3D-2D Dimensional Crossover in $YBa_2Cu_3O_7$ Films

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We show that, in fully oxidized $YBa_2Cu_3O_7$ c-axis oriented films, the changes induced in the angular and field dependence of the magnetoresistivity ρ_{ab} by increasing the temperature towards T_c are similar to those caused by a lowering in oxygen content. This remarkable behavior can be interpreted as due to a crossover from a three-dimensional to a two-dimensional system as T approaches T_c. Moreover, our critical current data mimic the behavior observed by Qi Li *et al.* in $YBa_2Cu_3O_7/(Pr_xY_{1-x})Ba_2Cu_3O_7$ multilayers, suggesting the possibility that chain planes are superconducting.

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High temperature superconductors are intrinsic multilayered systems, in which the anisotropy of the crystalline structure is clearly reflected in their superconducting and normal state transport properties. The degree of anisotropy is usually characterized within the framework of the Ginzburg-Landau theory by the parameter $\gamma=(m_c/m_{ab})^{1/2}$, where m_c and m_{ab} are the effective masses for pair motion along the c axis and in the a-b ($Cu2O_2$) planes, respectively. In artificially grown multilayered structures, the value of γ is easily changed by varying either the distance between two adjacent superconducting layers or the properties of the material separating them. In particular, Qi Li *et al.* [1] used $(Pr_xY_{1-x})Ba_2Cu_3O_7$ [(PrY)BCO] layers in order to tune the coupling between one-unit-cell-thick (1-UCT) $YBa_2Cu_3O_{7-z}$ (YBCO) layers. Depending on the concentration x of Pr, the (PrY)BCO layers are normal (N) or superconducting (S). For the superconducting (PrY)BCO the critical temperature T_c(Pr) can be lower than the value T_c for the YBCO layers by a proper choice of x. In this case the interlayer coupling is switched from S/S' to S/N by increasing the temperature. This results in significant changes of the field and angular dependence of the critical current density $J_c(H,\theta)$. A crossover from a three-dimensional (3D) system [S/S' coupling for $T<T_c$(Pr)] to a two-dimensional (2D) system [S/N coupling for $T>T_c$(Pr)] may explain the observations. This interpretation is consistent with the recent observation of a Kosterlitz-Thouless (KT) type transition [2] in (1 UCT) YBCO sandwiched by PrBCO layers [3]. Thus it seems that an isolated 1 UCT YBCO layer behaves like a 2D superconductor.

The problem of determining the dimensionality of bulk YBCO material is complicated by the existence of finite coupling between the 2D adjacent $Cu2O_2$ bilayers. The nature of this coupling, i.e., whether it is due to Josephson or proximity effects, has not yet been clarified. Some experimental evidence of a KT transition has been reported for fully oxidized YBCO thin films [4] and $ErBa_2Cu_3O_7$ films [5]. The sudden collapse near T_c of the lower critical field, $H_{C_1}(T)$, in fully oxidized YBCO single crystals was interpreted as due to a decoupling between superconducting layers induced by thermal fluctuations [6]. The anisotropy in YBCO single crystals, measured as a function of oxygen concentration [7], shows a trend towards more 2D-like behavior when oxygen is removed from the $Cu1O_z$ chain planes. Other experiments in YBCO bulk [8] and thin films [9] also support the increase of the anisotropy γ in YBCO due to a gradual decoupling between the $Cu2O_2$ planes with decreasing oxygen content.

In this Letter we report on the field, temperature, and angular dependence of the magnetoresistivity $\rho_{ab}(H,T,\theta)$ and critical current density $J_c(H,T,\theta)$ of fully oxidized YBCO films. The changes observed in $\rho_{ab}(H,\theta)$ when the temperature is increased are strikingly similar to those induced in $\rho_{ab}(H,\theta)$ when the oxygen content is lowered. The variations in $J_c(H,\theta)$ with increasing temperature mimic the behavior observed in YBCO/PrYBCO multilayers [1] when the separating PrYBCO layer is switched from the superconducting to the normal state. These remarkable analogies suggest that in fully oxidized YBCO films a 3D-2D crossover in the vortex structure develops as T increases towards T_c. We show that this crossover can be explained in a consistent way by modeling the YBCO material as a stacking of two superconducting subsystems.

