2D to 3D Crossover in Bi-Sr-Ca-Cu-O: Comparison with Synthetic Multilayered Superconductors

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(Received 2 April 1991)

We show that in a highly c-oriented 2:2:1:2 Bi-Sr-Ca-Cu-O film the angular-dependent magnetic field H^* at the onset of the resistivity behaves experimentally in a way completely analogous to the critical field found in synthetic multilayered superconductors. In particular, on varying the temperature, the field H^* exhibits a crossover from a 2D to an anisotropic 3D behavior as a function of the angle ϑ between the external magnetic field and the a-b plane.

PACS numbers: 74.60.Ec, 74.70.Vy, 75.30.Gw

High-T_c superconductors exhibit a large anisotropy in their dissipative properties when the direction of the external magnetic field **H** is changed with respect to the crystallographic c axis of the sample. In Bi-Sr-Ca-Cu-O, Batlogg *et al.* [1] have obtained, by means of the extrapolation of the linear portion of the resistivity $\rho(T)$ to $\rho=0$, the Ginzburg-Landau (GL) coherence lengths $\xi_\parallel=\xi_{ab}=31$ Å and $\xi_\perp=\xi_c=4$ Å, parallel and perpendicular to the Cu-O layers, respectively. More recently, Kadowaki *et al.* [2] have found $\xi_\parallel \cong 20$–23 Å. The discrepancy between the data available in the literature depends on the measurement techniques, as pointed out by Malozemoff *et al.* [3]. Precise angular-dependent transport measurements [4] for different values of the magnetic field in films of both Y-Ba-Cu-O and Bi-Sr-Ca-Cu-O have shown anisotropy, but while in Y-Ba-Cu-O samples a qualitative consistence with the Lorentz-force-driven flux motion has been observed, analogous measurements carried out in Bi-Sr-Ca-Cu-O have shown the dissipation to be independent of the relative angle between the current **J** and the magnetic field **H**. The origin of the anomalous Lorentz-force independence for Bi-Sr-Ca-Cu-O has been discussed in a model for the flux dynamics in highly anisotropic layered superconductors [4,5]. Measurements of resistive properties [4,6–8], magnetic torque [9], and magnetization [10] carried out by several authors suggest a layered structure for the high-T_c superconductors.

In this paper we show that in highly oriented 2:2:1:2 Bi-Sr-Ca-Cu-O films the angular-dependent magnetic field H^* at the onset of the resistivity ρ behaves as the upper critical field H_{c2} in synthetic multilayered superconductors. The field H^* exhibits a dimensional crossover from a 2D to an anisotropic 3D behavior.

Many experimental studies have been carried out on artificially prepared layered systems, in particular, Nb/Ge [11], Nb/Cu [12,13], and V/Ag [14] systems; they show a high degree of anisotropy in the fields $H_{c2\parallel}$ and $H_{c2\perp}$ and, as a consequence, in the GL coherence lengths $\xi_\parallel$ and $\xi_\perp$.

The experimental facts on artificially layered systems are well described in the framework of the extended GL theory. Depending on the value of d, the layer thickness, and s, the interlayer spacing, two regimes have been found for the angular dependence of the critical field H_{c2}.

(i) 2D behavior when $d<\xi_\perp<s$.—In this case the Tinkham model is valid and $H_{c2}(\vartheta)$ is given by solving the equation [15]

$$\left|\frac{H_{c2}(\vartheta)\sin\vartheta}{H_{c2\perp}}\right| + \left[\frac{H_{c2}(\vartheta)\cos\vartheta}{H_{c2\parallel}}\right]^2 = 1\,, \tag{1}$$

with ϑ the angle between the external magnetic field and the layer plane. From Eq. (1) one obtains

$$\left|\frac{dH_{c2}}{d\vartheta}\right|_{\vartheta=0} = \frac{H_{c2\parallel}^2}{2H_{c2\perp}} \neq 0\,, \tag{2}$$

and the curve $H_{c2}(\vartheta)$ shows a cusp at $\vartheta=0$, as observed experimentally in layered Nb/Cu [13].

(ii) 3D anisotropic behavior when $\xi_\perp>s$.—In this case the superconducting layers are coupled via Josephson or proximity effects. For a Josephson coupling, Lawrence and Doniach have shown that $H_{c2}(\vartheta)$ is given by [16]

$$H_{c2}(\vartheta) = \frac{\phi_0}{2\pi\xi_\parallel^2(T)[\sin^2\vartheta + (m/M)\cos^2\vartheta]^{1/2}}\,, \tag{3}$$

where ϕ_0 is the flux quantum and m and M are the equivalent effective masses perpendicular and parallel to the c axis, respectively. From Eq. (3) one finds

$$\left|\frac{dH_{c2}}{d\vartheta}\right|_{\vartheta=0} = 0 \tag{4}$$

and the curve $H_{c2}(\vartheta)$ shows a round maximum at $\vartheta=0$.

