Magnetoresistance and Hall effect in unidirectionally twinned $YBa_2Cu_3O_{7-\delta}$ thin films

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(Received 31 July 1998)

Longitudinal and Hall resistivity measurements were performed on an unidirectionally twinned $YBa_2Cu_3O_{7-\delta}$ film, with current parallel and perpendicular to the twin boundaries, in fields up to 16 T. In the normal state, the ratio between the longitudinal resistivity measured across and along the twin boundaries is $\rho^{\perp}/\rho^{\parallel}\approx 1.6$, while the ratio for the Hall resistivity is $\rho_H^{\perp}/\rho_H^{\parallel}\approx 1$. These results are discussed in the framework of existing theories for normal-state transport in the cuprates. In the mixed state, for high magnetic fields, the ratios between the longitudinal and Hall resistivities diverge from the normal-state values for temperatures below the characteristic temperature of twin boundary pinning: the ratio $\rho^{\perp}/\rho^{\parallel}$ increases with decreasing temperature, whereas the ratio $\rho_H^{\perp}/\rho_H^{\parallel}$ decreases with decreasing temperature; as a result, it is shown that the Hall conductivity is influenced by twin boundary pinning. These high-field results are in qualitative agreement with an extended version of the Wang, Dong, and Ting model, which takes into account the anisotropy introduced by the twin boundaries. [S0163-1829(99)14201-2]

I. INTRODUCTION

The Hall effect in high-temperature superconductors has been one of the most controversial and discussed subjects concerning these materials, both in the normal and in the mixed state. In the normal state, the anomalous T^2 dependence found for cotg $\theta_H=\rho_{xx}/\rho_{xy}$, where θ_H is the Hall angle, together with the linear T dependence for the longitudinal resistivity, has been interpreted as evidence for the existence of two different relaxation rates for magnetotransport in the normal state. Anderson[1] proposed that the two relaxation rates, with a different temperature dependence, correspond to the relaxation of two types of quasiparticles, the holons and the spinons, whereas other models invoke charge-conjugation symmetry[2] or skew scattering[3] to justify the existence of two relaxation rates. Alternative explanations suggest that the relaxation rate has a different temperature dependence on different regions of the Fermi surface,[4–6] leading to the observed experimental results.

In the mixed state, the vortex pinning effect on the Hall conductivity σ_{xy} is still a highly debated issue. Vinokur *et al.*,[7] treating vortex pinning by point defects in an averaged way, arrived to the result $\rho_{xy}=\alpha\rho_{xx}^2/\Phi_0 B$, where $\alpha(T,B)$ is a microscopic parameter, pinning independent; consequently, the Hall conductivity $\sigma_{xy}\approx\alpha/\Phi_0 B$ is also independent of pinning. In a different approach, Wang, Dong, and Ting,[8] considering the effect of backflow current due to pinning, arrived to a result formally equivalent to that of Vinokur *et al.*, $\rho_{xy}=\alpha\rho_{xx}^2/\Phi_0 B$, but the parameter α depends explicitly on pinning, leading to a pinning-dependent Hall conductivity. Experimental results on irradiated samples have motivated some controversy, since they were interpreted as showing a pinning effect on the Hall conductivity[9] or the independence of Hall conductivity on pinning,[10] leaving the question unanswered. In a recent theoretical work, Mawatari[11] studied the dynamics of vortices in planar pinning centers and arrived to the conclusion that planar pinning has no effect on the Hall conductivity. However, previous results of Morgoon *et al.*[12] and our own recent results,[13] have shown that pinning by twin boundaries (TB)'s in $YBa_2Cu_3O_{7-\delta}$ can affect the Hall conductivity.

In $YBa_2Cu_3O_{7-\delta}$, the TB's play an important role in the electric transport properties. Villard *et al.*[14] using an unidirectionally twinned $YBa_2Cu_3O_{7-\delta}$ film have shown that TB's reduce significantly the electrical conductivity in the normal state when current flows perpendicular to them. In the mixed state, it was early established[15] that these defects act like strong pinning centers against vortex motion perpendicular to them. On the other hand, it has been predicted[16] that in a *d*-wave superconductor, time symmetry-breaking states may appear in the vicinity of TB's, yielding spontaneous currents along them.

In this article, to further clarify the TB's role on electric transport, particularly on the Hall effect, we report longitudinal and Hall resistivity measurements performed on an unidirectionally twinned $YBa_2Cu_3O_{7-\delta}$ film, with current parallel and perpendicular to the TB's. In the normal state, we found a ratio of 1.6 between the longitudinal resistivity measured with the current perpendicular and parallel to the TB's, in qualitative agreement with the Villard *et al.* results.[14] For the Hall resistivity, the ratio between the values measured for the two current directions is ≈ 1, leading to an Hall conduc-

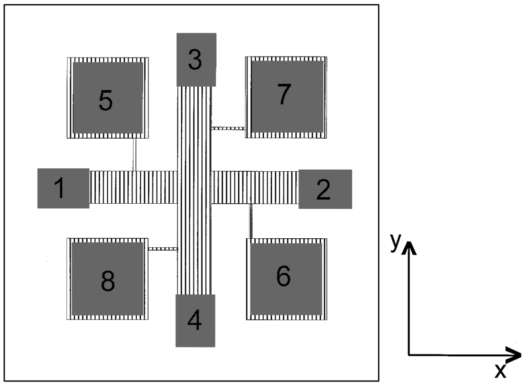

FIG. 1. Sketch of the patterning used to measure the longitudinal and Hall resistivities, with current parallel (current contacts 3 and 4) and perpendicular (current contacts 1 and 2) to the twin boundaries. Shaded areas (1–8) correspond to the electrical contacts (gold pads); heavy lines stand for the twin boundaries.

tivity which is independent of the current direction with respect to the TB's, contrarily to what happens for the longitudinal conductivity; these results are discussed in the framework of the various existing models for electric transport in the normal state. In the mixed state, the ratio between the longitudinal resistivities and the ratio between the Hall resistivities, measured for both current directions, remain equal to the normal state values in the fluctuation and flux-flow regimes; when the pinning by the TB becomes important, the longitudinal resistivity ratio increases with decreasing temperature, while the opposite happens for the Hall resistivity ratio. Consequently, the Hall conductivity in the mixed state depends on the direction of the current with respect to the TB's, which constitutes an apparent violation of the Onsager reciprocity relations: $\sigma_{xy}=-\sigma_{yx}$. At the same time, this fact implies that the Hall conductivity is affected by the pinning in the TB's, as previously reported. These results are shown to be in qualitative agreement with an extended version of the Wang, Dong, and Ting model, which takes into account the anisotropy introduced by the TB's.

