Anisotropy and dimensionality of $Bi_2Sr_2CaCu_2O_{8+x}$ from transport measurements

E. Silva
Dipartimento di Fisica ''E. Amaldi'' and INFM, Università degli Studi di Roma Tre, Via della Vasca Navale 84, 00146 Roma, Italy

S. Sarti
Dipartimento di Fisica and INFM, Università degli Studi ''La Sapienza,'' Piazzale A. Moro 2, 00185 Roma, Italy and ENEA, Centro Ricerche Frascati, Via Enrico Fermi 27, 00044 Frascati (Roma), Italy

M. Giura and R. Fastampa
Dipartimento di Fisica and INFM, Università degli Studi ''La Sapienza,'' Piazzale A. Moro 2, 00185 Roma, Italy

R. Marcon
Dipartimento di Fisica ''E. Amaldi'' and INFM, Università degli Studi di Roma Tre, Via della Vasca Navale 84, 00146 Roma, Italy

(Received 22 November 1996)

We analyze measurements of the anisotropy in several $Bi_2Sr_2CaCu_2O_{8+x}$ films of different magnetotransport properties: critical-current density, microwave dissipation, and resistively determined irreversibility line. It is shown that all those measurements present the same angular scaling property, irrespective of the different measured quantities. The anisotropy depends on the temperature, accordingly to the quasi-two-dimensional (2D), decoupled-layer picture. In the same picture, a single parameter $\varepsilon(T)$ (anisotropy ratio) is sufficient to describe the evolution of the angular scaling functions. All the data for all the samples follow the same identical curve of ε versus the reduced temperature. Departures from the quasi-2D model are observed very close to T_c. [S0163-1829(97)02017-1]

The interest in anisotropic superconductors has gained intensive attention after the discovery of the copper-oxide superconductors. Due to their intrinsically layered structure, such compounds present strong anisotropic properties: in particular, quantities that depend on the applied magnetic field H show a strong dependence on the angle ϑ between the direction of the field and the superconducting (a,b) planes. Experimental studies[1] have shown that, in high-T_c superconductors, several of these quantities Q obey an angular scaling law, at fixed temperature T:

$$Q(H,\vartheta)\rightarrow Q[H/f(\vartheta)], \tag{1}$$

where the scaling function $f(\vartheta)$ may depend on the temperature. This scaling property has been predicted in general[2] for thermodynamical quantities, provided that $H\gg H_{c1}$, the lower critical field. In this case, Q should depend on H only through the reduced field $h=H/H_{c2}(\vartheta)$ so that, writing

$$H_{c2}(\vartheta)=H_{c2\perp}f(\vartheta), \tag{2}$$

where $H_{c2}(\vartheta)$ is the angle-dependent upper critical field, and $H_{c2\perp}=H_{c2}(90°)$, the experimental result (1) is easily explained. The obtained scaling function $f(\vartheta)$ should reproduce the angular dependence of the upper critical field H_{c2}. We have previously shown[3–5] that in $Bi_2Sr_2CaCu_2O_{8+x}$ (BSCCO) analogous scaling properties are verified also for transport measurements. This scaling is not trivial, since transport properties might be affected by pinning phenomena, which are not taken into account in the mentioned theory. Also, different dynamical regimes (low-high current, low-high frequency) could be *a priori* differently affected by the pinning, resulting in different angular scaling functions. In this work we analyze several experimental results concerning the anisotropic behavior of transport quantities in BSCCO epitaxial films, and we show that the obtained curves $f(\vartheta)$ depend on the temperature but not on the particular transport quantity under study. We also discuss a general interpretative frame that allows one to consistently describe the scaling functions obtained at different temperatures: in particular, from a few K below T_c down to low temperature the $f(\vartheta)$'s are found to be in agreement with the angular behavior of the upper critical field as predicted for the case of weakly interacting superconducting thick planes (quasi-2D model), while approaching T_c the data depart from this simple 2D picture.

The samples under study are four epitaxial BSCCO films, grown by liquid phase epitaxy[6] onto $LaGaO_3$ and $NdGaO_3$ substrates. Sample II was cut into three pieces for different measurements. Onto samples I and III the contacts were attached after the microwave measurements. In Table I we report the main features of the samples. Large sets of measurements of the surface resistance at microwave frequency R_s at 21 GHz, of the critical-current density J_c and of the resistivity ρ were performed on these samples as functions of

TABLE I. Sample parameters. T_c has been determined as the zero resistance (within the experimental resolution).