According to the temperature dependence of the GL coherence length, a crossover between regimes (i) and (ii) should be found when varying the superconductor temperature. Precisely, lowering the temperature one should go from a Lawrence-Doniach to a Tinkham regime, as previously found in Nb/Cu systems [13].

Here we present the angular dependence of the critical magnetic field $H^*(\vartheta)$, defined as the onset of the reduced resistivity ρ/ρ_n vs H at a given temperature, for a sample of Bi-Sr-Ca-Cu-O. In our experimental setup ϑ is the angle between the direction of the external magnetic field and the a-b plane. The measurements of resistivity are made with the four-probe dc resistance method; they are completely reversible and independent of the direction of the current. The sample is a highly c-axis-oriented epi-

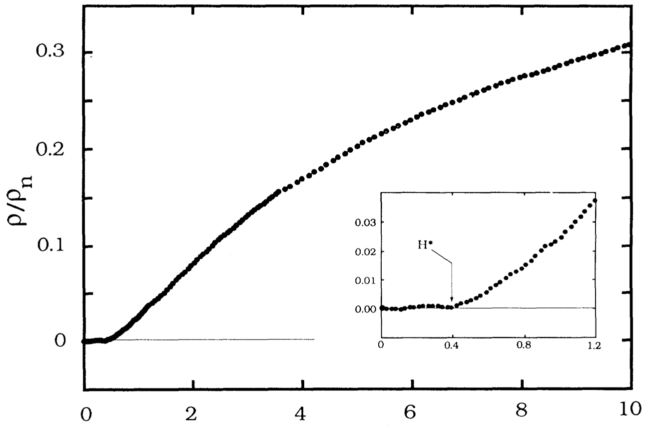

FIG. 1. Typical behavior of the reduced resistivity ρ/ρ_n vs the applied magnetic field H ($T=76.6$ K, $\vartheta=5°$). Inset: An enlargement of the curve at low fields showing the onset field H^*.

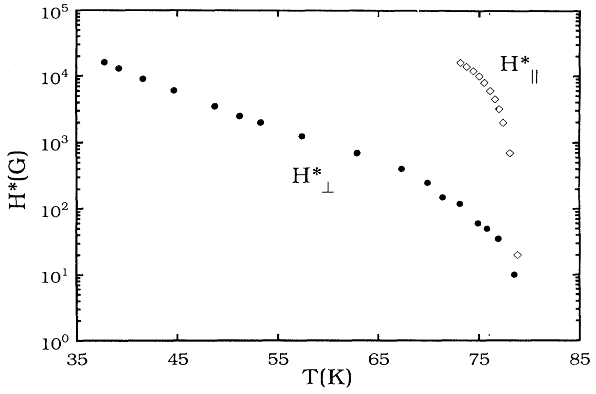

FIG. 2. Onset fields measured when the external magnetic field is respectively parallel ($H_\parallel^*$, open diamonds) and perpendicular ($H_\perp^*$, solid circles) to the *a-b* plane, as a function of the temperature.

taxial film of 2:2:1:2 Bi-Sr-Ca-Cu-O grown on a $LaGaO_3$ substrate with a mosaic spread less than 0.15° [17]. The film thickness is about 1 μm, and the zero-resistance temperature at $H=0$ is 79.1 K. The normal-state dc resistivity at the onset of the transition is $\rho_n=90$ $\mu\Omega$ cm. The sample holder was adjusted and fixed so that the *a-b* plane lies in a vertical plane. The magnetic field, supplied by a traditional electromagnet, can rotate in the horizontal plane. The rotation angle ϑ was measured to be accurate to 0.1°.

The field $H^*(\vartheta)$, which should not be confused with the upper critical field $H_{c2}(\vartheta)$, is the onset field of the motion of fluxons. Hence, as will be seen, the strong anisotropy in $H^*(\vartheta)$ corresponds to a large difference in the flux-flow viscosity, as recent theories seem to suggest [5]. Our measurements show that the curves $H^*(\vartheta)$ at various temperatures are analogous to the curves $H_{c2}(\vartheta)$ of the artificial layered superconductors. On the other hand, the anisotropic behavior of the viscosity must be somehow related to the structure anisotropy of the superconductor; therefore it is plausible that the angular dependence of $H^*(\vartheta)$ is like $H_{c2}(\vartheta)$. Anyway, measurements on artificial layered superconductors have shown that the choice of the critical field as the midpoint of the transition curve or as the onset of resistivity did not result in a significant quantitative change in the behavior of the critical-field angular dependence [13]. So, in the following, we interchange $H_{c2}(\vartheta)$ with $H^*(\vartheta)$ in the fit of the data.