II. EXPERIMENTAL

The sample was grown on a $YAlO_3$ (001) substrate by metal organic chemical vapour deposition (CVD). The CVD reactor description as well as the deposition conditions can be found elsewhere.[17] The film is epitaxial with the c-axis perpendicular to the substrate plane and has a thickness of 240 nm. A fourfold symmetry is observed on the 102/012 ϕ scans demonstrating a strong in-plane orientation ($\Delta\phi^2=1.5°$). The twinning geometry was studied by performing ϕ scans on the 114 reflections of $YBa_2Cu_3O_{7-\delta}$ and on the 044 and 404 reflections of $YAlO_3$. It was found that the twinning directions of $YBa_2Cu_3O_{7-\delta}$ align only along one direction of the substrate (namely the $\langle 010\rangle$ direction). This particular twinning was confirmed by grazing incidence x-ray diffraction. Details about the analysis are given in Ref. 18. A special patterning was used (Fig. 1), which allowed the measurement of the longitudinal and Hall resistivities for current parallel and perpendicular to the TB's. Let us stress that, with this patterning, the Hall resistivity is measured in the same region of the sample for both current directions; therefore possible effects due to sample inhomogeneities are avoided. To eliminate spurious effects due to the Hall contacts misalignments or to inhomogeneous current flow, the Hall resistivity is calculated using the transverse voltage measured for symmetric magnetic-field directions. The current used was 100 μA, and all the measured $I-V$ characteristics were Ohmic. The magnetic field was applied perpendicularly to the substrate, i.e., parallel to the c axis of the film. The zero-field critical temperature, $T_c=89.7$ K and the transition width, $\Delta T_c\approx 1.5$ K, are the same for both orientations of the current.

The existence of TB's exclusively in one direction breaks the fourfold symmetry of the transport properties and the transformation from the resistivity to the conductivity tensor must be cautiously made. In the following, we will establish the notation used throughout the paper. The resistivity tensor is defined through the relations

$$E_x=\rho_{xx}J_x+\rho_{xy}J_y, \tag{1a}$$

$$E_y=\rho_{yx}J_x+\rho_{yy}J_y. \tag{1b}$$

Choosing the y axis along the TB's and the x axis perpendicular to them (Fig. 1), we will use the notation

$$\begin{aligned}\rho^{\perp}&=\rho_{xx}, \quad \rho_H^{\parallel}=-\rho_{xy},\\ \rho_H^{\perp}&=\rho_{yx}, \quad \rho^{\parallel}=\rho_{yy},\end{aligned} \tag{2}$$

where the symbols $\parallel$ and $\perp$ indicate the direction of the current with respect to the TB's. We have chosen $\rho_H^{\parallel}=-\rho_{xy}$ in order to keep $\rho_H^{\parallel}$ and $\rho_H^{\perp}$ with the same sign (ρ_{xy} and ρ_{yx} have opposite signs). The conductivity tensor components are

$$\begin{aligned}\sigma_{xx}&=\frac{\rho_{yy}}{\rho_{xx}\rho_{yy}-\rho_{xy}\rho_{yx}}\cong\frac{1}{\rho_{xx}},\\ \sigma_{xy}&=\frac{-\rho_{xy}}{\rho_{xx}\rho_{yy}-\rho_{xy}\rho_{yx}}\cong\frac{-\rho_{xy}}{\rho_{xx}\rho_{yy}},\\ \sigma_{yx}&=\frac{-\rho_{yx}}{\rho_{xx}\rho_{yy}-\rho_{xy}\rho_{yx}}\cong\frac{-\rho_{yx}}{\rho_{xx}\rho_{yy}},\\ \sigma_{yy}&=\frac{\rho_{xx}}{\rho_{xx}\rho_{yy}-\rho_{xy}\rho_{yx}}\cong\frac{1}{\rho_{yy}},\end{aligned} \tag{3}$$

where the simplifications are due to the experimental fact that $\rho_{xy},\rho_{yx}\ll\rho_{xx},\rho_{yy}$. With our notation, we obtain

$$\begin{aligned}\sigma^{\perp}&=\sigma_{xx}\cong\frac{1}{\rho^{\perp}}, \quad \sigma_H^{\parallel}=\sigma_{xy}\cong\frac{\rho_H^{\parallel}}{\rho^{\parallel}\rho^{\perp}},\\ \sigma_H^{\perp}&=-\sigma_{yx}\cong\frac{\rho_H^{\perp}}{\rho^{\parallel}\rho^{\perp}}, \quad \sigma^{\parallel}=\sigma_{yy}\cong\frac{1}{\rho^{\parallel}}.\end{aligned} \tag{4}$$

Again we have chosen $\sigma_H^{\perp}=-\sigma_{yx}$ in order to keep $\sigma_H^{\parallel}$ and $\sigma_H^{\perp}$ with the same sign.

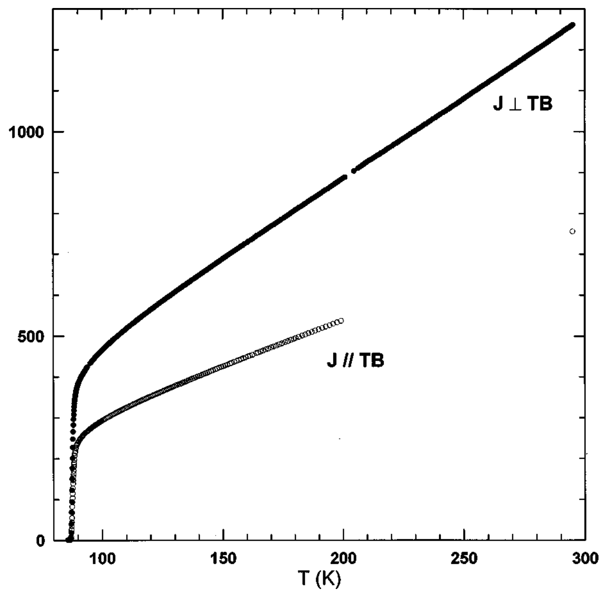

FIG. 2. Temperature dependence of the longitudinal resistivity for current perpendicular (full circles) and parallel (open circles) to the twin boundaries.

