Power laws in the resistive state in high-T_c superconductors

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Temperature dependence of power laws in the mixed state of an oxide superconductor film, $ErBa_2Cu_3O_{7-x}$, is investigated under the influences of both a transport current and an external magnetic field. A critical jump of the exponent $n(T,H)=\log V/\log I$ is found at the universal value of $n=3$ in the presence of the magnetic field. The exponent $m(T,I)=\log V/\log H$ shows a sharp bend universally at $m=2$. Clear evidence of the Kosterlitz-Thouless transition is given in the exponents of two kinds of power laws. The coexistence of these power laws and the relationship of the exponents are an important key in the total understanding of the resistive state in an oxide superconductor.

It is well established that high-T_c oxide superconductors are classified as type II with a high value of Ginzburg-Landau parameter.[1] Dissipative properties such as flux-flow resistivity in the mixed state of oxide superconductors have recently attracted much attention from the standpoint of the vortex (or flux) transport phenomena. Undoubtedly the important features are the layered structures of CuO_2 planes and the large thermal fluctuation common to the whole class of new oxide superconductors. These features give rise to novel dissipative properties due to the Kosterlitz-Thouless (KT) transition[2–4] between binding ($T<T_{KT}$) and unbinding ($T>T_{KT}$) states of thermally excited vortex-antivortex pairs, where T_{KT} is the KT transition temperature.

There is some evidence of consistency with the KT picture. A power law of I-V characteristics in high-T_c oxide superconductors in the absence of an external magnetic field, $V \propto I^n$, has been reported by several authors and is interpreted in terms of the KT transition.[5,6] Recently, the power laws of the I-V characteristics and of the magnetoresistance in $ErBa_2Cu_3O_{7-x}$ at $T=77$ K were reported, and the magnetic-field-dependent exponent and the current-dependent one were shown.[7] They are represented by $V \propto I^{n(H)}$ and $V \propto H^{m(I)}$, respectively. The similar power law of the magnetoresistance as $V \propto H^{m(T)}$ for $Bi_2Sr_2CaCu_2O_x$ is also observed in the lower magnetic field region and is explained by the KT transition.[8]

In this paper, observations of the peculiar temperature dependence in the power laws of both I-V characteristics and magnetoresistance of a single crystalline thin film $ErBa_2Cu_3O_{7-x}$ are reported. The result is discussed in terms of the KT transition in the external magnetic field. We have discovered the universal jump in the power-law exponent, which is direct evidence of the KT transition, as pointed out by Halperin and Nelson[4] in two-dimensional superconductors. We also address the importance of a systematic treatment of both current-induced and field-induced vortex-antivortex depairings through presenting a newly found relationship between the exponents.

The observed power-law behaviors are totally different from the linear or exponential law derived from the standard flux-flow or flux-creep phenomena,[9,10] which may occur in a much higher magnetic field in our sample and are ascribed to the independent motion of individual flux lines penetrating through the sample. All our results in thin films of single crystals suggest that the thermally excited and depaired vortex (and antivortex) can flow freely on each CuO_2 plane until pair annihilation without suffering from the pinning. This is reasonable because the pinned vortex can be annihilated by the collision with the antivortex, and because the pinning effect itself is much smaller than the thermal fluctuation in a two-dimensional plane. The vortex-antivortex pair creation and annihilation processes, or the pairing and depairing processes, which will give power-law transport behavior, become dominant in conditions of large thermal fluctuation. Although the pinning effect of the external flux which penetrates all CuO_2 planes of the sample is still controversial, we are almost free from the effect as far as we treat the thermally excited vortex.

The measured sample is a 0.7-μm-thick film of $ErBa_2Cu_3O_{7-x}$ grown epitaxially on a MgO[100] surface with the rf magnetron sputtering. This film is the single crystal with the c axis perpendicular to the substrate and with the a,b axis including twin structures.[11] The sample is cut mechanically to form the Hall bridge along the a,b axis. Its channel width is 0.2 mm. The superconducting transition temperature in the absence of the external magnetic field is $T_c=87$ K, where T_c is defined as the midpoint temperature so that $R(T_c)=R_N/2$. The induced voltage drop V along the transport current, -300 mA $<I<300$ mA, is measured in the presence of an external magnetic field, -14 kOe $<H<14$ kOe, parallel to the c axis. The sample is mounted on a copper block, where the temperature is controlled between 65 and 100 K within an accuracy of 0.1 K. A sufficient amount of helium exchange gas (approximately one atmospheric pressure at 77 K) is introduced in order to avoid the self-heating effect and in order to get quick stabilization of the sample temperature throughout the experiment. The self-heating is safely negligible in our experimental range since the result observed in such a condition, with temperature controlled at 77 K, agrees exactly with the result for the sample immersed directly in liquid N_2 ($T=77$ K).

