Mechanism of the Lorentz-Force-Independent Dissipation in $Bi_2Sr_2CaCu_2O_y$

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A novel power law was found above 65 K in the I-V characteristics of $Bi_2Sr_2CaCu_2O_y$ single crystals with the magnetic field perpendicular to the c axis. At 80 K, the power-law exponent decreased sharply up to 1.5 T but remained nearly constant above it, suggesting an abrupt crossover to a different mechanism. An unusual field dependence of resistivity was also found, which cannot be explained by simple flux-flow theory. The above novel features of the Lorentz-force-independent dissipation can be consistently explained by a model based on two-dimensional vortex-antivortex pair breaking.

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It has been recognized that highly anisotropic high-T_c oxides show Lorentz-force-independent energy dissipation in the mixed state. This phenomenon has been reported for La-Sr-Cu-O [1], $Bi_2Sr_2CaCu_2O_y$ [2], $Y_2Ba_4Cu_8O_{16}$ [3], and Tl-Ba-Ca-Cu-O [4,5]. A clear experiment performed by Iye, Nakamura, and Tamegai [2] has shown that the resistivity in the a-b plane does not change when the applied magnetic field is rotated within the plane. This brought up serious questions as to whether flux creep or flux flow, which are driven by the Lorentz force, are truly the origin of dissipation. Although many theories to explain this Lorentz-force independence have been proposed [4,6–8], the mechanism of the dissipation has not yet become clear.

In this Letter, we report the first observation of clear power-law current-voltage (I-V) characteristics in the Lorentz-force-independent dissipative state in $Bi_2Sr_2CaCu_2O_y$. The existence of a power law and the behavior of the power-law exponent give us clues to solve the origin of the dissipation. Studies focused on the Kosterlitz-Thouless (KT) transition have revealed that high-T_c oxides show power-law I-V characteristics in the vicinity of the mean-field transition temperature in zero magnetic field [9] or for a field applied parallel to the c axis [10–12]. At lower temperatures, nonlinear I-V characteristics are also observed for the field parallel to the c axis [13,14]. These are interpreted in terms of the vortex-glass superconductivity [13] or other mechanisms [14–16]. However, clear power-law I-V characteristics have not yet been reported for the case of the field perpendicular to the c axis, although Iye, Nakamura, and Tamegai [2] reported a nonlinear relation between the current and the voltage.

Most of the theories [4,6,7] to explain the Lorentz-force-independent dissipation predict flux-flow- or flux-creep-type I-V characteristics, which means that the dissipation is Ohmic if the current density is sufficiently small. Therefore, our observation of power-law I-V characteristics in the Lorentz-force-independent dissipation imposes a significant restriction on the explanation of the dissipation mechanism. We also find an abrupt change in the magnetic-field dependence of the power-law exponent and the resistivity around 2 T. We interpret these observations by a novel model, which considers the vortex-antivortex pair breaking combined with the stiffness of the flux-line lattice formed parallel to the CuO_2 layers.

Single-crystalline $Bi_{2.2}Sr_{1.8}CaCu_2O_y$ samples used for this study were grown with the floating-zone method in an oxygen atmosphere. The growth speed was 0.5 mm/h. The crystals were cleaved into a typical thickness of 0.05 mm. The zero-resistance temperature was 86 K, and the resistivity was 2–4 $\mu\Omega$ m at 100 K. Four low-resistance contacts were made on the a-b plane with Au paste with a heat treatment of 20 h at 800 °C in air, which is also useful for improving the sample quality. After the heat treatment, fine Au wires were attached with Ag paste. The measurements were done using a standard dc four-probe method. The maximum current was 100 mA (which corresponds to the current density [17] j of about 120 $A\,cm^{-2}$) and the voltage resolution was well within 10^{-8} V. The temperature was measured with a carbon-glass resistor. The stability of the temperature during the I-V measurement was within 0.05 K, but the absolute values of the temperature in high fields may have errors of up to 0.5% due to the magnetoresistance of the thermometer. We used a sample holder whose sample stage can be rotated in an 8-T solenoidal magnet. The resolution of the rotation angle is better than 0.2°.

