ab-Plane Anisotropy of Transport Properties in Unidirectionally Twinned YBa$_2$Cu$_3$O$_{7-\delta}$ Films

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A unidirectionally twinned, c oriented YBa$_2$Cu$_3$O$_{7-\delta}$ film was prepared on a (001) NdGaO$_3$ substrate. In the normal state between 100 and 300 K, the unidirectional twin plane lattice induces a strong anisotropy of ρ_{ab}, leading to a temperature independent ratio of 6 between the resistivities across and along the twin boundaries. At 77 K, the self-field critical current parallel to twin planes is 1.2×10^6 A/cm^2, a value which is 25 times higher than along the perpendicular direction. This shows that, at this temperature, twin boundaries control the critical current values in YBCO films by either channeling or pinning effects. [S0031-9007(96)01504-9]

The role of twin planes in YBa$_2$Cu$_3$O$_{7-\delta}$ (YBCO) has been extensively studied. Very early, the question of whether twin boundaries cause a local enhancement of superconductivity [1] or a decrease of the order parameter has been discussed [2]. Main attention has been focused on the pinning properties of twin boundaries in the mixed state. It is now well established that these intrinsic defects act as strong pinning centers against perpendicular flux motion [3], whereas vortex channeling along twin planes has recently been investigated [4]. Since detwinning would suppress pinning and also channeling effects, and ideal system to study the impact of these natural two-dimensional defects is a unidirectionally twinned sample, i.e., with twin planes oriented in a single direction. However, both (110) and (1$\bar{1}$0) twin planes usually coexist in orthorhombic YBCO. Indeed, usual experimental conditions associated either with melt-textured bulk preparation or thin film deposition produce heavily bidirectional twinned samples (see Fig. 2 of Ref. [5] for a demonstration of the patch-worklike structure of twin domains). This twinning behavior should be compared with the twinning of single crystals, where large domains containing the same orientation of twin planes are commonly observed. Angle dependent magnetic studies of the unidirectional twin boundary arrays on suitably cut single crystals have then been reported [6]. However, direct critical current measurements allowing for a quantitative analysis of the twin plane influence are still missing in unidirectional twinned samples. Moreover, to the authors' knowledge, nothing has been reported on the impact of twin planes on the normal state resistivity above 100 K.

In the present study, results on unidirectionally twinned YBCO films deposited at relatively high oxygen pressure on NdGaO$_3$ substrates are reported for the first time. These samples are ideally suited for clarifying the properties of a dense array of extended planar defects (the twin boundaries) on the normal and superconducting state of YBCO.

A 210 nm thick film deposited on a NdGaO$_3$ substrate under a high oxygen pressure (4 Torr = 550 Pa) by dc sputtering [7] has been extensively studied. Texture analysis was performed on this film, using the substrate-free (102/012) reflections of YBCO. Scans showed that only the so-called $c\perp$ and $a\perp$ orientations (relative to the film plane) exist, and the data analysis gave 6.8% of $a\perp$ orientation relative to the total irradiated volume of the film. Normal Bragg θ-2θ spectrum on the (001) reflections yields a c axis value of 11.63 Å. This film was also studied by grazing incidence diffraction to probe its in-plane structure. Let us remember that the orthorhombic (h^*k^*0) reciprocal lattice plane of a YBCO crystal containing four twinned individuals exhibits a characteristic fourfold splitting of all spots, except those related to the ($h^*k^* = \pm h^*0$) reflections which are only split into three (see, for example, Fig. 2 of Ref. [8]). Our film's grazing incidence diagrams are shown in Fig. 1. Here, the reflections associated with the (020) and (200) YBCO planes show only a twofold splitting. Moreover, while the (1$\bar{1}$0) YBCO plane spot also exhibits a twofold pattern, the single reflection of the (110) YBCO plane is merged into the (220) substrate spot. These results are definitive evidence for the presence of only two twin variants in our film, associated with the presence of a

single direction of the twin planes, namely, the (110) one, oriented along the (200) substrate direction.

