Scaling Properties of the Anisotropic Magnetoresistivity of $Bi_2Sr_2CaCu_2O_8$ Thin Films below T_c

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We report on scaling properties of the angular dependence of the magnetoresistance of $Bi_2Sr_2CaCu_2O_8$ thin films below $T_c = 88$ K up to 20 T. As recently suggested by Kes *et al.* [Phys. Rev. Lett. **64**, 1063 (1990)], the dissipation is only related to the transverse field component along the *c* axis. Breakdown of the scaling appears between the angle when the field is parallel to the superconducting planes and a critical angle ($\sim 1°$), which reflects the finite anisotropy of the compound. We interpret the dissipation in the tilted magnetic-field orientation as resulting from the easy motion of vortex kinks along the CuO_2 planes.

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After the discovery of high-T_c superconductivity in $Bi_2Sr_2CaCu_2O_8$ (hereafter referred as Bi-2:2:1:2) it was very soon realized that one of the main differences between this compound and the previously known $YBa_2Cu_3O_7$ (1:2:3 compound) was the stronger anisotropy in the superconducting properties of the bismuth compound.[1-5] This anisotropy is expressed in terms of the effective masses for pair motion in the CuO_2 *a-b* planes and perpendicular to them along the *c* axis, as $\Gamma = m_c/m_{ab} = (\xi_{ab}/\xi_c)^2$, where ξ is the temperature-dependent coherence length. Estimations of Γ have been made from resistivity,[1] magnetoresistance,[2-4] and torque magnetometry measurements[5] with very large values (3000 at 77.5 K and 1 T in Ref. 5). These values have to be compared to a value $\Gamma \sim 30-40$ for $YBa_2Cu_3O_7$.[6] The anisotropy of the electronic properties can be viewed as a direct consequence of the anisotropy of the crystallographic structure. The distance d between the CuO_2 double layers which are at the origin of the superconductivity is indeed much larger for Bi-2:2:1:2 (15.5 Å) than for the 1:2:3 compounds (11.7 Å). According to the value of ξ_c with respect to d, the layered superconductors can be described either with the three-dimensional (3D) anisotropic effective-mass model or with the Lawrence-Doniach model of two-dimensional (2D) superconducting layers weakly coupled through Josephson junctions.[7] The crossover between the 3D and 2D descriptions occurs at $\xi_c(T) \sim d$. This crossover temperature has been estimated to be about 4% below T_c in 1:2:3 compounds but $\sim 0.03\%$ in Bi-2:2:1:2 (i.e., 0.5 K below T_c).

In such a situation of decoupled 2D superconducting planes Kes *et al.*[8] have very recently pointed out that the concept of the Abrikosov flux-line lattice (FLL) breaks down when the magnetic field H is applied parallel to the superconducting planes and they have proposed that the formation of the FLL is only related to the perpendicular field component. In this Letter we effectively show that magnetoresistance measurements of Bi-2:2:1:2 thin films up to 20 T as a function of the angle θ between the applied H and the CuO_2 layers ($\theta = \pi/2$ when H is parallel to c) can be perfectly scaled with the perpendicular component of H along c between $\theta_{crit} < \theta < \pi/2$. θ_{crit} is only 1° or 2° away from the parallel orientation and it corresponds to the finite anisotropy in the system. The dissipation mechanism in resistance measurements is still a subject of intensive investigation. It is often related to flux-creep and flux-flow resistance.[9-11] However, this interpretation is questionable especially with reference to recent reports which show a small contribution[11] (as in $YBa_2Cu_3O_7$) or the absence of anisotropy (as in Bi-2:2:1:2) in the dissipative regime[4,12-14] when the Lorentz force is operative or not. Our measurements are performed in the part of the (H,T) phase diagram where one expects the Abrikosov lattice to be melted and the vortex structure to be in a vortex-fluid state.[15] Therefore we interpret our measurements in the tilted magnetic-field orientation as resulting from the easy motion of vortex kinks along the CuO_2 planes.

Highly *c*-axis-oriented 1000-Å-thick Bi-2:2:1:2 thin films have been deposited onto single-crystal MgO substrates. Details of the preparation have been published previously.[16,17] In order to verify the $00l$ preferential orientation of the sample, the 0010 reflection was chosen and we have performed ω scans for two different orthogonal ϕ angles. We have also checked the rocking curve of the MgO 200 substrate reflection. The results are 0.5° HWHM and 0.015° HWHM for the film and the substrate, respectively. The measurements are performed on laser-patterned strip lines 10–100 μm wide and 500 μm long. The magnetoresistance is measured up to 20 T in a Bitter coil of the Service National des Champs Intenses at Grenoble. The sample holder can be rotated relative to H with an accuracy better than 0.5°. The experimental setup is identical to that of Ref. 3.