The measurements were performed on high quality c-axis oriented YBCO films (film thickness $\simeq 100$ nm) deposited onto MgO (100) substrates using *in situ* 90° off-axis sputtering [10]. X-ray diffraction as well as Rutherford backscattering channeling measurements show that the YBCO films are grown epitaxially on the MgO (100) substrates, with a channeling minimum yield $\chi_{min}\leq 7\%$. The layers are purely c-axis oriented ($c_0=1.169$ nm), and have narrow rocking curves ($\Delta\omega_{(005)}\leq 0.3°$), in agreement with the low χ_{min} values. The as-prepared films have a critical temperature $T_c\simeq 89$ K and a normal to superconducting transition width of less than 2 K. We defined T_c as the temperature at which the resistivity values within the transition width extrapolate to zero, i.e., $T_c=T(\rho_{ab}=0)$. The results described below do not de-

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pend, however, on the criterion used to define T_c. The nominal oxygen content, $x_n = 7 - z$, in the films is adjusted to the desired value by a controlled heat treatment in a well defined oxygen partial pressure [11]. The magnetoresistance R_{ab} and critical current I_c measurements are performed on photolithographically patterned films (40 μm wide and 1 mm long) using a standard dc four probe technique. The critical current I_c is defined using the 10 μV/cm criterion. The R_{ab} measurements at a fixed temperature T are performed with a slightly lower measuring current compared to $I_c(H=0,\theta=0,T)$. In this way $R_{ab}(H,\theta,T) = V(H,\theta)/I_c(T) = 0$ for H and θ equal to zero. The same measuring current is used for all H and θ values. The rotatable sample holder is temperature stabilized to within 10 mK and is placed inside a superconducting magnet. The angle θ between the applied magnetic field H and the film plane (a-b or $Cu2O_2$ planes) can be varied with an accuracy and reproducibility better than 0.5°.

Figure 1 shows the magnetoresistivity ρ_{ab} as a function of the perpendicular field component $H\sin\theta$ measured near $T_c = 88.4$ K in a fully oxidized film for three different values of the angle θ. Here θ is the angle between the applied magnetic field H and the a-b plane of the film [see inset Fig. 1(a)]. A remarkable transition in the field dependence of ρ_{ab} is observed when T is increased: The paraboliclike behavior at $T=83.8$ K changes gradually towards a cusplike behavior at $T=87.8$ K [see inset Fig. 1(c)]. Moreover, it is evident that the scaling of ρ_{ab} is only possible near T_c. The maximum relative deviation of $\rho_{ab}(\theta)$,

$$\delta_\theta = [\rho_{ab}(\theta) - \rho_{ab}(90°)]/\rho_{ab}(90°),$$

is $\delta_{30°} \simeq 34\%$ and $\delta_{20°} \simeq 14\%$ at $T=83.8$ K, $\delta_{30°} \simeq 15\%$ and $\delta_{20°} \simeq 3\%$ at $T=86.5$ K and $\delta_{20°,30°} < 2\%$ at $T=87.8$ K. Both features are reminiscent of the behavior observed in $Bi_2Sr_2CaCu_2O_{8+y}$ single crystals [12], which has been explained in the framework of a 2D model [13]. According to this model, the magnetic field applied parallel to the a-b planes penetrates the structure uniformly, while a small misalignment produces 2D pancake vortices in the a-b planes. The motion of these pancake vortices dominates the dissipation, since no vortices are present between the a-b planes. This 2D model [13] is clearly consistent with the $\rho_{ab}(H\sin\theta)$ behavior near T_c [Fig. 1(c)], suggesting that the vortex system undergoes a 3D-2D transition as the temperature approaches T_c.