In Fig. 1 the typical behavior of the normalized resistivity ρ/ρ_n as a function of the magnetic field H is shown. The field H^* for the onset of dissipation is clearly detectable in the limit of the accuracy of our measurements (5 nV with $I=10$ μA).

In Fig. 2 the field H^* as a function of the temperature T is reported with the external magnetic field respectively parallel ($H_\parallel^*$) and orthogonal ($H_\perp^*$) to the *a-b* plane. The behavior of $H_\parallel^*$ as a function of the temperature is quite different from that of $H_\perp^*$, as occurs in synthetic multilayers when the coherence length $\xi_\perp$ is lower than the interlayer spacing s. In order to investigate this analogy, the critical field H^* vs ϑ has been measured. A cusp for $\vartheta=0$ in the $H^*(\vartheta)$ curve seems to be present when the temperature is well below the transition, as shown in Fig. 3 for $T=76.6$ K. In the same figure the fits of the measurements are reported: for $\vartheta>0$, we have used the

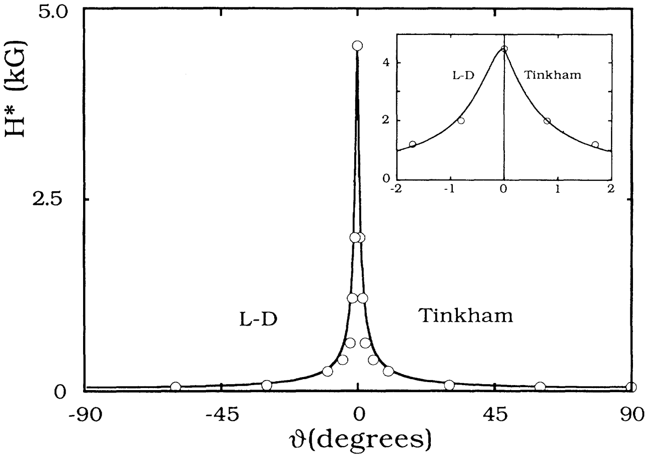

FIG. 3. Open circles refer to the angular dependence of $H^*(\vartheta)$ at $T=76.6$ K. The fits by means of Eq. (1) for $\vartheta>0$ and by means of Eq. (5) for $\vartheta<0$ (solid lines) are reported. ϑ is the angle between the *a-b* plane and the direction of the external magnetic field. The inset shows that it is necessary to perform many measurements in the range $-1.0° \leq \vartheta \leq 1.0°$ in order to discriminate between the 2D Tinkham and the anisotropic 3D Lawrence-Doniach (LD) model.

Tinkham theory expressed by Eq. (1), and for $\vartheta < 0$, the Lawrence-Doniach equation rewritten in the form [16]

$$\left[\frac{H_{c2}(\vartheta)\sin\vartheta}{H_{c2\perp}}\right]^2 + \left[\frac{H_{c2}(\vartheta)\cos\vartheta}{H_{c2\parallel}}\right]^2 = 1 . \tag{5}$$

For the fit of Fig. 3 we have used $H^*_\parallel$ and $H^*_\perp$ instead of $H_{c2\parallel}$ and $H_{c2\perp}$ in Eqs. (1) and (5), as previously explained. As one can see, because of the strong anisotropy, the fit to the angular-dependent data for angles not strictly close to $\vartheta = 0$, using the current models given by theory, does not allow one to discriminate between the 2D Tinkham formula and the anisotropic 3D Lawrence-Doniach model. However, at $\vartheta = 0$ the two models have a completely different behavior in the derivative $dH_{c2}/d\vartheta$: Equation (1) exhibits a cusp while Eq. (5) a round maximum. Hence, in order to distinguish the two regimes, accurate measurements must be carried out in a narrow range around $\vartheta = 0$.

In Fig. 4 the data of $H^*(\vartheta)$ for $T = 76$ and 78 K in the angular range $-1.0° \leq \vartheta \leq 1.0°$ are shown: At $T = 78$ K the cusp is replaced by a round maximum. In the same figure, with dashed and solid lines the theoretical curves are reported. It is clear that at $T = 76$ K the cusp shows that the behavior is Tinkham-like, while at $T = 78$ K the round maximum proves that the behavior is Lawrence-Doniach-like. Therefore at $T \cong 77$ K there is a crossover between a 2D ($T < 77$ K) and an anisotropic 3D behavior ($T > 77$ K). Analogous experimental results have been obtained in a 2:2:1:2 Bi-Sr-Ca-Cu-O epitaxial film grown on a $SrTiO_3$ substrate. The crossover temperature for this sample is between 79 and 80 K with $T = 80.2$ K for the zero-resistance temperature at $H = 0$.

Angular and temperature dependences of a "critical field" in 2:2:1:2 Bi-Sr-Ca-Cu-O single crystals have been measured by other authors [7,8]. However, a dimensional crossover was not found because in one case [7] the angular resolution ($\simeq 3°$) was not good enough and in the other [8], measurements at only one temperature were reported.