We have measured the magnetoresistance according to two types of scans: one at fixed θ as a function of H, and the other at fixed H for given values of θ. Figure 1(a) shows the magnetoresistance at $T=80$ K of a Bi-2:2:1:2 thin film for different orientations θ between H and the plane of the film. For this film, $R=0$ below $T=88$ K. The normal resistance at $T=80$ K can be extrapolated from the $R(T)$ above T_c and is equal to 910 Ω. The strong anisotropy of Bi-2:2:1:2 is even better shown in Fig. 2(a) when, at the same temperature, $R(\theta)$ is measured at fixed values of H. As already noted by Iye *et al.*[13] the cusplike behavior near the parallel orientation ($\theta \sim 0$) becomes more and more apparent when H is increased.

Following the suggestion of Kes *et al.*,[8] a spectacular scaling is achieved by plotting the resistance as a function of the transverse component (along c) of the applied field, i.e., $H \sin\theta$, as can be seen in Figs. 1(b) and 2(b). All the magnetoresistance curves can be reduced to a single one for $4° \lesssim \theta < 90°$, where the arrows in Fig. 1(b) indicate the maximum value of R reached at 20 T for the given angle and those in Fig. 2(b), the maximum value reached for the given field. The scaling parameter for the curves in Fig. 1(a) is $\gamma = 1/\sin\theta$. For $H_\perp$, $\gamma(\theta = \pi/2) = 1$, but when H approaches the parallel configuration γ undergoes an unphysical divergence ($\theta \sim 0$). In order to study the deviation from the $\sin\theta$ law, we plotted R vs $\log H$ and determined γ for each orientation from the translation that provides a superposition of the R vs $\log H$ curves. This plot emphasizes the behavior at reduced low fields. The results are shown in Fig. 3, which shows, at $T=80$ K, that the scaling is excellent except for the strictly parallel configuration. The scaling parameter $\gamma(\theta)$ is plotted in Fig. 4 as a function of $2\theta/\pi$ in a log-log plot. γ derived in this way resembles the angular dependence of the upper critical field as obtained

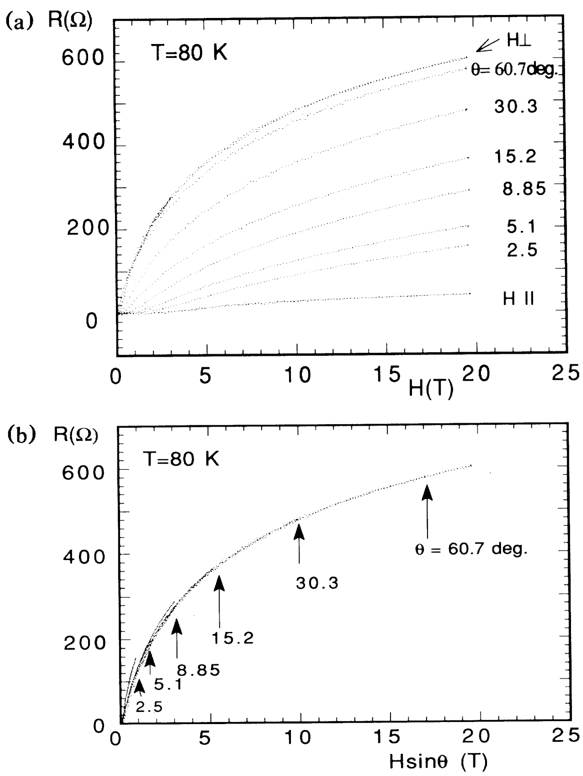

FIG. 1. (a) Resistance of a Bi-2:2:1:2 thin film at 80 K as a function of the magnetic field for different orientations: θ is the angle between H and the CuO_2 planes ($\theta=0$ when H is parallel to the CuO_2 planes). (b) Scaling of the resistance curves of (a) as a function of $H \sin\theta$. The arrows indicate the maximum resistance reached at 20 T for the given angles.