In the following, an interpretation for the occurrence of the unidirectionally twin structure is presented. First, note that the planar distance between the (110) planes of YBCO is close to the distance between the (200) planes of NdGaO$_3$ (0.38% mismatch), whereas the lattice match is not as good between the ($1\bar{1}0$) and (020) planes of YBCO and NdGaO$_3$, respectively (0.81% mismatch). Then, consider the deposition conditions of the DC sputtered film ($P_{oxygen} = 550$ Pa; $T_{substrate} \approx 750$ °C): The oxygen content of the growing YBCO film will be about 6.15 ($\delta = 0.85$) [8]. According to Hodeau et $al.$ [9], a tetragonal sample characterized by $\delta < 1$ consists of a multidomain crystal containing two perpendicular orientations of short chains. They are only a few unit cells long, otherwise orthorhombicity would be detected in the x-ray diffraction measurements. At the O-T transition, the dc sputtered film will thus have to accommodate the already existing chains in two $perpendicular$ $directions,$ which will act as "seeds" for the development of longer chains in the fully oxygenated orthorhombic structure. Therefore, because of the lattice match considerations and the initial oxydation state, the system will prefer the unidirectional twinning. This situation is different than that found by Sherer et $al.$ [10]. In their experiments, the deposition pressure was only 5 Pa. This led to films characterized by a strictly $\delta = 1$ oxygen content during deposition that resulted finally in untwinned structure. In our experiments, the twin boundary spacing can be qualitatively understood as the average distance between two perpendicular sets of original short chains. This distance should vary strongly with the deposition pressure. This parameter allows then a simple control of the twin spacing without changing the overall oxygen content of the samples, which is determined, in a large deposition pressure range, by the cooling procedure following the deposition step. A rough calculation taking into account the behavior of only one CuO plane, and using a reasonable 10 unit cell chain length and a homogeneous 15% occupation of the O4 sites, yields a twin spacing of about 100 Å. This estimation is the first evidence that our sample made under an oxygen pressure of 4 Torr would be characterized by a dense array of twin planes.

The transport properties of our film were measured on 30 μm wide and 1 mm long bridges chemically patterned by photolithography and etched with dilute orthophosphoric acid. In order to probe the in-plane anisotropy, a specific mask has been designed (inset to Fig. 2). The resistivity versus temperature curves of the bridges were measured during the same cooling run with the aid of a multichannel setup using a bias current of 1 μA. Critical currents versus temperature were separately measured on each bridge.

Figure 2 shows that the residual extrapolated resistivities are almost zero for all curves, with superconducting transitions above 89 K. One can see that the film is
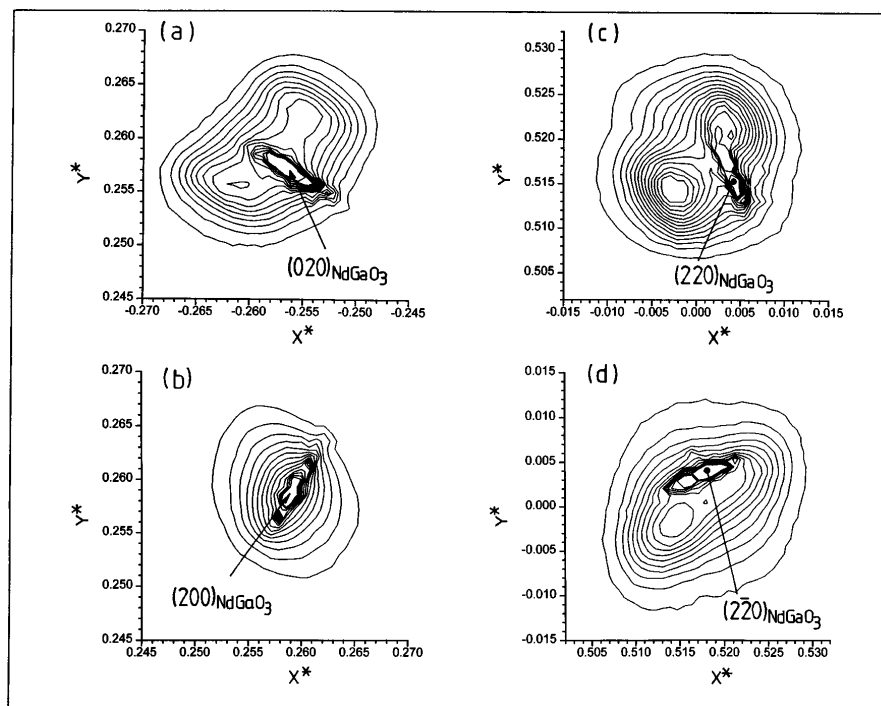