Power-law *I-V* curves are observed with temperature-dependent exponents taking values between 1 and 10, when the external magnetic field is absent. Even under a relatively strong magnetic field up to 14.0 kOe, the power-law *I-V* curves are observed with smaller exponents, but with higher induced voltages. An example of the power-law behavior of the *I-V* curves at $H=8.0$ kOe is shown in Fig. 1 for various temperatures. It is evident from the figure that induced voltage is represented by

$$V \propto I^{n(T,H)} . \quad (1)$$

It should be noted that the exponent $n(T,H)$ depends on both the temperature T and the applied magnetic field H.

The temperature dependence of the exponent $n(T,H)$ in various magnetic fields is shown in Fig. 2. In the absence of the external magnetic field [see curve (1) in Fig. 2], as observed in Refs. 5 and 6, the temperature dependence is smooth around $n=3$ and shows no sign of the critical jump expected at the KT transition temperature. This smearing out of the critical jump is due to the effect of the finite size of the two-dimensional system and to the effect of the critical fluctuation near the superconducting transition temperature. The KT transition temperature $T_{KT}(H=0)=84$ K is observed from $n(T,H=0)=3$. On the other hand, it is found that the exponent $n(T,H)$ shows a remarkable indication of the universal jump at $n[T_{KT}(H),H]=3$ in the presence of the external magnetic field [denoted by curves (2)–(7) in Fig. 2], where $T_{KT}(H)$ means the magnetic-field-dependent KT transition temperature. From Fig. 2, $T_{KT}(H)$ has a tendency to shift from 83 to 80 K as the magnetic field H becomes stronger from 2.0 to 13.5 kOe. It is surprising that the external magnetic field reveals the remarkable features of the universal jump, and that the exponent anomaly of $n=3$ remains unchanged even in a strong field. Thus, our data give visible evidence of the KT transition in a strong magnetic field.

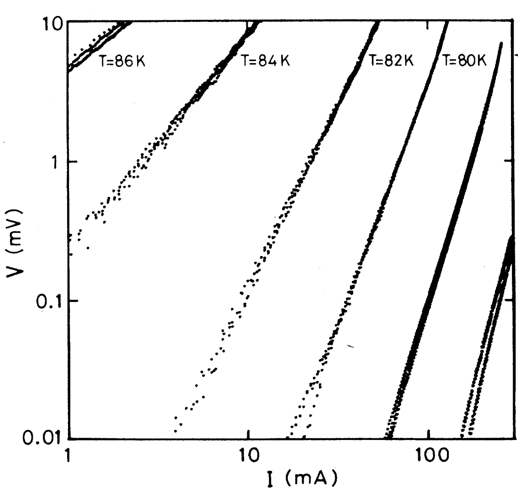

FIG. 1. Plots of log*I*-log*V* for the temperature range of 73–86 K in the presence of a magnetic field of 8.0 kOe.

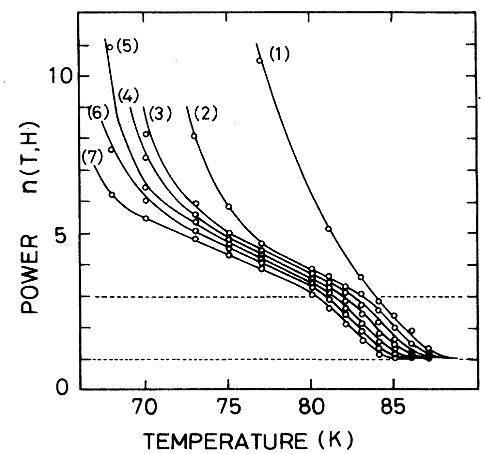

FIG. 2. Temperature dependence of the power $n(T,H)$: (1) $H=0.0$, (2) $H=2.0$, (3) $H=4.0$, (4) $H=6.0$, (5) $H=8.0$, (6) $H=10.0$, and (7) $H=13.5$ (unit: kOe).

The behavior of the exponent $n(T,H)$ above $T_{KT}(H)$ is independent of the magnetic field, except for the effect of the shifted transition temperatures. This is reasonable because the tail in the exponent $n(T,H)$ above $T_{KT}(H)$ is caused by the finite-size effect of the system. Below $T_{KT}(H)$, the exponent is depressed in the higher magnetic field since field-induced dissociation of thermally excited vortex-antivortex pairs will become relatively important.

In the same temperature region (64–87 K), the power-law *H-V* curves depending on the transport current are found. The *H-V* curve is represented by

$$V \propto H^{m(T,I)} . \quad (2)$$

Here, note again that the exponent $m(T,I)$ depends on both the temperature T and the transport current I. Power-law behavior in the magnetoresistance and its current dependence are reported at $T=77$ K in a previous paper (see Fig. 2 in Ref. 7). In all temperature regions, the log*V*-log*H* plots are quite straight up to 13.5 kOe. The behavior is reproducible in two samples having different dimensions, shapes, and twin sizes. This kind of magnetoresistance power law has been observed recently for $Bi_2Sr_2CaCu_2O_x$ by Martin *et al.*[8] and the relationship with the KT transition has been discussed. The magnetic fields of Martin *et al.*, however, are much smaller than in this experiment, and they did not observe the power law in the *I-V* characteristics. Figure 3 shows the temperature dependence of the exponent $m(T,I)$ for various values of the transport current I. Attention should be paid to the sharp bending of the m-T curve at $m(T,I)=2$. The bending is sharper at lower currents. This behavior could be closely related to the universal