Sample	Substrate	T_c (K)	T_{2D} (K)	Measurements
I	$LaGaO_3$	79.1	76.7	R_s,H^*
II	$NdGaO_3$	82.4	82.2	R_s,J_c,H^*
III	$LaGaO_3$	83.1	80.5	R_s,H^*
IV	$NdGaO_3$	80.4	78.0	H^*

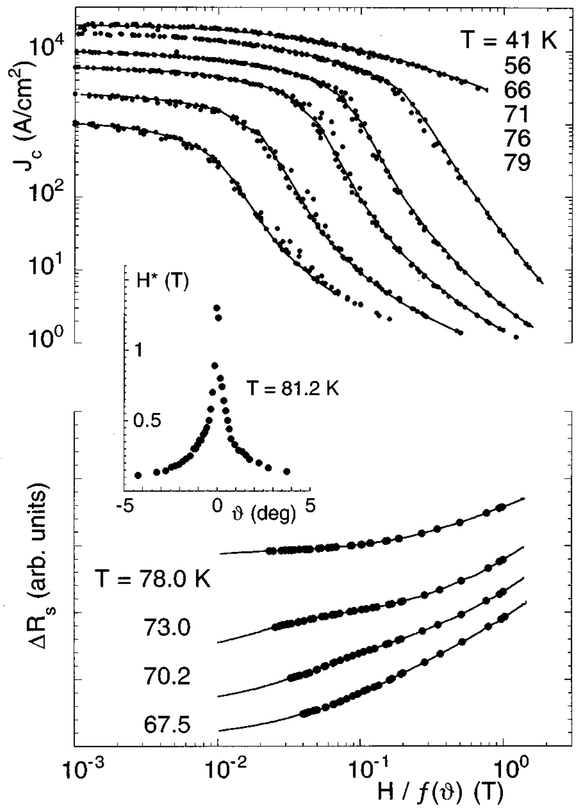

FIG. 1. Upper panel: scaled data of J_c vs the reduced field $H/f(\vartheta)$ at various temperatures. At each temperature, the solid line is the curve for $H_\perp$, the solid circles are the scaled data from $J_c(H,\vartheta)$ for ten different angles. Lower panel: similar data for the surface resistance R_s. Both kinds of measurements show successful scaling. Inset: angular behavior of the resistively determined irreversibility line, $H^*(\vartheta)$, showing the cusp at $\vartheta=0°$. All the data in this figure are taken on sample II.

T, H, ϑ. This allowed one to check different dynamical regimes [high-frequency (R_s), high current and low frequency (J_c), low current and low frequency (ρ)]. The details on the experimental setups and on the operative definitions of J_c and of the field H^* (onset field for the dissipation) were given in the references quoted.

As can be seen in Fig. 1, where we have reported some sample measurements, the scaling rule, Eq. (1), applies very well in BSCCO, for J_c and R_s. At each temperature, both J_c and R_s, measured at various H and ϑ, collapse onto a single curve when plotted against a properly rescaled field $H/f(\vartheta)$. Both quantities were measured from $\sim$40 K to a few K below T_c and always showed the scaling property. As $T\to T_c$, the field variations of both R_s and J_c go below the experimental sensitivity, and it is thus not possible to check this scaling rule close to T_c. However, in this region the field H^* for the onset of the resistivity (resistively determined irreversibility line) could be accurately measured (inset of Fig. 1). In this case, $f(\vartheta)$ is defined as the ratio $H^*(\vartheta)/H^*(90°)$.

In Fig. 2 we report the experimental scaling functions $f(\vartheta)$ as obtained from different techniques (R_s, J_c, and H^*) and on different samples (samples I and II, in the figure), at different temperatures. This figure exemplifies the first result of this paper: while the angular behavior at various temperatures is markedly different, it is insensitive to the measuring

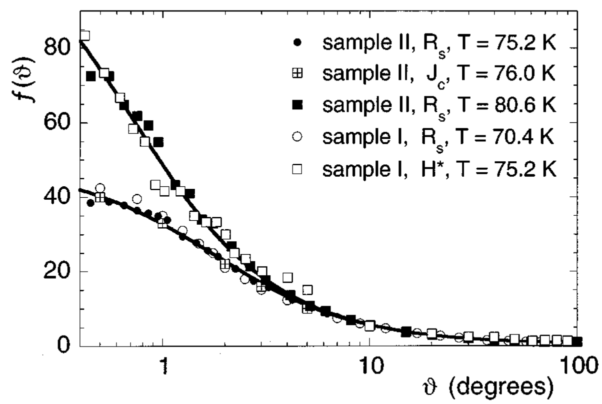

FIG. 2. Scaling functions $f(\vartheta)$ for different techniques, temperatures, and samples. Different techniques on the same sample yield (a) same $f(\vartheta)$ at the same temperature, (b) increased anisotropy with increasing temperature. Different samples present identical $f(\vartheta)$ with a renormalization of the temperature. Continuous lines: fits of the scaling functions through Eq. (3). The data are shown for $\vartheta>0.3°$, due to the anomaly at $\vartheta=0°$.