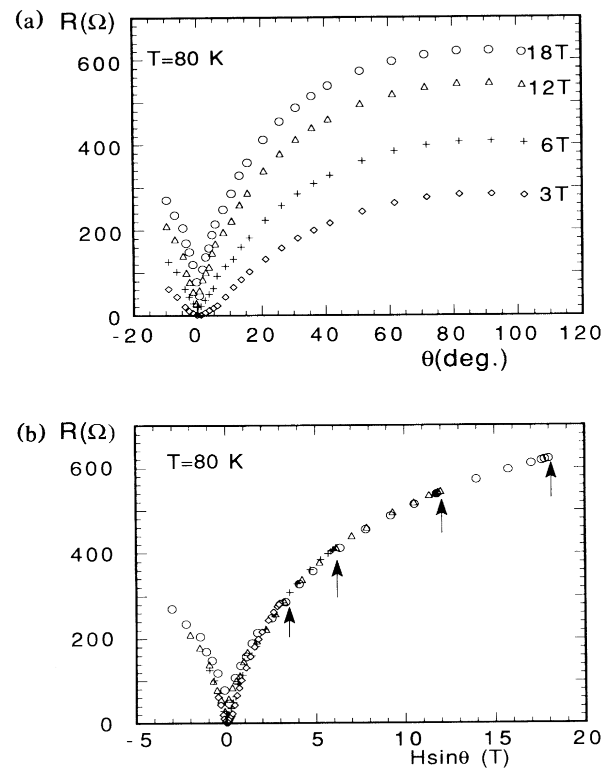

FIG. 2. (a) Resistance of a Bi-2:2:1:2 thin film at 80 K as a function of θ for different values of the magnetic field ($\theta=0$ when H is parallel to the CuO_2 planes). (b) Scaling of the resistance curves of (a) as a function of $H \sin\theta$. The arrows indicate the maximum resistance reached at $\theta=\pi/2$ for the given field.

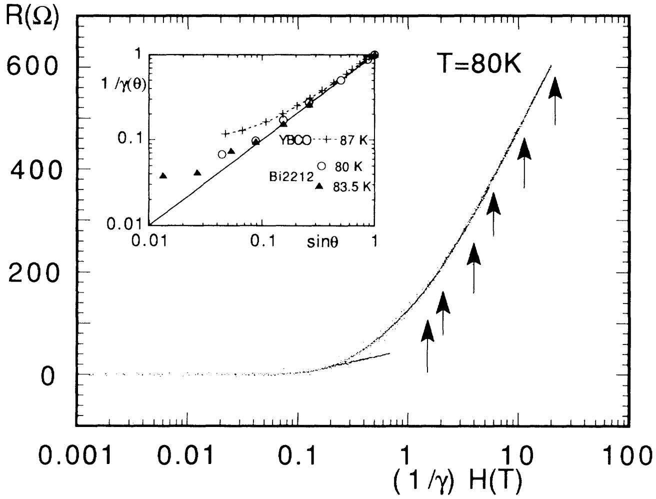

FIG. 3. Variation of the resistance of a Bi-2:2:1:2 thin film as a function of $H/\gamma(\theta)$ on a logarithmic scale at $T=80$ K. $\gamma(\theta)$ is the scaling parameter of the resistance curves of Fig. 1(a). Inset: $1/\gamma(\theta)$ against $\sin\theta$ for Bi-2:2:1:2 at $T=80$ and 83.5 K and for $YBa_2Cu_3O_7$ at 87 K (Ref. 18).

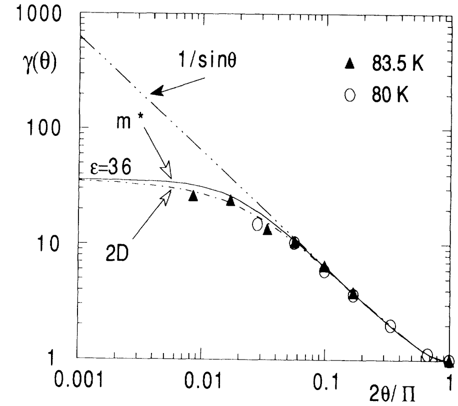

FIG. 4. Scaling parameter $\gamma(\theta)$ as a function of $(2/\pi)\theta$ for a Bi-2:2:1:2 thin film at $T=80$ and 83.5 K. Also drawn: $-\cdots-$, $1/\sin\theta$ variation; ——, the anisotropic effective-mass model [Eq. (1)]; -·-·-, the Tinkham model [Eq. (2)] with an anisotropy of 36.