The I-V characteristics in 8 T at various temperatures are shown in Fig. 1. It is clear that the I-V characteristics can be well fitted by a power law above 65 K. Figure 2 shows the I-V characteristics in various fields for (a) 80 K and (b) 75 K. The power law holds for every magnetic field measured. The magnetic field was applied precisely perpendicular to the c axis; this direction was determined by rotating the sample in the magnetic field to obtain the minimum resistance. These data were taken for the sample which has the zero-field resistive transition shown in the inset of Fig. 1. This sample was 1.6 mm wide and 0.050 mm thick. The distance between the two voltage probes was 5.4 mm. We confirmed by remounting the

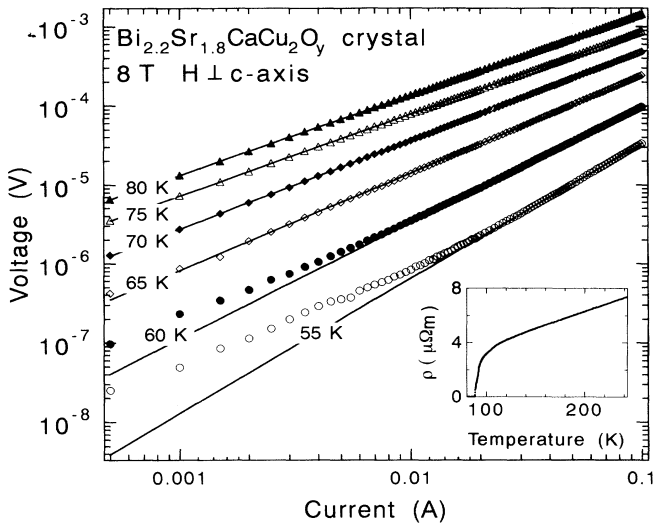

FIG. 1. I-V characteristics in 8 T for a wide range of temperatures: 55, 60, 65, 70, 75, and 80 K. The lines are power-law fits to the data. Inset: Zero-field resistivity up to 240 K.

sample in different orientations that the resistivity is essentially independent of the relative direction between the field and the current for the field perpendicular to the c axis; namely, energy dissipation is Lorentz-force independent. In the measurement of Figs. 1 and 2, the current direction was essentially parallel to the applied field.

The dependence of the power-law exponent α of the I-V characteristics on the magnetic field is shown in the insets of Fig. 2. Note that α decreases rapidly with increasing field up to about 2 T, at which point it becomes nearly constant. The precise value of the field where this anomaly occurs showed slight sample dependence; it varied from 1.5 to 2 T. It also depends slightly on the temperature; however, the sharpness of the change in the behavior of α diminishes with decreasing temperature. We have also found a change in the magnetic-field dependence of the resistivity around 2 T, possibly corresponding to the change in the behavior of α. This can be seen in Fig. 3 where the magnetic-field dependence of the voltage at a nominal current of 6.0 mA (which corresponds to $j=7.5\ \mathrm{A\,cm^{-2}}$) is plotted rather than the resistivity because of the nonlinearity of the I-V characteristics. This magnetic-field dependence of the voltage is totally different from what is expected from the Bardeen-Stephen behavior [18] of flux-flow resistivity, which is linear in magnetic field.

Our experimental results show that a model to explain the Lorentz-force-independent dissipation should also explain the following points: (1) the power-law I-V characteristics, (2) the L-shaped magnetic-field dependence of the power-law exponent, and (3) the S-shaped magnetic-field dependence of the resistivity. In view of the power law, most of the models [4,6,7] which predict flux-flow-