technique and, provided that a proper renormalization of the temperature is performed, to the sample under study. In fact, data from the same sample give identical $f(\vartheta)$ when taken with different techniques but at the same temperature (see J_c and R_s of sample II at $T\approx75.5$ K). In the same figure it is also seen that, at different temperatures, the anisotropy is different [see $f(\vartheta)$ on sample II at $T\approx75.5$ and 80.6 K]. Moreover, $f(\vartheta)$ from different samples (I and II in the figure) coincide if the temperature of sample I is normalized by a factor ≈1.07 (this reflects the different T_c's).

We will now show that the evolution of the obtained $f(\vartheta)$ can be described through a single temperature-dependent parameter. To quantitatively define the anisotropy, one often refers to the anisotropy ratio, ε, defined as $\varepsilon=H_{c2\parallel}/H_{c2\perp}$, where $H_{c2\parallel},H_{c2\perp}$ are the upper critical fields parallel and perpendicular to the layers, respectively. In terms of the scaling function [see Eq. (2)], $\varepsilon=f(0°)$. However, it is a well-known experimental fact[7] that the angular magnetic response of BSCCO close to $\vartheta=0°$ has a strong anomaly (at least from a few K below T_c down to low temperatures), so that the direct measurement of f at $\vartheta=0°$ can be misleading, and a model for $f(\vartheta)=H_{c2}(\vartheta)/H_{c2\perp}$ is needed to obtain the anisotropy ratio.

Since our experimental $f(\vartheta)$ varies with the temperature, the effective-mass model (or, equivalently, the Lawrence-Doniach model in the strong-coupling limit[8]) cannot be considered: in fact, in that model ε is temperature independent. The simplest theory where the apparent anisotropy depends on the temperature is the Tinkham quasi-2D model.[9] Considering the samples as constituted by superconducting slabs (the double CuO layers, of thickness $d\approx3$ Å), separated by a nonsuperconducting interlayer (of thickness $s\approx12$ Å), when the transverse coherence length $d<\xi_\perp<s/\sqrt{2}$,[10] the quasi-2D model predicts

$$f_{2\mathrm{D}}(\vartheta)=\frac{H_{c2}(\vartheta)}{H_{c2\perp}}=\frac{\sqrt{\sin^2\vartheta+4\varepsilon^{-2}\cos^2\vartheta}-|\sin\vartheta|}{2\varepsilon^{-2}\cos^2\vartheta}. \quad (3)$$

In this case $f(\vartheta)$ shows a cusp at $\vartheta=0°$, and ε is an effective anisotropy that turns out to increase with the temperature according to the expression

$$\varepsilon(T)=\frac{\varepsilon(0)}{\sqrt{1-T/T_{2D}}}. \tag{4}$$

Here, T_{2D} is the critical temperature of an isolated superconducting layer, in principle different from the critical temperature of the bulk (see Ref. 11 for a theoretical discussion of such a case). More complete models take into account not only the limiting cases, but also the intermediate situations, in which the magnetic field strength is effective in the determination of the angular dependence of $H_{c2}(\vartheta)$.[11,12]

The values of ε can be deduced from the fit of the experimentally determined $f(\vartheta)$ with Eq. (2). In Fig. 2 we show that the fits accurately reproduce the data. It must be mentioned that this procedure, valid from low temperatures to about 2 K below T_c, loses its validity at high temperatures, where the shape of the curve $H^*(\vartheta)$ changes from a cusplike to a rounded behavior through a continuous crossover. The presence and the properties of such a crossover were already studied, and interpreted as a signature of a dimensional crossover (2D→3D) as $T\to T_c$, due to the divergence of $\xi_\perp$ at T_c.[3] In this regime the only possible definition of ε is the ratio $H_\parallel^*/H_\perp^*$.

To compare the data from all our samples, it is necessary to plot ε as a function of some reduced temperature t. A consistent choice of this reduced temperature is $t=T/T_{2D}$. The temperature T_{2D} is determined by plotting ε^{-2} vs T, since according to Eq. (4) one has $\varepsilon^{-2}(T_{2D})=0$. As shown in the upper panel of Fig. 3 for sample II, this linear behavior is verified and T_{2D} (sample II)=82.25 K. The values of T_{2D} for the other samples are given in Table I. As can be seen in Fig. 3, all the anisotropy ratios collapse onto one single curve, when plotted vs the reduced temperature T/T_{c2D}.