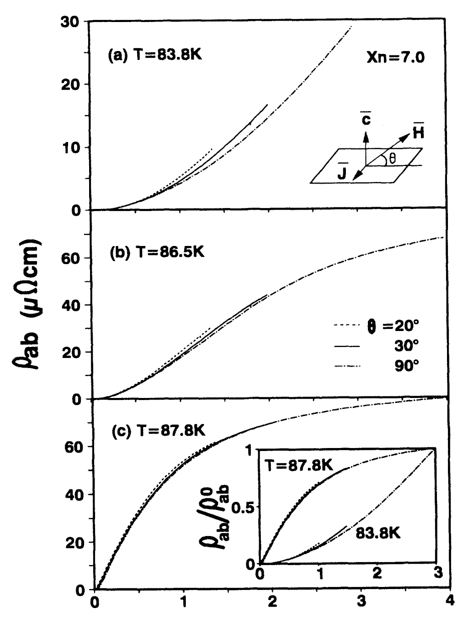

FIG. 1. Magnetoresistivity ρ_{ab} as a function of the perpendicular field component $H\sin\theta$ measured in a fully oxygenated YBCO film ($x_n = 7.0$) at different temperatures T. The inset in (a) shows the applied field and current orientation with respect to the c axis of the oriented film; the inset (c) shows the normalized resistivity [$\rho^0_{ab} = \rho(90°, 3\text{ T})$] versus $H\sin\theta$.

As already mentioned, there is experimental evidence that the anisotropy (i.e., γ) of YBCO is increased when oxygen is removed from the bridging $Cu1O_z$ chain planes [7-9]. It is therefore interesting to compare the evolution of ρ_{ab} in films with reduced oxygen content with the $\rho_{ab}(H,T)$ behavior seen in the fully oxygenated film.

Figure 2 shows ρ_{ab} as a function of $H\sin\theta$ measured at $T/T_c = 0.90$ in three YBCO films with different oxygen contents. Notice that the same remarkable transition is observed as in Fig. 1 when the oxygen content is reduced from $x_n = 7.0$ to $x_n = 6.6$, i.e., the development of a cusplike shape in $\rho_{ab}(H)$ [see also inset, Fig. 2(c)], and an improved scaling of $\rho_{ab}(H\sin\theta)$. ($\delta_{20°,30°} \simeq 20\%$ for $x_n = 7.0$ while $\delta_{30°} \simeq 8\%$ and $\delta_{20°} \simeq 42\%$ for $x_n = 6.8$ and $\delta_{20°,30°} < 2\%$ for $x_n = 6.6$.) It should be noted that these data were obtained in different samples, which may explain the less clear trend in the improvement of the ρ_{ab} scaling.

The striking similarity between the data presented in Figs. 1 and 2 [see also insets, Figs. 1(c) and 2(c)] indicates that a reduction in the oxygen content produces similar effects as an increase in temperature for a fixed oxygen concentration. Therefore, the *anisotropy γ of fully oxidized YBCO increases as T is increased,* and strongly suggests that a temperature driven decoupling of the $Cu2O_2$ planes is responsible for the change in the field dependence of ρ_{ab} in a fully oxidized YBCO film. A similar physical picture has been used by Safar *et al.* [6] in order to explain the sudden collapse of $H_{C_1}(T)$ near T_c, as measured in fully oxidized YBCO single crystals. These authors suggest that when the thermal energy is of the same order of magnitude as the Josephson coupling energy between the $Cu2O_2$ bilayers, the phase of the superconducting order parameter fluctuates between these planes and effectively decouples them. This model seems