III. RESULTS AND DISCUSSION

A. Normal state

Figure 2 shows the temperature dependence of the longitudinal resistivity in the normal state, in zero applied magnetic field, with current parallel and perpendicular to the TB's. In accordance with the previously reported work,[14] the resistivity measured across the TB's, $\rho^{\perp}$, is significantly higher than the resistivity measured along the TB's, $\rho^{\parallel}$. The ratio $\rho^{\perp}/\rho^{\parallel}$ remains in the range 1.59–1.67 between 100 and 300 K, increasing slightly with temperature [Fig. 3(a)]. This ratio is relatively lower than the ratio reported by Villard *et al.* (≈ 6), a fact that can be explained by a lower density or a shorter length of TB's in our film. Both resistivity curves are well described by a linear temperature dependence down to 120 K: $\rho^{\perp}=3.95\,\mathrm{T}+94$ ($\mu\Omega$ cm), $\rho^{\parallel}=2.33\,\mathrm{T}+74$ ($\mu\Omega$ cm). It must be pointed out that the temperature dependence of the ratio $\rho^{\perp}/\rho^{\parallel}$, in the considered temperature range, is probably caused by the existence of a nonvanishing residual resistivity at zero temperature for both current directions; if this residual resistivity is subtracted from the $\rho(T)$ curves, we obtain a reasonably temperature-independent ratio between 120 and 300 K: $\rho^{\perp}/\rho^{\parallel}\approx 1.72$ [Fig. 3(a)]. The temperature dependence of the resistivity can be ascribed to the temperature dependence of the transport relaxation rate, $\rho \propto 1/\tau_{\mathrm{tr}}=\alpha T+\beta$, where the constant term β is due to impurities. In our sample this constant term presents a moderate anisotropy between both current directions: $\beta^{\perp}/\beta^{\parallel}\approx 1.3$, which may reflect the existence of anisotropic defects like the TB's. However, the experimental determination of β, by the means of a linear extrapolation, is not very accurate and the above interpretation may be questionable. In defect-free samples, the physical origin of a resistivity term depending linearly on temperature is controversial and has been attributed to electron-electron scattering mediated by spin fluctuations,[4] to electron-phonon scattering[5] or to the decay of electrons in spinons and holons.[1] Therefore, the undoubted anisotropy of the slope $\alpha^{\perp}/\alpha^{\parallel}\approx 1.7$ is not easily understood, since we do not expect the TB's to modify the relaxation rate of an intrinsic scattering mechanism as the ones mentioned above. Phenomenologically, we can describe our results by introducing a scattering rate for the electrons by the TB's, which is linear in temperature, leading to different relaxation rates for the two current directions: $\rho^{\parallel}\propto 1/\tau_{\mathrm{tr}}^{\parallel}=\alpha_i T+\beta^{\parallel}$ and $\rho^{\perp}\propto 1/\tau_{\mathrm{tr}}^{\perp}=\alpha_i T+\alpha_{\mathrm{TB}}T+\beta^{\perp}$, where α_i and α_{TB} correspond to the intrinsic and to the TB scattering mechanisms. A microscopic explanation for the temperature dependence of the scattering mechanism by the TB's is required.

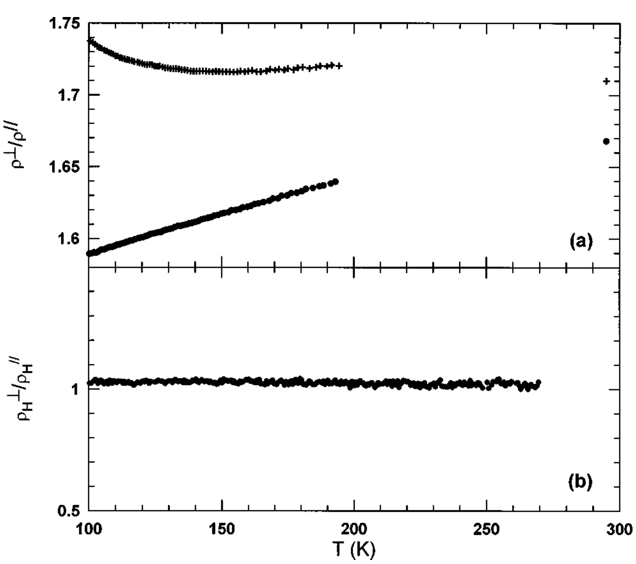

FIG. 3. (a) Temperature dependence of the ratio between the longitudinal resistivities measured for the two current directions (full circles); temperature dependence of the ratio between the longitudinal resistivities measured for the two current directions after subtracting the residual resistivity (crosses) (see text). (b) Temperature dependence of the ratio between the Hall resistivities measured for the two current directions, for $B=10$ T.

Another type of explanation for the anisotropy of the resistivity may be found if we admit that the TB's are regions (7–40 Å wide[19]) with an associated relaxation rate also linear in temperature, but with electronic microscopic parameters (density of states at the Fermi surface, effective mass, etc.) different from the bulk values. Then, our sample would behave as a collection of regions with different resistivity (but with the same temperature dependence for the resistivity), linked in series when the current is perpendicular to the TB's and linked in parallel when the current is parallel to them. The experimental values obtained for $\rho^{\perp}$ and $\rho^{\parallel}$ would not be intrinsic, but would also depend on the length and width of the regions. However, since this explanation would also imply the existence of an anisotropy for the Hall resistivity, it is ruled out by the results we obtained for the Hall resistivity, which do not confirm this prediction.

