the spontaneous creation of vortices or vortex lines in Josephson-coupled layered superconductors. Good agreement of the experimental data with the KT-type scaling behavior of resistivity suggests that some features of the motion of the vortex lines in Josephson-coupled layered superconductors are similar to those of 2D vortices.

Another possible explanation for the observed long resistance tail in the present experiment is thermally activated phase slippage[28] which was successfully used to explain the unusual broadening of the resistivity versus temperature curves in a magnetic field,[29] and the broad foot structure caused by the transition of the grain-

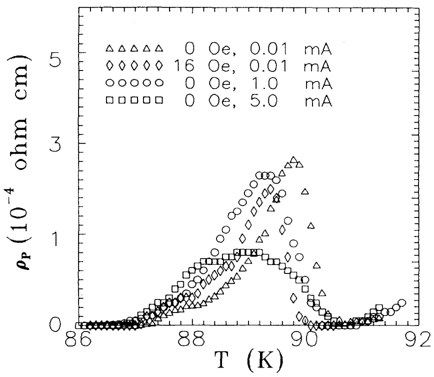

FIG. 5. Variation of the dissipation peak ρ_p, for different magnetic fields and transport currents.

boundary Josephson junction.[30] According to this model, the temperature dependence of the resistivity is of the form $\rho \sim \{I_0[C(1-T/T_c)^n]\}^{-2}$ where I_0 is the modified Bessel function, C is a constant, and $n=1$ or 2. However, our data do not fit this theory as it has a different temperature dependence for the resistivity.

As shown in the insets of Fig. 2, the foot of the ρ_{ab}-T curve can be regarded as a superposition of two parts: a long resistance tail which can be described by Eq. (2), and a dissipation peak. In the cases of low transport currents and low magnetic fields, the vortex motion will basically not be modified, and we can use Eq. (2) to separate the background of the long resistance tail from the dissipation peak. The net result of this is the peak ρ_p, shown in Fig. 5. It is evident that the peak is current and field dependent. With increasing transport current and/or magnetic field the peak becomes smaller, and shifts slowly towards lower temperature, but the width of the peak appears to be unchanged with a value of approximately 3 K. Generally, the features of the peak are similar to those observed by Wan *et al.*[10] in the measurement of the zero-field resistive transition which was performed using a "flux transformer" electrode geometry, but this phenomenon is observed in *ab*-plane resistive transition measurements. We believe the origin of the present dissipation peak is similar to that for the case of the flux transformer electrode geometry, and can be explained by the use of the fluxon transition concept proposed by Horovitz.[11] Following his model, the current along the c direction is expressed as[11]

$$I^c \sim J(L/\xi_{ab})\exp[(E_c/2\tau)(1-2T/\tau)/(T/\tau-1/8)] , \tag{3}$$

where J is the Josephson coupling between layers, L^2 is the area of the layer, E_c is the core energy, $\tau=\phi_0^2 d/4\pi^2\lambda^2$. As analyzed in Ref. 11, I^c has a sharp crossover at $T\approx\tau/2$, reflecting the fluxon transition which corresponds to the first transition step of ρ_{ab} [see also Fig. 1(a)]. Below this temperature, the resistivity obtained from measurements involving the flux transformer electrode geometry and our experimental methods involves the current I^c as well as the dissipation of vortices with density ξ_v^{-2} (where $\xi_v=\xi_{ab}\exp[E_c/(2T-\tau/4)$ is the mean distance between vortices), and can be expressed, in the present case, as

$$\rho_p \sim (1/\xi_{ab})\exp[(-E_c/2\tau)/(T/\tau-1/8)] . \tag{4}$$

Since $\xi_{ab}\sim(1-T/T_{c0})^{-1/2}$, ρ_p will vanish both at T_{c0} and at $T=\tau/8$, producing a maximum in between, as observed in the present experiment and those reported by Wan *et al.*[10] The suppression of the peak by a magnetic field is the result of a fluxon transition which is indeed suppressed by H as analyzed in Ref. 12. This analysis shows that the fluxon transition plays a significant role in the occurrence of the dissipation peak in the resistive transition measurements.

As analyzed above, the occurrence of the dissipation peak depends on the fluxon transition in which an in-plane current controlled by the current along the c direction, I^c, interacts with the vortices in the plane. In the measurement of $\rho_{ab}(T)$, the current and voltage leads are placed in the top surface layer of the crystal; if the CuO_2 planes are perfect, as in the case of dislocation-free crystals, the current flowing in the top layer is almost independent of I^c, and thus no dissipation peak will be observed. In the flux transformer electrode geometry measurements, the current flowing in the bottom layer is controlled by I^c, and therefore, a dissipation peak can be seen even in the crystals without dislocation, as reported in Ref. 10. In the measurement of $\rho_c(T)$, the transport current flows along the c axis of the crystals. In this case, the influence of fluxon and 2D vortices is not manifested. Hence the behavior is quite different from that of the ab-plane measurements.

In summary, an anomalously broad foot structure is observed in the zero-field resistive transition for the *ab* plane of Bi-2212 single crystals which have a high density of dislocations. It is found that the foot structure can be regarded as a superposition of two components: a long resistance tail and a dissipation peak. The former obeys the KT scaling behavior of resistivity, revealing that it originates from the excitation of the vortices in Josephson-coupled layered superconductors; the latter is related to the fluxon transition in this Josephson-coupled layered superconductor.

ACKNOWLEDGMENTS

We gratefully acknowledge the financial support of the Australian Research Council (Y. Zhao) and the University of New South Wales (G. D. Gu).

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