FIG. 1. Grazing incidence spectra of the patterned YBCO film. Spots in the reciprocal space are represented through their contour of equal diffracted intensity. Strong narrow substrate peaks are visible. (a) and (b) exhibit the ($1\bar{1}0$) and (110) YBCO plane reflections, respectively, while (c) and (d) show the twofold diffraction spots of the (200) and (020) YBCO planes.
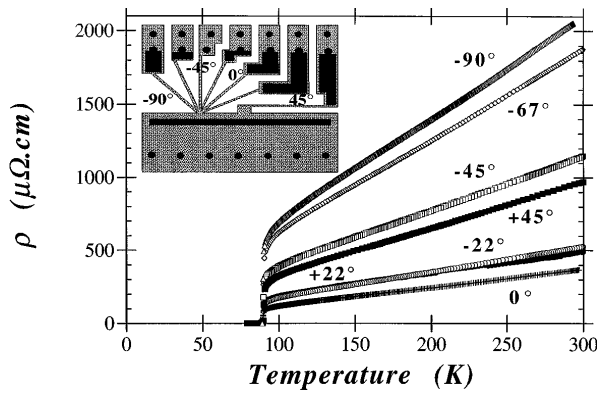
FIG. 2. Resistivity versus temperature curves for seven bridges. Inset: the film geometry after patterning; dots represent electrical contact areas, while black rectangular shapes correspond to silver paint pads.

characterized by a large in-plane anisotropy, with a ratio between the highest and lowest resistivities of about 6 (see the inset in Fig. 3). Note the weak dependence of this ratio on the temperature. The lowest resistivity is found along the twin boundary direction (marked by $\theta = 0°$). These results provide, for the first time, strong evidence that twin planes are efficient and coherent barriers for electronic transport in the normal state. This feature has so far been hidden by percolation effects in the normally bidirectional twinned YBCO samples. The value $\rho \, (\theta = 0°) = 370 \; \mu\Omega$ cm at 300 K is indeed close to the ρ_{ab} value of good quality bidirectional twinned YBCO films on various substrates. However, the 2100 $\mu\Omega$ cm resistivity perpendicular to the twin boundaries is the highest in-plane resistivity reported in the literature associated with such a high superconductive transition temperature in YBCO films. Electrons scattering at the twin plane interfaces, or a lower electronic density of state within twin planes, could be invoked to explain the difference between $\rho \, (\theta = 0°)$ and $\rho \, (\theta = 90°)$. This large anisotropy of the resistivity is a second indication that our film has a denser twin plane lattice compared to unidirectional single crystals.

Assuming that our system is described by a matrix relation between the vectors **E** and **j** (respectively, the electric field and the current density in the bridges) through a diagonal tensor of conductance in the x, y reference frame of the anisotropy axis yields

$$\begin{pmatrix} j_x \\ j_y \end{pmatrix} = \begin{pmatrix} \sigma_x & 0 \\ 0 & \sigma_y \end{pmatrix} \begin{pmatrix} E_x \\ E_y \end{pmatrix}, \qquad (1)$$

where x and y are the directions parallel and perpendicular to twin planes, respectively. Treating this matrix relation in a new orthogonal reference frame (z, t), where the z axis is parallel to a given bridge and makes an angle θ with the twin boundaries, gives

$$\rho(\theta) = \rho_x \cos^2 \theta + \rho_y \sin^2 \theta. \qquad (2)$$

As shown in Fig. 3, a very reasonable fit is obtained with this simple law deduced only from symmetry con-