The Hall resistivity measured for current parallel ($\rho_H^{\parallel}$) and perpendicular ($\rho_H^{\perp}$) to the TB's, at $T=100$, 150, and 200 K and in fields up to 16 T, is shown in Fig. 4: $\rho_H^{\parallel}$ and $\rho_H^{\perp}$ are approximately the same, with a temperature-independent ratio $\rho_H^{\perp}/\rho_H^{\parallel}\approx 1$, determined for $B=10$ T [Fig. 3(b)]. The temperature dependence of cotg θ_H is shown in Fig. 5, for

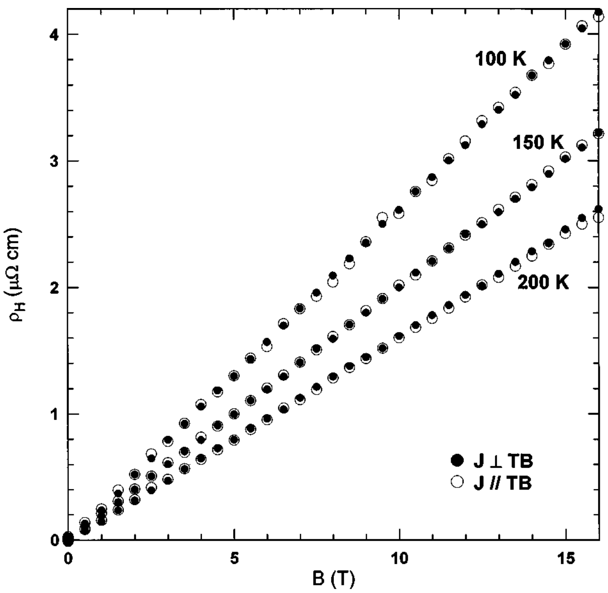

FIG. 4. Magnetic-field dependence of the Hall resistivity measured with current perpendicular (full circles) and parallel (open circles) to the twin boundaries, at $T=100$, 150, and 200 K.

$B=10$ T. Significant deviations of the T^2 dependence are present for both current directions below 200 K, also found in underdoped or overdoped samples.[20] As established in Eq. (4), $\sigma_H^{\parallel}=\rho_H^{\parallel}/\rho^{\perp}\rho^{\parallel}$ and $\sigma_H^{\perp}=\rho_H^{\perp}/\rho^{\perp}\rho^{\parallel}$; hence, the Hall conductivities for the two current directions are simply related by $\sigma_H^{\perp}/\sigma_H^{\parallel}=\rho_H^{\perp}/\rho_H^{\parallel}$. Then, according to our results, the Hall conductivity in the normal state is the same for both current directions, $\sigma_H^{\perp}\approx\sigma_H^{\parallel}$ and thus, the Onsager reciprocity relations ($\sigma_{yx}=-\sigma_{xy}$) are obeyed. As mentioned above, to explain the temperature dependences found experimentally for the Hall angle (cotg $\theta_H\propto T^2$) and for the Hall resistivity ($\rho_H\propto 1/T$), two different relaxation rates have been introduced. The models diverge about the physical origin of these two relaxation rates: several models link them to the anisotropy of the Fermi surface,[4–6] whereas in other models the two rates correspond to scattering processes of different physical origin.[1–3] We will focus first in the latter group: in Anderson's model,[1] the longitudinal conductivity $\sigma=1/\rho$ is proportional to τ_{tr}, and the Hall conductivity σ_H is proportional to the product $\tau_{\mathrm{tr}}\tau_H$, τ_{tr} and τ_H corresponding to the relaxation of different types of quasiparticles in the two-dimensional Luttinger liquid. According to our results, we have: $\sigma^{\perp}/\sigma^{\parallel}\approx 1/1.6$ and $\sigma_H^{\perp}/\sigma_H^{\parallel}\approx 1$; this leads to: $\tau_{\mathrm{tr}}^{\parallel}/\tau_{\mathrm{tr}}^{\perp}=\tau_H^{\perp}/\tau_H^{\parallel}\approx 1.6$. The existence of this close relationship between the two types of relaxation times, with equal valued ratios, seems difficult to conciliate with Anderson's model, which establishes a completely different origin for τ_{tr} and τ_H.

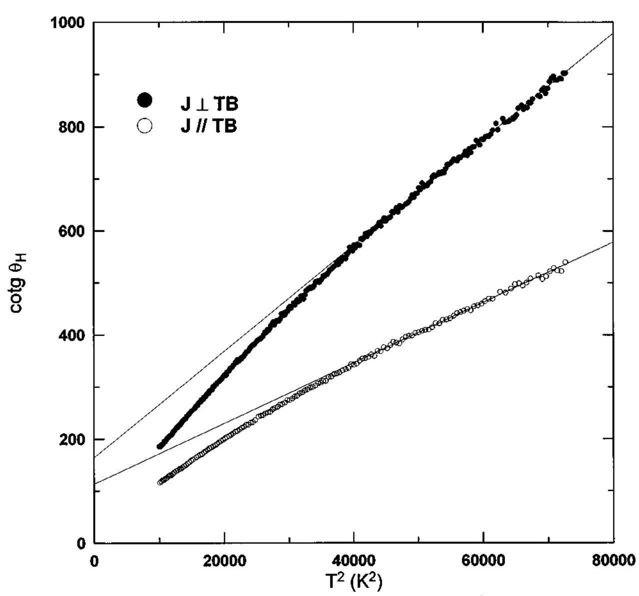

FIG. 5. cotg θ_H versus T^2 for current perpendicular (full circles) and parallel (open circles) to the twin boundaries, for $B=10$ T.

In a different approach, Coleman *et al.*[2] suggest the existence of two relaxation rates to be a consequence of scattering effects sensitive to the charge-conjugation symmetry of the quasiparticles. According to this model there are two relaxation times: a short one, τ_{tr} and a long one, τ_H, corresponding to quasiparticles of opposite parity. The longitudinal conductivity is proportional to τ_{tr}, while the Hall conductivity is proportional to the product $\tau_{\mathrm{tr}}\tau_H$. By the same reasoning made above, our results imply that $\tau_{\mathrm{tr}}^{\perp}\approx\tau_{\mathrm{tr}}^{\parallel}/1.6$, which means that the shortest relaxation time is reduced when $J\perp$ TB's due to scattering of the quasiparticles in the TB's. At the same time, our results lead to $\tau_H^{\perp}\approx 1.6\tau_H^{\parallel}$, but it is not clear to us why is this relaxation time affected by the TB's. Moreover, our results lead to a close relationship between the two relaxation times, $\tau_{\mathrm{tr}}^{\parallel}/\tau_{\mathrm{tr}}^{\perp}=\tau_H^{\perp}/\tau_H^{\parallel}\approx 1.6$, contrary to the spirit of the model.