In summary, high-T_c superconductors exhibit an anisotropic behavior in their dissipative properties when the angle ϑ between the applied magnetic field H and the *a-b* plane is changed. Anisotropy is ascribable to the layered structure of these materials, in which the superconductivity seems to be confined to the Cu-O planes coupled to each other via Josephson or proximity effects. The determination of the angular dependence of the upper critical field $H_{c2}(\vartheta)$ at various temperatures allows us, in principle, to calculate the thickness d of the superconducting layers and the spacing s between them.

In traditional superconductors this has been experimentally proved by means of measurements on artificially prepared layered systems. Further, considering that the length scale is determined by the temperature-dependent Ginzburg-Landau coherence length $\xi(T)$, different behaviors of $H_{c2}(\vartheta)$ have been observed when $\xi(T)$ crosses the lengths d and s, upon varying the temperature.

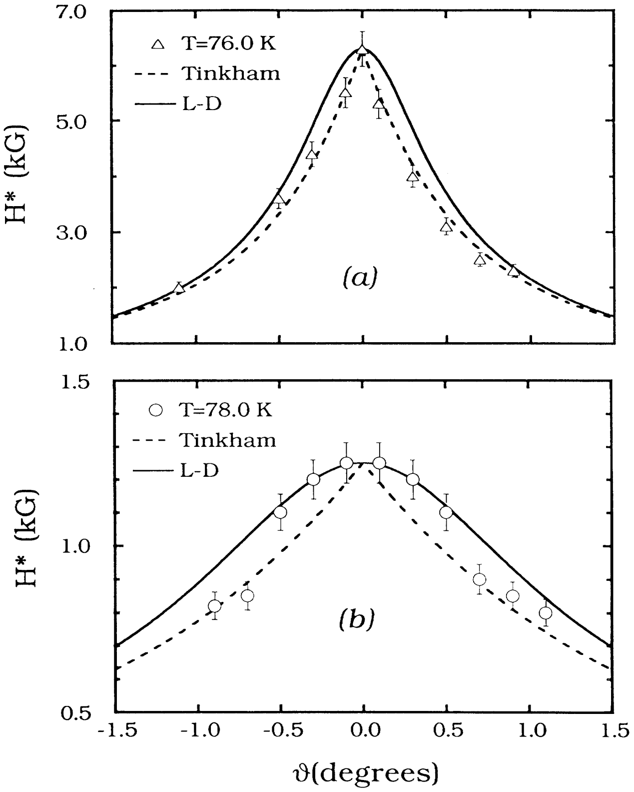

FIG. 4. The behavior of $H^*(\vartheta)$ at two different temperatures in a narrow angular range around $\vartheta = 0$ ($-1.0° \leq \vartheta \leq 1.0°$). A crossover between a 2D and an anisotropic 3D behavior going from (a) to (b) is present: A cusp is clearly detectable at $\vartheta = 0$ for $T = 76.0$ K, while $dH^*/d\vartheta = 0$ at $\vartheta = 0$ in the curve at $T = 78.0$ K. For each temperature the fit of the experimental results by means of the two theoretical models [Eqs. (1) and (5)] is reported for comparison.

All these measurements can be repeated in high-T_c materials, but because of the broadening of the superconducting transition with the magnetic field and the high value of dH_{c2}/dT, it is practically impossible to obtain precise numerical values for d and s, so that the data presently available in the literature only give an order of magnitude for them. Anyway, we have experimentally shown that the angular dependence of H^* is completely analogous to that of $H_{c2}(\vartheta)$ in artificial layered superconductors. Then the knowledge of H^* can give useful information in the same way as H_{c2}. The main result of this work, obtained by studying the behavior of H^*, is the existence of a crossover from a 2D to an anisotropic 3D behavior near the transition temperature in 2:2:1:2 Bi-Sr-Ca-Cu-O. The fact that H^* and H_{c2} have the same angular dependence is crucial and needs a theoretical explanation.

We would like to thank Dr. E. Milani for the sample preparation. Special thanks go to Dr. L. Maritato for comments and discussions on synthetic multilayered superconductors. This work has been partially supported by the National Research Council of Italy, CNR, under the Progetto Finalizzato "Superconductive and Cryogenic Technologies"; Gruppo Nazionale di Struttura della Materia of the Consiglio Nazionale delle Ricerche; and Consorzio Interuniversitario Nazionale di Fisica della Materia del Ministero dell'Università e della Ricerca Scientifica e Tecnologica.

Note added.—Just as the ϑ dependence exhibits a 2D-3D crossover, so does the T dependence of $H_{\parallel}^{*}$. Subsequent measurements show a sharp variation in the slope $dH_{\parallel}^{*}/dT$ at the angular crossover temperature.

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