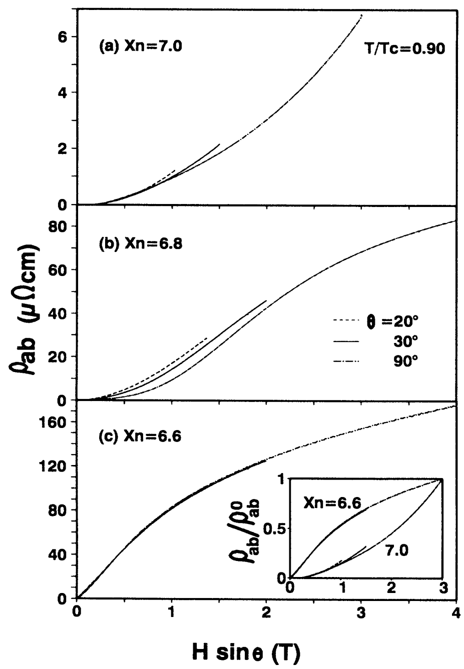

FIG. 2. Magnetoresistivity ρ_{ab} as a function of the perpendicular field component $H\sin\theta$ measured at $T/T_c=0.90$ in YBCO films with decreasing oxygen content x_n. The inset in (c) shows the normalized resistivity $[\rho^0_{ab}=\rho(90°,3\ \mathrm{T})]$ versus $H\sin\theta$.

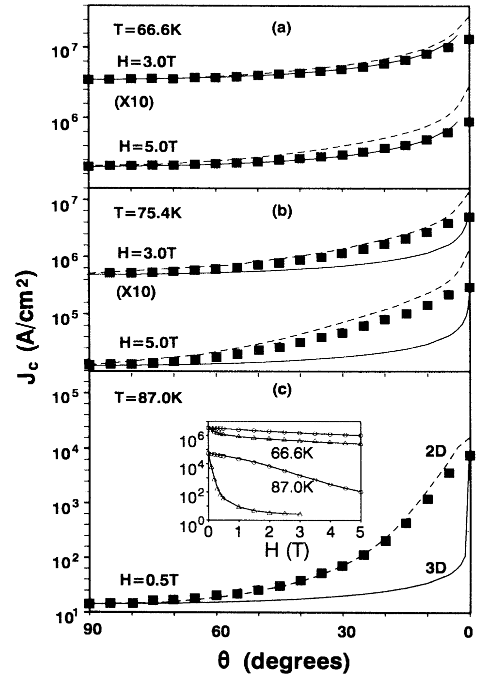

FIG. 3. Critical current density J_c as a function of the angle, θ, between H and the a-b planes of the fully oxygenated YBCO film measured at different temperatures T. The dashed lines are calculated values using the 2D model [Eq. (2)]. The solid lines are obtained using the anisotropic 3D model [Eq. (1)]. The inset shows the field dependence of J_c measured at two temperatures. (○) $H\perp c$; (△) $H\parallel c$.

to be in sharp contrast with the temperature and field independence of γ predicted by the anisotropic Ginzburg-Landau theory. It should, however, be noted that thermal fluctuations are not included in this theory. In a very recent Letter Daemen *et al.* [14] showed that the anisotropy parameter γ becomes temperature and field dependent above a decoupling field $B_D(T)$ due to a renormalization of the critical current perpendicular to the Cu2O$_2$ planes, which rapidly drops to zero above $B_D(T)$ due to thermal fluctuations. It is worth noticing that in this model the superconductivity is assumed to be restricted to the 2D Cu2O$_2$ planes at all $T<T_c$.

In the following, and based on the behavior we observe for $J_c(\theta,H,T)$, we propose an alternate physical picture.