Kotliar *et al.*[3] solved a Boltzmann equation including skew scattering, arising from a different right- and left-handed scattering on the Fermi surface, with respect to the magnetic-field direction. In the framework of this model, the longitudinal conductivity is proportional to the usual transport relaxation time τ_{tr}, whereas the Hall conductivity is proportional to $\tau_{\mathrm{tr}}^2(a+b/\tau_s)$, τ_s being the skew scattering rate. For $YBa_2Cu_3O_{7-\delta}$, the authors assume $a\approx 0$, i.e., a quasiperfect particle-hole symmetry, thus obtaining for the Hall conductivity: $\sigma_H\propto\tau_{\mathrm{tr}}^2/\tau_s$. Our results for σ and σ_H imply that $\tau_{\mathrm{tr}}^{\parallel}/\tau_{\mathrm{tr}}^{\perp}=(\tau_s^{\parallel}/\tau_s^{\perp})^{1/2}\approx 1.6$. The resulting dependence of τ_s on the current direction (and thus on defects) and the close relationship between the two types of relaxation times go against the assumed *intrinsic* nature of the skew scattering.

In summary, our results do not seem to fit into the predictions of these models, one reason being probably the models disregard for the defects influence on transport properties. However, in anisotropic samples and as far as the Onsager reciprocity relations hold ($\sigma_H^{\perp}=\sigma_H^{\parallel}$), any model involving the product or quotient of two relaxation times (the so-called ''multiplicative two-τ models'') will always imply a close relationship between them, a fact that has to be taken into account.

Alternatively, in the framework of the Fermi-liquid model, two relaxation times were introduced, τ_1 and τ_2, associated with different parts of the Fermi surface (FS), e.g., with the flat parts and with the corners. Using the Boltzmann equation for a fourfold symmetric FS, the longitudinal and Hall conductivities can be approximately described by: $\sigma\propto a\tau_1+b\tau_2$ and $\sigma_H\propto\alpha\tau_1^2+\beta\tau_2^2$, where a, b, α, and β are integrals over the different parts of the FS. Phenomenological,[5] semimicroscopical,[6] or microscopical[4] models have suggested the dependences: $1/\tau_1 \propto T$ and $1/\tau_2 \propto T^2$, which describe reasonably the temperature dependences of σ and σ_H. In our sample, the existence of TB's in one direction leads to the introduction of a third relaxation time τ_3, to account for the electron collision with the TB's when the current is perpendicular to them. The introduction of this relaxation rate breaks the fourfold symmetry of the mean free path curve or l curve [the l curve is obtained by $l(\mathbf{k}) = \mathbf{v}(\mathbf{k})\tau(\mathbf{k})$, as the wave vector $\mathbf{k}$ moves around the FS; $\mathbf{v}(\mathbf{k})$ is the Fermi velocity), leading to the anisotropy of the longitudinal conductivity shown by our results. As shown by Ong,[21] the Hall conductivity is a direct measure of the area A_l enclosed by the l curve; thus, it must not depend on the direction of the current with respect to the TB, in agreement with our results ($\sigma_H^{\perp} \approx \sigma_H^{\parallel}$). In spite of this qualitative agreement, it is our belief that any attempt to obtain a quantitative description of our results, namely of the temperature dependence of σ and σ_H, is not entirely reliable because of its dependence on uncontrolled parameters, such as the limits of the FS corresponding to τ_1, τ_2, and τ_3.

Nevertheless, the diminishing of the relaxation time caused by the TB provides a powerful way to test the predictions of these models. In the case of a sample with high enough density of TB's in two perpendicular directions, the shortest relaxation time in any direction will be the one imposed by the TB's; therefore, τ_1 and τ_2 will have the same temperature dependence and, according to this model, the Hall resistivity $\rho_H \approx \sigma_H / \sigma^2$ will become temperature independent. Using the fact that the experimental results for the longitudinal conductivity imply a linear temperature dependence for the relaxation rate associated with the TB's; we predict a crossover from $\rho_H \propto 1/T$ at high temperatures to $\rho_H \approx$ const at low temperatures, indicating that this relaxation rate becomes more efficient than the one varying with T^2. In samples with only one TB direction, the area A_l enclosed by the l curve will decrease as the TB density increases and thus, the Hall conductivity will also decrease. Information on the reduction of the area A_l can be obtained measuring the ratio $\sigma^{\perp}/\sigma^{\parallel}$, since $\sigma^{\parallel}$ will remain constant while $\sigma^{\perp}$ will decrease. Measurements on samples with different TB spacing would thus provide a test for these models, as long as the film makers succeeded on having a good control over the TB density, keeping the other parameters unchanged.

B. Mixed state

The longitudinal resistivity as a function of temperature, for high magnetic fields and for both orientations of the current with respect to the TB's, is shown in Fig. 6. As in the normal state, the resistivity measured across the TB's, $\rho^{\perp}$, is significantly higher than the resistivity measured along the TB's, $\rho^{\parallel}$. In Fig. 7, we show the ratio $\rho^{\perp}/\rho^{\parallel}$: for all fields the ratio remains equal to the normal-state value (≈ 1.6) down to a temperature $T_{\mathrm{TB}}(B)$ corresponding to $\rho/\rho(100\,\mathrm{K}) \approx 0.3$, i.e., the characteristic temperature of TB pinning.[13,15] Below this temperature, the ratio $\rho^{\perp}/\rho^{\parallel}$ increases rapidly with decreasing temperature. The usual signature of TB pinning, a shoulder in the $\rho(T)$ curves for $\rho/\rho(100\,\mathrm{K}) \approx 0.3$, is not clearly visible for any of the two current orientations, which may result from a small length of the TB's. We interpret these results as follows: above T_{TB}, the vortices are in the fluctuation or flux-flow regime, where pinning effects are irrelevant; the viscosity coefficient for vortex motion is inversely proportional to the normal-state resistivity, leading to a resistivity in the flux-flow region proportional to the normal-state value; hence the ratio $\rho^{\perp}/\rho^{\parallel}$ is the same as in the normal state. Below T_{TB}, the TB pinning becomes effective and the TB's oppose vortex motion perpendicular to them; this happens when the current is parallel to the TB's,