siderations. Equation (1) yields $\frac{j_x}{j_y} = \frac{\sigma_x}{\sigma_y} \frac{E_x}{E_y}$ that is $tg\theta = \Gamma tg\gamma$, where θ and γ are the angles between the twin boundaries and the directions of the current density and the electric field, respectively, and Γ the anisotropy ratio. This shows that, except for the two cases where j is parallel or perpendicular to the twin planes, the electric field E is no collinear with the current direction and thus has a transverse component. Let us remark that there is an evident analogy between our system of currents flowing in an electronically anisotropic structure and the penetration of vortices in a lamellar superconductor at $H = H_{cl}$ [11]. The transverse voltage V_T can be express as

$$V_T(\theta) = \rho(\theta = 0)(\Gamma - 1) \sin \theta \, \cos \theta \, \frac{I}{e}, \qquad (3)$$

where I is the applied current and e the film thickness. Our film characteristics and a current of 1 mA yield $V(45°) \approx 4 \times 10^{-2}$ V. Thus, this kind of "Hall effect" in zero field arising from the sample anisotropy could be easily measured using a suitably patterned film. It has to be pointed out that, while numerous experiments performed on artificial uniaxial multilayers characterized by a symmetry axis perpendicular to the substrate's plane (i.e., parallel to the growth direction) have been reported, it is very difficult to build in-plane anisotropic structures using conventional growth and photolithographic techniques. Unidirectionally twinned thin films naturally provide such an anisotropic system.

We now focus on the critical current anisotropy in the unidirectional twinned film. While the resistivity ratio $\rho(-90°)/\rho(0°)$ is almost 6, we have measured a ratio $Jc(\theta = 0°)/Jc(\theta = -90°)$ equal to 25 at 77 K, with $Jc(\theta = 0°, 77 \text{ K}) = 1.2 \times 10^6$ A/cm. In a bridge, the displacement of vertical vortices created by a current j due to the self-field effects [12] is expected to be transversal (i.e., perpendicular to j). Then, for a bridge patterned perpendicularly to the twin boundary direction, flux lines will move in the direction
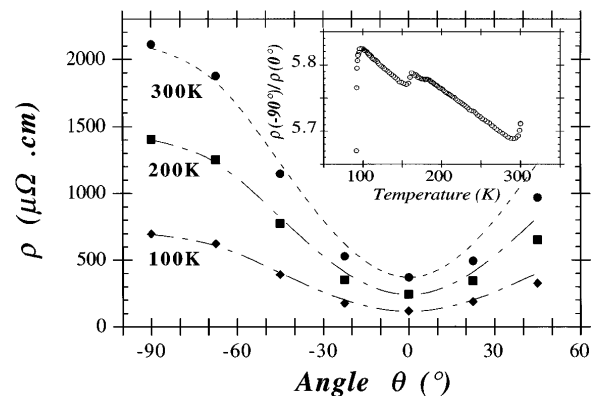

FIG. 3. Angular variation of ρ_{ab} for three temperatures. The solid line is a fit by Eq. (2). Inset: the resistivity ratio versus temperature between the directions parallel and perpendicular to the twin planes.

of these defects. The strong lowering of the critical current in this configuration can be explained by the existence of a vortex channeling effect within twin boundaries. The opposite situation is found in a bridge patterned along the twin plane direction, where vortices are expected to be trapped within these defects in their transverse motion. This large critical current anisotropy cannot be observed in bidirectional twinned samples, where pinning by twin planes always occurs, except under high magnetic field [13]. These two phenomena could be the result of a depression of the order parameter within twin planes due to the proximity effect, as proposed earlier by Deutscher and Müller [2]. However, if we assume the existence of a temperature dependent proximity effect, channeling inside twin boundaries should disappear near the superconductive transition temperature of these natural barriers. In artificial edge junctions, a rapid increase of the critical current around the transition temperature of the barrier has already been observed [14], and we can thus expect a similar behavior in the temperature dependence of $Jc(\theta = -90°)$.

In conclusion, we have succeeded in preparing and characterizing unidirectionally twinned YBCO thin films which are ideally suited for the investigation of the twin plane properties.

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