In conclusion, we have shown that a large set of different transport properties present a unified behavior of their anisotropic dependence on the magnetic field, following a general scaling rule. The overall temperature and angular dependences of the scaling functions can be interpreted in a natural way within a decoupled-layer model, with a crossover to a more three-dimensional behavior at T_c. It is a result that properties that should depend differently on the pinning obey the same angular scaling law. This common scaling behavior is still looking for a complete theoretical explanation. Moreover, the scaling function coincides with the one predicted for the upper critical field in the quasi-2D model.

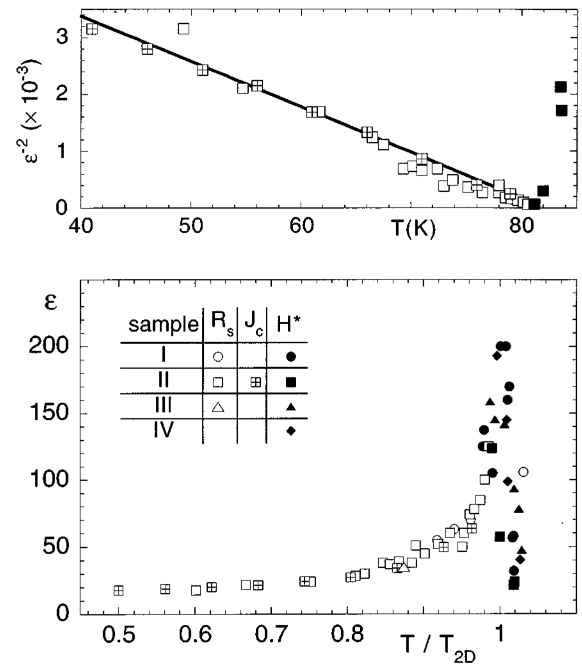

FIG. 3. Lower panel: universal behavior of the anisotropy $\varepsilon(T/T_{2D})$ as determined from the scaling procedure on all samples, through the different experimental techniques. Upper panel: determination of T_{2D} from the linear fit of the data for $\varepsilon^{-2}(T)$ through Eq. (4) (data for sample II).

This work was partially supported by CNR, under ‘‘Progetto finalizzato Tecnologie Superconduttive e Criogeniche.’’

[1] Y. Iye *et al.*, Physica C **159**, 433 (1989); H. Raffy *et al.*, Phys. Rev. Lett. **66**, 2515 (1991); E. Silva *et al.*, Phys. Rev. B **45**, 12 566 (1992); S. Labdi *et al.*, Physica C **197**, 274 (1992); M. Golosovski *et al.*, Phys. Rev. B **45**, 7495 (1992); **47**, 9010 (1993); G. Jakob *et al.*, *ibid.* **47**, 12 099 (1993).

[2] Z. Hao and J. R. Clem, Phys. Rev. B **46**, 5853 (1992); G. Blatter *et al.*, Phys. Rev. Lett. **68**, 875 (1992).

[3] R. Fastampa *et al.*, Phys. Rev. Lett. **67**, 1795 (1991); R. Marcon *et al.*, Phys. Rev. B **46**, 3612 (1992); E. Silva *et al.*, Physica C **214**, 175 (1993); S. Sarti *et al.*, Phys. Rev. B **49**, 556 (1994).

[4] R. Marcon *et al.*, Phys. Rev. B **50**, 13 684 (1994); E. Silva *et al.*, Physica C **243**, 303 (1995).

[5] R. Fastampa *et al.*, Phys. Rev. B **49**, 15 959 (1994).

[6] G. Balestrino *et al.*, Appl. Phys. Lett. **57**, 2359 (1990).

[7] Y. Iye *et al.*, Physica C **174**, 227 (1991); R. Fastampa *et al.*, Europhys. Lett. **18**, 75 (1992); M. Chaparala *et al.*, Phys. Rev. B **53**, 5818 (1996).

[8] W. E. Lawrence and S. Doniach, in *Proceedings of the 12th International Conference on Low Temperature Physics*, Kyoto, Japan, 1970, edited by E. Kanda (Kiegaku, Tokyo, 1971), p. 361.

[9] M. Tinkham, Phys. Rev. **129**, 2413 (1963).

[10] L. N. Bulaevskii, Int. J. Mod. Phys. B **11-12**, 1849 (1990).

[11] T. Schneider and A. Schmidt, Phys. Rev. B **47**, 5915 (1993).

[12] R. Klemm, A. Luther, and M. R. Beasley, Phys. Rev. B **12**, 877 (1975).