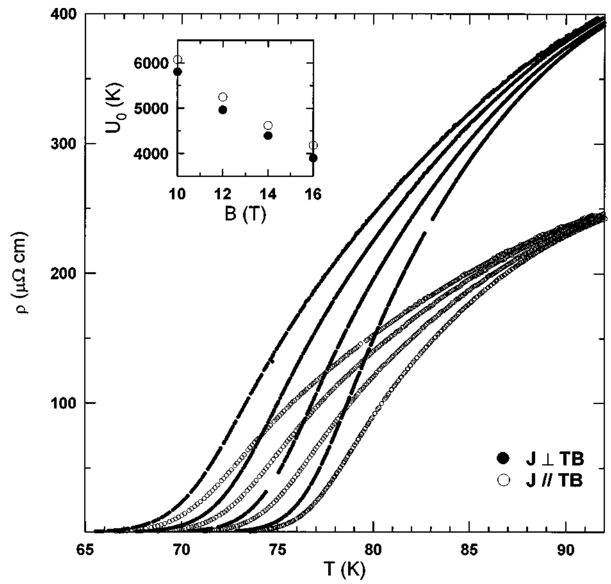

FIG. 6. Temperature dependence of the longitudinal resistivity for current perpendicular (full circles) and parallel (open circles) to the twin boundaries, for fields $B = 16$, 14, 12, and 10 T. Inset: Pinning energy versus magnetic field for both directions of the current.

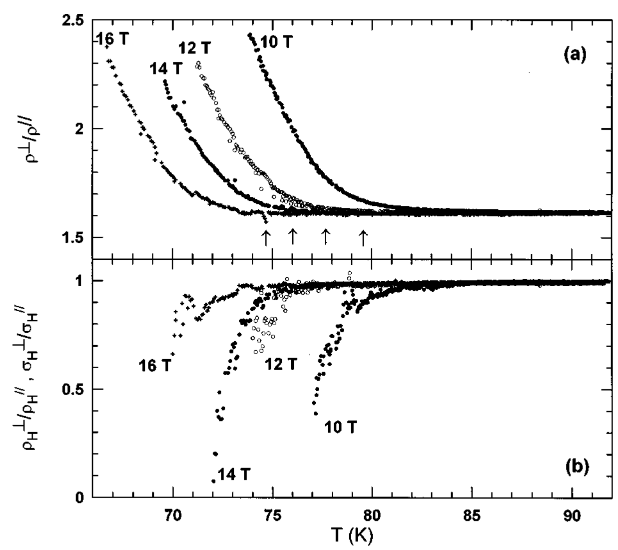

FIG. 7. Temperature dependence of the ratios between the longitudinal resistivities (a) and the Hall resistivities (b) measured for current perpendicular and parallel to the twin boundaries, at several magnetic fields. The arrows correspond to the onset temperature of twin boundary pinning, determined as $\rho/\rho(100\,\mathrm{K}) \approx 0.3$ for each field.

due to the Lorentz force acting on the vortices, $\mathbf{F_L}=\Phi_0\mathbf{J}\times\hat{z}$ (if we ignore the small component of the vortex velocity parallel to the current, responsible for the Hall effect); when the current is perpendicular to the TB's, the Lorentz force is directed along the TB's, and the vortices can move easily along them. Therefore, the resistivity $\rho^{\parallel}$ drops more rapidly to zero with decreasing temperature than $\rho^{\perp}$, leading to the observed increase in the $\rho^{\perp}/\rho^{\parallel}$ ratio. This is confirmed by the pinning energy values (inset Fig. 6), obtained as the slope of $\ln\rho$ versus $1/T$ in the interval $0.1\,\mu\Omega\ \mathrm{cm}<\rho<100\,\mu\Omega\ \mathrm{cm}$: for all fields, the pinning energy presents higher values for the parallel current orientation.

For the Hall resistivity (Fig. 7), our results show a related behavior: above T_{TB}, the ratio $\rho_H^{\perp}/\rho_H^{\parallel}$ remains ≈ 1, as in the normal state; below T_{TB}, the ratio $\rho_H^{\perp}/\rho_H^{\parallel}$ decreases with decreasing temperature, showing that $\rho_H^{\perp}$ falls more rapidly to zero than $\rho_H^{\parallel}$, contrarily to the case for the longitudinal resistivity. The Hall conductivity ratio presents exactly the same behavior since, as we showed before, $\sigma_H^{\perp}/\sigma_H^{\parallel}=\rho_H^{\perp}/\rho_H^{\parallel}$ [cf. Eq. (4)]. As a first consequence of these results, the usual scaling relation $\rho_H\propto\rho^{\beta}$ observed in the pinning regime[9,10,22] cannot hold for both current directions; if this was the case, we would have $\rho_H^{\perp}\propto(\rho^{\perp})^{\beta}$ and $\rho_H^{\parallel}\propto(\rho^{\parallel})^{\beta}$, i.e., $\rho_H^{\perp}/\rho_H^{\parallel}\propto(\rho^{\perp}/\rho^{\parallel})^{\beta}$ and thus, below T_{TB}, the two ratios should have the same type of temperature dependence, a fact discarded by our results. A failure of the scaling relation when the current is perpendicular to the TB's was predicted by Mawatari,[11] in a recent theoretical paper. Extending the model for isotropic pinning of Vinokur *et al.*[7] to the anisotropic case, Mawatari solved a Langevin equation considering explicitly the effect of planar pinning centers, parallel to the *y* axis. He arrived at the conclusion that the Hall resistivity and the Hall conductivity do not depend on the direction of the current with respect to the TB's: $\rho_H^{\perp}=\rho_H^{\parallel}$ and $\sigma_H^{\perp}=\sigma_H^{\parallel}$; furthermore, according to his results, the Hall conductivity does not depend on pinning effects, as in the isotropic case. Above T_{TB}, our results are in agreement with Mawatari's predictions, since $\rho_H^{\perp}\approx\rho_H^{\parallel}$ and so $\sigma_H^{\perp}\approx\sigma_H^{\parallel}$. However, below T_{TB}, our results show a clear dependence of the Hall resistivity and of the Hall conductivity on the current direction with respect to the TB's. Therefore, according to our results, the TB pinning effects on the Hall resistivity and on the Hall conductivity are not correctly described by Mawatari's model. As recognized by Mawatari, it is probably necessary to take into account the interaction of vortices and the superconducting fluctuations to find a pinning-dependent Hall conductivity,[23] in agreement with our results.