previously on single crystals.[18] In Fig. 4 are drawn the $1/\sin\theta$ law, the angular dependence

$$\frac{H(\theta)}{H_\perp}=\frac{\varepsilon}{(\varepsilon^2\sin^2\theta+\cos^2\theta)^{1/2}} \tag{1}$$

expected for an anisotropic effective-mass model[7] with $\varepsilon=(m_{ab}/m_c)^{1/2}$, and the Tinkham expression[19]

$$\left\{\frac{H(\theta)\cos\theta}{H_\parallel}\right\}^2+\left|\frac{H(\theta)\sin\theta}{H_\perp}\right|=1 \tag{2}$$

expected for a two-dimensional superconducting layer. Experimentally we find that $H_\parallel/H_\perp=29$ and 36, respectively, at $T=80$ and 83.5 K. In a log-log plot as in Fig. 4 the differences between the two functional variations are not really striking. However, it should be noted that the Tinkham formula yields a cusp in $H(\theta)$ near θ parallel which has been experimentally observed.[2] It can be seen that for strongly anisotropic materials both formulas are reducible to a $1/\sin\theta$ variation for θ not too near the parallel configuration. For Bi-2:2:1:2, as seen in Fig. 4, the deviation from the $1/\sin\theta$ variation occurs at $(2/\pi)\theta\sim0.02$, i.e., θ around 1° or 2°, which corresponds to the angle below which the simple scaling proposed by Kes *et al.* is no longer followed, as seen in Fig. 3. For comparison we have plotted in the inset of Fig. 3, $1/\gamma(\theta)$ against $\sin\theta$ for Bi-2:2:1:2 at 80 and 83.5 K and also for $YBa_2Cu_3O_7$ at 87 K.[18] For these latter data $H_\parallel/H_\perp$ is only 9 and deviations from the $\sin\theta$ law occur at larger angles. Estimation of this critical angle can be made from (1): It corresponds to $\varepsilon\sin\theta_{crit}\sim1$. θ_{crit} is as small as the anisotropy is large. Taking $\varepsilon\simeq36$ for Bi-2:2:1:2, θ_{crit} is equal to 1.5°, in good agreement with the scaling properties. Thus there is a correspondence between the scaling in $R(H)$ for different θ values and the angular variation of the magnetic field anisotropy [Eqs. (1) and (2)] in $1/\sin\theta$. Between $0<\theta<\theta_{crit}$, the finite anisotropy of the system causes the scaling properties to break down.

Figure 3 also yields a very interesting result. At large H, $R(H)$ follows a logarithmic variation. Such a variation in $\log H$ is at variance with that expected from flux flow or flux creep. We have recently shown[20] that the functional dependence of the transverse magnetoresistance of Bi-2:2:1:2 thin films below the three-dimensional $T_c=88$ K is the same as that resulting from the effect of H on the superconducting (Maki-Thompson) fluctuations of a 2D film above its superconducting transition.[21,22] However, the relation between this result and the melted nature of the flux-line lattice remains to be more deeply analyzed.

In the parallel configuration ($\theta=0$) the cores of flux lines lie between the superconducting layers and suffer a strong pinning by the crystalline lattice itself which yields a high critical current.[23] The small finite dissipation for $\theta\sim0$ shown in Fig. 1(a) may be due to a slight misalignment of the sample. However, it is clearly shown in Fig. 3 that R vs $\log H$ for $\theta\sim0$ does not show the same variation as for larger angles and the scaling cannot be improved even by choosing an arbitrary θ value. Thus the dissipation near $\theta\sim0$ has another origin than that for larger angles. A lock-in transition of flux lines towards the layer planes has been recently proposed.[24] In the tilted orientation the gain in the condensation energy in the region of the core yields the configuration of a steplike vortex, i.e., a vortex with long intervals parallel to the layers strongly pinned by the lattice, separated by short kinks, rather than a rectilinear vortex.[24,25] We interpret dissipation in such a geometry as the easy motion of these kinks along the CuO_2 layers. These kinks are also those which form the 2D lattice in the perpendicular orientation. The normal cores are in the CuO_2 layers and are joined by a coreless vortex or Josephson vortex running between the layers.

In conclusion, we have shown that dissipation in Bi-2:2:1:2 thin films is only related to the transverse component along c of the applied magnetic field for a very large angular variation. These results confirm the recent suggestion of Kes *et al.*[8] We interpret this dissipation as the easy motion of 2D vortices along the CuO_2 planes.

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