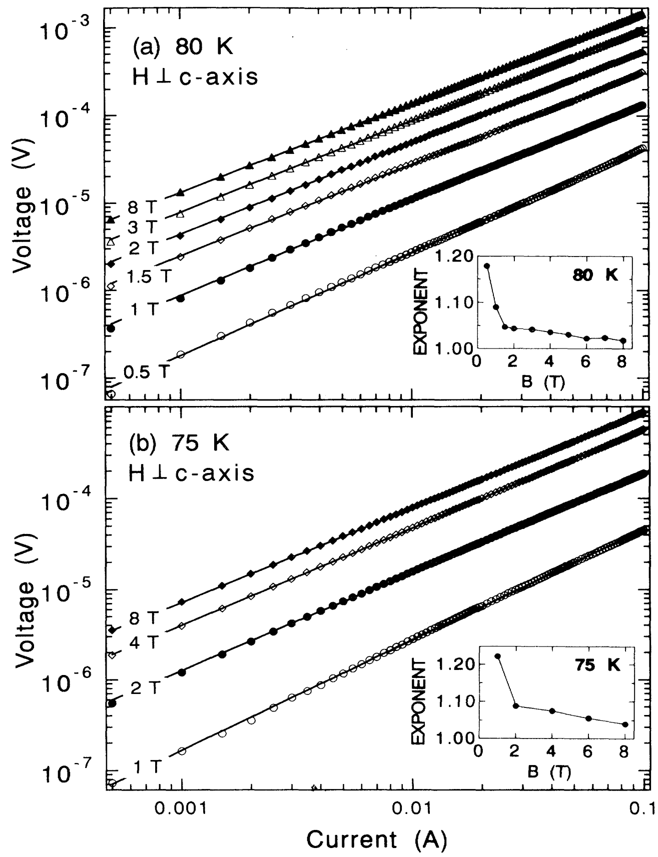

FIG. 2. (a) I-V characteristics at 80 K in selected magnetic fields, 0.5, 1, 1.5, 2, 3, and 8 T, oriented perpendicular to the c axis. The lines are power-law fits to the data. (b) I-V characteristics at 75 K in 1, 2, 4, and 8 T. Insets: Magnetic-field dependence of the power-law exponent.

or flux-creep-type I-V characteristics are not applicable. One exception is the theory proposed by Blatter, Ivlev, and Rhyner [8] which predicts a power-law I-V characteristic above 15 T, but a large critical current density of the order of $10^6\ \mathrm{A\,cm^{-2}}$ below this field. This contradicts our experimental results, which show no sign of such strong intrinsic pinning. Therefore, there is no theory we are aware of that can explain our results satisfactorily.

Here we propose a novel model to explain our experimental results. First, it takes into account the small but finite random misalignment of the c axis within the crystal [6]. Such misalignment can be estimated by the half width at half maximum of the rocking curve of the crystal for the (00 10) peak [4], and the misalignment of our crystal was estimated to be about 0.6°. Therefore, even though we have carefully aligned the magnetic field perpendicular to the c axis of the sample, because of the small variation of the c-axis direction within the sample, there will always be a component of the field parallel to the c axis. Second, the interlayer coupling in highly anisotropic superconductors such as $Bi_2Sr_2CaCu_2O_y$ is so

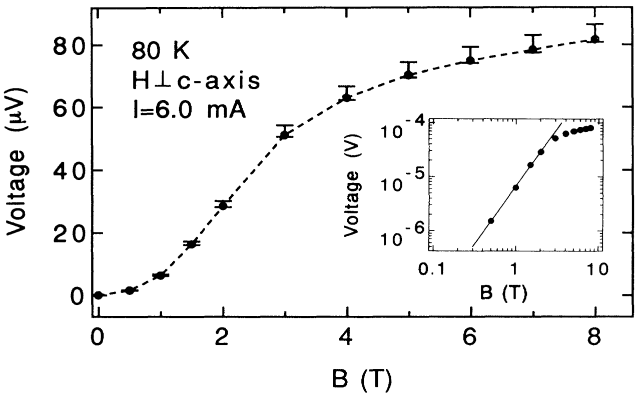

FIG. 3. Dependence of the voltage at the nominal current of 6.0 mA ($j=7.5\ \mathrm{A\,cm^{-2}}$) at 80 K on the magnetic field perpendicular to the c axis. Errors are mainly due to the magnetoresistance of the thermometer. Inset: Double-logarithmic plot of the voltage vs magnetic field. The line is a power-law fit to the data for fields below 2 T. The slope of this fit is 2.14.

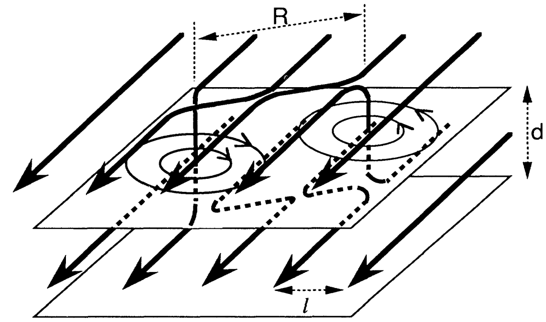

FIG. 4. A 2D vortex-antivortex pair in a CuO_2 plane. The pair creates a dislocation in the interlayer flux-line lattice.

weak that two-dimensional (2D) vortex-antivortex pairs are thermally activated *within* a CuO_2 plane [10,16]. Since the magnetic-field component parallel to the c axis, $H_\parallel$, enhances pair breaking [10], free 2D vortices are created due to the crystalline misalignment. Therefore, we assume that the origin of the apparent Lorentz-force-independent dissipation observed is the motion of such free vortices: The Lorentz force acting upon the 2D vortices in a CuO_2 plane is independent of the relative angle between the current and the magnetic-field component perpendicular to the c axis, $H_\perp$. Since this activation process is basically of a KT type, the I-V characteristic obeys a power law.