We will show now that the Wang, Dong, and Ting (WDT) model,[8] extended to account for the anisotropy introduced by the TB's, is in qualitative agreement with our results. In the WDT model, the equation of motion for a single vortex is[8]

$$\eta\mathbf{v_L}=\mathbf{F_L}+\langle\mathbf{F_p}\rangle-\beta_0(1-\overline{\gamma})\mathbf{F_L}\times\hat{\mathbf{z}}-\beta_0(1+\overline{\gamma})\langle\mathbf{F_p}\rangle\times\hat{\mathbf{z}}, \tag{5}$$

where $\mathbf{v_L}$ is the time-averaged velocity of the vortex, $\eta=\Phi_0 B_{c2}/\rho_n=Ne^2\tau_{\mathrm{tr}}\Phi_0 B_{c2}/m$ is the usual viscosity coefficient, and ρ_n is the normal-state resistivity, $\mathbf{F_L}$ is the Lorentz force, $\langle\mathbf{F_p}\rangle$ is the time-averaged pinning force, $\beta_0=\mu_m B_{c2}$ with $\mu_m=\tau_{\mathrm{tr}}e/m$ being the mobility of charge carriers, and $\overline{\gamma}=\gamma(1-\overline{H}/H_{c2})$ with γ describing the contact force on the surface of the vortex and $\overline{H}$ being the average magnetic field over the core of the vortex. The term $\langle\mathbf{F_p}\rangle\times\hat{z}$ is induced due to the backflow current inside the normal core and constitutes the essential feature of the WDT model.

Considering now the existence of TB's parallel to the *y* axis, η and β_0 will depend on the direction of the current with respect to the TB's, since both coefficients are proportional to the normal-state relaxation time τ_{tr}. Denoting the coefficients by $\eta^{\parallel}$ and $\beta_0^{\parallel}$ when the current is parallel to the TB's and by $\eta^{\perp}$ and $\beta_0^{\perp}$ when the current is perpendicular to the TB's, we have the relations

$$\frac{\eta^{\parallel}}{\eta^{\perp}}=\frac{\beta_0^{\parallel}}{\beta_0^{\perp}}=\frac{\tau_{\mathrm{tr}}^{\parallel}}{\tau_{\mathrm{tr}}^{\perp}}=\frac{\rho_n^{\perp}}{\rho_n^{\parallel}}. \tag{6}$$

The pinning force has the form $\langle\mathbf{F_p}\rangle=-\hat{\Gamma}\mathbf{v_L}$, where, as in the Mawatari model, $\hat{\Gamma}$ is a diagonal tensor with elements $\Gamma_{xx}=\Gamma\neq 0$ and $\Gamma_{yy}=0$, assuming that the pinning force will be always directed perpendicular to the TB's. Solving Eq. (5) with these assumptions, we obtain

$$\rho^{\parallel}=\frac{\Phi_0 B}{\eta^{\parallel}+\Gamma}, \tag{7a}$$

$$\rho_H^{\parallel}=\beta_0^{\parallel}\,\frac{\eta^{\parallel}(1-\overline{\gamma})-2\overline{\gamma}\Gamma}{\eta^{\parallel}(\eta^{\parallel}+\Gamma)}\,\Phi_0 B, \tag{7b}$$

for current parallel to the TB's and

$$\rho^{\perp}=\frac{\Phi_0 B}{\eta^{\perp}}, \tag{8a}$$

$$\rho_H^{\perp}=\beta_0^{\perp}\,\frac{(1-\overline{\gamma})}{\eta^{\perp}+\Gamma}\,\Phi_0 B, \tag{8b}$$

for current perpendicular to the TB's.

The ratio of the longitudinal resistivities is simply

$$\frac{\rho^{\perp}}{\rho^{\parallel}}=\frac{\eta^{\parallel}+\Gamma}{\eta^{\perp}}, \tag{9}$$

which agrees qualitatively with our results (Fig. 7): above T_{TB} the pinning by the TB's is negligible ($\Gamma\approx 0$) and we obtain $\rho^{\perp}/\rho^{\parallel}\approx\eta^{\parallel}/\eta^{\perp}=\rho_n^{\perp}/\rho_n^{\parallel}$; below T_{TB}, the pinning becomes more important as temperature decreases and so the ratio $\rho^{\perp}/\rho^{\parallel}$ increases with decreasing temperature.

The ratio of the Hall resistivities is

$$\frac{\rho_H^{\perp}}{\rho_H^{\parallel}}=\frac{\beta_0^{\perp}}{\beta_0^{\parallel}}\,\frac{\eta^{\parallel}(\eta^{\parallel}+\Gamma)(1-\overline{\gamma})}{(\eta^{\perp}+\Gamma)[\eta^{\parallel}(1-\overline{\gamma})-2\overline{\gamma}\Gamma]}, \tag{10}$$

which is also in agreement with our results (Fig. 7): above T_{TB}, $\Gamma\approx 0$ and we obtain $\rho_H^{\perp}/\rho_H^{\parallel}\approx(\beta_0^{\perp}/\beta_0^{\parallel})(\eta^{\parallel}/\eta^{\perp})=1$; below T_{TB}, we make use of the WDT assumption that $\overline{\gamma}\approx 0$ at relatively low temperature or high magnetic field and thus the ratio becomes

$$\frac{\rho_H^{\perp}}{\rho_H^{\parallel}}\approx\frac{\beta_0^{\perp}}{\beta_0^{\parallel}}\,\frac{(\eta^{\parallel}+\Gamma)}{(\eta^{\perp}+\Gamma)}=\frac{A\eta^{\perp}+\Gamma}{A\eta^{\perp}+A\Gamma}, \tag{11}$$

where we have set $A=\rho_n^\perp/\rho_n^\parallel$ and thus $A>1$. From this last expression, we conclude that the ratio $\rho_H^\perp/\rho_H^\parallel$ decreases as Γ increases, i.e., the ratio $\rho_H^\perp/\rho_H^\parallel$ decreases as the temperature decreases, in agreement with our results.