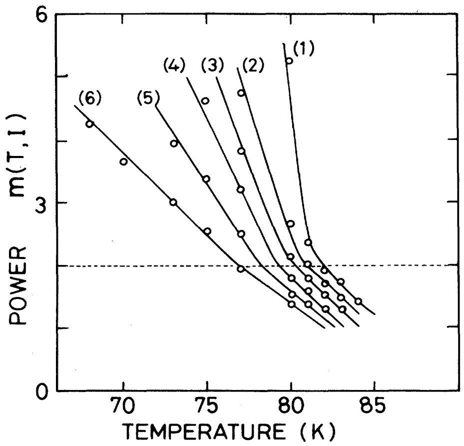

FIG. 3. Temperature dependence of the power $m(T,I)$: (1) $I=20$, (2) $I=40$, (3) $I=60$, (4) $I=80$, (5) $I=120$, and (6) $I=200$ (unit: mA).

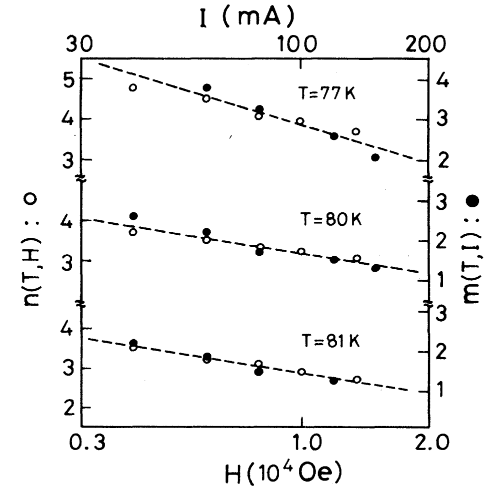

FIG. 4. Magnetic field dependence of the power $n(T,H)$ and current dependence of the power $m(T,I)$ at temperatures of $T=77$ K, $T=80$ K, and $T=81$ K.

jump occurring at the n-T curve and at the KT transition.

The two types of power laws and their anomalous temperature dependences suggest the importance of the systematic and self-consistent treatment of both transport current and external magnetic field. The dissociation mechanism of thermally excited vortex-antivortex pairs in the presence of the magnetic field can be made up of two parts; current-induced depairing and field-induced depairing. The current-induced depairing gives the power-law I-V curves, and its renormalization treatment gives the KT transition behavior in the exponent $n(T)$.[4–6] On the other hand, field-induced depairing leads to the power law in the magnetoresistance.[8] The two types of mechanisms, however, can never stand independently, as shown in this experiment. Although there is no theory for treating both mechanisms with consistency, an important relationship in systematic treatment is described empirically in the following.

The results of this experiment show that both of the power-law relationships given by Eqs. (1) and (2) are valid simultaneously. This allows a unique relationship, represented by

$$\log(V/V_0)=a\log(I/I_0)\log(H/H_0)\ , \tag{3}$$

where a, V_0, H_0 ($>H$), and I_0 ($>I$) are the normalization factors depending on the temperature in general. An identical form is suggested in Ref. 7 for the same kind of sample at $T=77$ K. It should be noted that Eq. (3) can be written in terms of the exponents $n(T,H)$ and $m(T,I)$ as follows:

$$\log(V/V_0)=n(T,H)m(T,I)/a\ . \tag{4}$$

Furthermore, $n(T,H)$ and $m(T,I)$ can be represented by

$$n(T,H)=a\log(H/H_0) \tag{5}$$

and

$$m(T,I)=a\log(I/I_0)\ , \tag{6}$$

respectively. In order to check Eqs. (3)–(6) with the experimental data, the $n(T,H)$-log$H$ and $m(T,I)$-log$I$ curves are plotted in Fig. 4. It is shown in this figure that $n(T,H)$ and $m(T,I)$ are linear functions of log$H$ and log$I$, respectively, and have the same gradient at a fixed temperature. This fact strongly supports Eqs. (5) and (6). Thus, Eqs. (3) and (4) are found to be valid. The newly found relationship is realized in a wide range of measurement temperatures.

In summary, we have found the coexistence of symmetric power laws $V\propto I^{n(T,H)}$ and $V\propto H^{m(T,I)}$ in an oxide superconductor film, $ErBa_2Cu_3O_{7-x}$, and have found the universal and somewhat peculiar relationship,

$$\log(V/V_0)=a\log(I/I_0)\log(H/H_0)$$
$$=n(T,H)m(T,I)/a\ .$$

A critical jump in the exponent $n(T,H)$ is clearly found at $n=3$ in the presence of an external magnetic field, and the KT transition temperature is given. The external magnetic field visually reveals the critical jump and gives clear evidence of the KT transition. A sharp bend in the exponent $m(T,I)$ is observed at $m=2$. These are considered the results of the synthetic effect of current-induced and magnetic-field-induced dissociation of thermally excited vortex-antivortex pairs.

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