The behavior of the power-law exponent below 2 T can be expressed by the formula proposed empirically by Ban, Ichiguchi, and Onogi [12],

$$\log(V/V_0) = [a\log(H_0/H_\parallel)]\log(I/I_0)\,, \qquad (1)$$

where a (>0), V_0, H_0, and I_0 are normalization factors which depend on the temperature. From Eq. (1), it is easily seen that the power-law exponent of the I-V characteristics decreases with increasing field. This explains the magnetic-field dependence of the exponent (insets of Fig. 2) in lower magnetic fields. Furthermore, Eq. (1) implies that the voltage at a fixed current also shows a power-law dependence on the magnetic field. This explains the magnetic-field dependence of the voltage (Fig. 3) in low magnetic fields as can be seen in the data of Fig. 3 replotted on a double-logarithmic scale in the inset. It is clear that the voltage below 2 T can be fitted by a power law.

Let us consider the case for higher magnetic fields. According to Kes *et al.* [6], $Bi_2Sr_2CaCu_2O_y$ actually behaves as if the CuO_2 planes are decoupled; therefore, the field $H_\perp$ penetrates completely, and the interplane spaces are filled with Josephson-vortex chains. The distance d between the chains along the c-axis direction is equal to $c/2=1.5$ nm. When $B_\perp=2$ T, the lateral distance between each Josephson vortex in a chain is $\Phi_0/B_\perp d=0.67\ \mu$m. On the other hand, the diameter of a Josephson vortex along the CuO_2 plane is given by $\lambda_c=\lambda_{ab}\Gamma^{1/2}$ [19], where λ_c and λ_{ab} are the penetration depths along the c axis and the a-b plane, respectively, and Γ is the effective-mass anisotropy ratio [20]. Using $\Gamma=280$ (Ref. [20]) and a typical value $\lambda_{ab}=0.14\ \mu$m [19], λ_c becomes as large as 2.3 μm.

In the presence of dense interlayer flux lines, the 2D vortex-antivortex-pair creation in the CuO_2 planes is suppressed. This can be understood by considering the interaction between a vortex pair and the interlayer flux lines. The creation of a vortex-antivortex pair is equivalent to the creation of a dislocation in the interlayer flux-line lattice [8] (Fig. 4). This dislocation increases the elastic energy E_{el} of the flux-line lattice by $E_{el}(R)\cong e_0R/\sqrt{\Gamma}$, where R is the size of a pair, and $e_0=(\Phi_0/4\pi\lambda_{ab})^2$ [8]. However, if the distance between interlayer flux lines, l, is larger than R, the creation of a pair produces no significant dislocations in the lattice. Therefore, $E_{el}(R)$ should have a lower cutoff at l, and $E_{el}(R)\cong 0$ for $R<l$. From this discussion, it can be said that, with increasing field, the suppression of pair creation sets in when l becomes smaller than some critical value l_c. The theoretical estimate of l_c is difficult at this stage; however, our experimental results suggest that significant suppression of pair creation sets in when the spacing l in a chain becomes $\sim 0.7\ \mu$m, about $\frac{1}{3}$ of the interlayer flux-line diameter.

Following the above discussions, the magnetic-field dependence of both the power-law exponent and the resistivity above 2 T can be qualitatively understood as follows: The effect of the suppression of pair creation on the dissipation is compensated by the enhancement of pair breaking due to increasing $H_\parallel$, and the power-law exponent, which is a measure of the ease of free-vortex creation, becomes nearly constant. At the same time, the number of free vortices created by pair breaking tends to be constant. Note that there also exist free vortices created directly by $H_\parallel$ (not by its pair-breaking effect), and the number of such vortices increases linearly with increasing field. Therefore, the resistivity never becomes constant with increasing field, though the number of free vortices created by pair breaking tends to be constant.

In conclusion, we found that the I-V characteristics in a field applied perpendicular to the c axis obey a power law above 65 K. The field dependence of the power-law exponent and the resistivity were found to show a qualitative change around 2 T. To explain our observation, we have proposed a novel model which assumes a KT behavior with the pair-breaking effect of the field component parallel to the c axis due to small misalignments of the c axis within the crystal. The interaction of vortex-antivortex pairs with interlayer flux lines has been considered in order to explain the magnetic-field dependence of the power-law exponent and the resistivity.

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