According to Qi Li *et al.* [1], the angular dependence of J_c in YBCO/PrYBCO superlattices can be fitted by the anisotropic 3D Tachiki and Takahashi (TT) model [15] for $T<T_c(\mathrm{Pr})$ (separating layers are superconducting), and the 2D model of Kes *et al.* [13] for $T>T_c(\mathrm{Pr})$ (separating layers are normal). Within the TT model, the magnetic field penetrates the structurelike staircase vortices with segments parallel to the a-b plane. These vortex segments are strongly pinned between the superconducting planes and the dissipation is mainly due to the movement of segments which are perpendicular to the a-b planes. Within this model, the angular dependence of J_c is given by

$$J_c(\theta)=\frac{J_{c\perp}}{(\sin\theta)^{1/2}}\,, \tag{1}$$

where $J_{c\perp}$ corresponds to the critical current when the field is applied parallel to the c axis. On the other hand, the model of Kes *et al.* predicts a scaling rule for J_c of the form

$$J_c(H,\theta)=J_c(H\sin\theta)\,, \tag{2}$$

which stresses the fact that only the perpendicular field component, $H\sin\theta$, is relevant.

Figure 3 shows the angular dependence of J_c measured in the fully oxidized ($x_n=7$) YBCO film, at different temperatures and applied magnetic fields. At low T, $J_c(\theta)$ is in good agreement with Eq. (1) for an anisotropic 3D system [Fig. 3(a), solid lines]. At temperatures close to $T_c=88.4$ K excellent agreement is obtained using Eq. (2) of the 2D model [Fig. 3(c), dashed line]. For computing the dashed lines in Fig. 3, the measured field dependence of $J_{c\perp}$ was used. The inset of Fig. 3(c) shows the field dependence of J_c at two different temperatures. It is evident that $J_c(H)$ drastically changes when T increases, and that $J_{c\perp}$ is much more affected than $J_{c\parallel}$, which is also in qualitative agreement with the experimental results of Qi Li *et al.* [1].

It is quite remarkable that an increase in temperature induces the same changes in the angular and field dependence of J_c as those reported for the YBCO/PrYBCO multilayer system [1]. These results seem to corroborate the existence of a 3D-2D crossover in our fully oxidized YBCO films. What seems even more interesting is that by extending the analogy we may speculate about the possibility that in fully oxidized YBCO, the "separating" $Cu1O_z$ chain planes are superconducting with a critical temperature $T_c(P)$ lower than the T_c of the $Cu2O_2$ bilayers. When $T < T_c(P)$, both systems are in the superconducting state and YBCO behaves as an anisotropic 3D superconductor; when $T > T_c(P)$, the $Cu1O_z$ chain planes are in the normal state while the $Cu2O_2$ planes remain superconducting, and consequently YBCO behaves like a stack of independent 2D superconductors. It is interesting to note that in YBCO untwinned single crystals the in-plane resistivity has been found to be anisotropic with $\rho_{aa} > \rho_{bb}$ [16], in contrast to what is expected from a purely structural point of view, since the lattice parameter $b > a$. It has also been shown in [7] that the anisotropy of the irreversibility field in the *a-b* plane suggests that the coherence length $\xi_b > \xi_a$, which is again in contrast with what would be expected from the structural anisotropy in the *a-b* plane. While the anisotropy of ρ in the *a-b* plane suggests that the chain planes contribute to the conductivity in fully oxidized YBCO, the irreversibility field anisotropy seems to indicate that chain planes may also play an active role in the development of superconductivity in this material, as already suggested in Ref. [7]. Our assumption of superconducting chain planes in fully oxidized YBCO seems to provide a natural link between these experimental results.

In summary, our magnetoresistance and critical current measurements suggest that a dimensional crossover from 3D to 2D occurs in fully oxidized YBCO films. This crossover near T_c is reflected in the angular and field dependences of ρ_{ab} and J_c, and is temperature driven. The nature of the decoupling process between the $Cu2O_2$ bilayers might be related to (i) phase fluctuations of the superconducting order parameter between the $Cu2O_2$ bilayers when the thermal energy is of the same order of magnitude as the Josephson coupling energy between them, or to (ii) the existence of superconductivity in the $Cu1O_z$ chain planes with a critical temperature $T_c(P)$ lower than that corresponding to the $Cu2O_2$ planes.

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