The Hall conductivity is easily calculated from Eqs. (4), (7), and (8) for both current directions; the main feature, however, is described by the ratio of the Hall conductivities, $\sigma_H^\perp/\sigma_H^\parallel=\rho_H^\perp/\rho_H^\parallel$, which is also described by Eqs. (10) and (11). Therefore, a clear effect of TB pinning on the Hall conductivity is predicted, in agreement with our results (Fig. 7).

Recently, Smith *et al.*[24] argued that ''inhomogeneities are likely responsible for experimental claims that σ_H depends on pinning.'' This argument clearly fails to explain our results: in our film, the Hall resistivity is measured in the same region of the film for both current directions and thus, any inhomogeneity effect is excluded from our results for $\rho_H^\perp/\rho_H^\parallel$ and $\sigma_H^\perp/\sigma_H^\parallel$. The independence of Hall conductivity on pinning may be valid for point defects, as predicted by Vinokur *et al.*,[7] but is no longer valid for planar defects. Recent results seem to confirm that also columnar defects affect the Hall conductivity.[25]

Our experimental results also show that the Onsager reciprocity relations, $\sigma_H^\perp=\sigma_H^\parallel$, no longer hold in the presence of TB's, below T_{TB}, which can be related to a breaking of time-reversal symmetry in the TB's, as predicted theoretically for the superconducting state.[16]

Let us note that Eqs. (7b) and (8b) provide a strong test for the WDT model. In this model, the sign reversal of the Hall resistivity, observed at low fields and at temperatures close to T_c, is a consequence of pinning.[26] In the case of strong anisotropic pinning ($\Gamma_{xx}=\Gamma\neq 0$ and $\Gamma_{yy}=0$) and according to our treatment, $\rho_H^\perp$ will be always positive [cf. Eq. (8b)], whereas $\rho_H^\parallel$ will change from positive to negative for low enough fields and temperatures close below T_c [cf. Eq. (7b)], as in the isotropic case. In a more realistic way, an isotropic (though weak) contribution to pinning must also be taken into account, leading to a finite Γ_{yy} $(0<\Gamma_{yy}\ll\Gamma_{xx})$ and so both $\rho_H^\perp$ and $\rho_H^\parallel$ may attain negative values, but at different temperature and field ranges. In order to check this prediction, the Hall resistivity was measured as a function of the magnetic field at several temperatures, for the two directions of the current, as shown in Fig. 8 for fields up to 12 T. Within the experimental error, the sign reversal and the minimum value of the Hall resistivity occur at the same fields for both directions of the current. This result seems to indicate that the Hall resistivity sign reversal occurring at low magnetic fields is more probably due to fluctuation or doping effects[27] rather than pinning. However, similar experiments performed in samples with higher anisotropy ratios $(\rho_n^\perp/\rho_n^\parallel)$ and more pronounced negative Hall effect, are required to test this prediction in a more conclusive way.

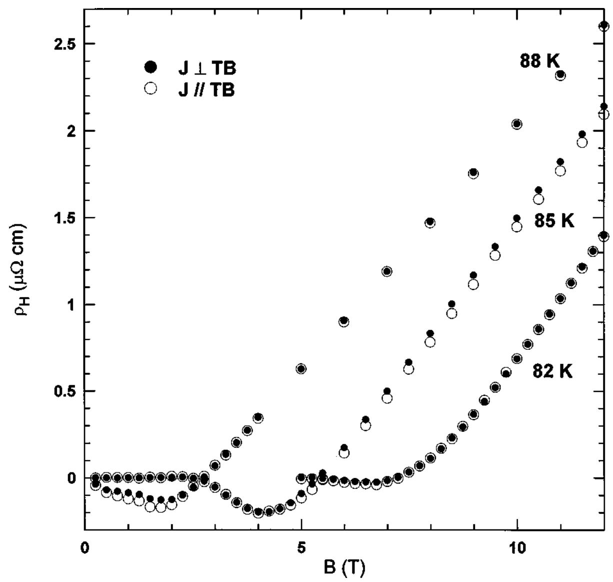

FIG. 8. Magnetic-field dependence of the Hall resistivity measured with current perpendicular (full circles) and parallel (open circles) to the twin boundaries, at $T=82$, 85, and 88 K.

IV. CONCLUSION

In summary, we have performed longitudinal and Hall resistivity measurements in one unidirectionally twinned YBCO film, with current parallel and perpendicular to the TB's, in fields up to 16 T. In the normal state, the ratio between the longitudinal resistivity measured across and along the TB's is $\rho^\perp/\rho^\parallel\approx1.6$, while the ratio for the Hall resistivity is $\rho_H^\perp/\rho_H^\parallel\approx1$. These results do not fit into the predictions of the multiplicative two-τ models for electronic transport in the normal state and, on the other hand, the presence of TB's in only one direction complicates substantially the calculations in the framework of the Boltzmann transport equation for Fermi liquids. Thus, a theory that takes explicitly into account the effect of TB's on normal transport is required. Furthermore, a careful study of the Hall effect as a function of the TB's density could provide a better understanding of the temperature dependence of the Hall resistivity and conductivity. In the mixed state, for high magnetic fields, the ratios between the longitudinal and Hall resistivities, $\rho^\perp/\rho^\parallel$ and $\rho_H^\perp/\rho_H^\parallel$, remain equal to the normal-state values in the fluctuation and flux-flow regime. Below the characteristic temperature of TB pinning, the ratio $\rho^\perp/\rho^\parallel$ increases with decreasing temperature, whereas the ratio $\rho_H^\perp/\rho_H^\parallel$ decreases with decreasing temperature; this last result implies that the ratio between the Hall conductivities, $\sigma_H^\perp/\sigma_H^\parallel$, also decreases with decreasing temperature, therefore revealing an effect of TB pinning on the Hall conductivity. These results contradict the predictions of the Mawatari model[11] which considers explicitly the effect of planar pinning centers like the TB's. We show that our results are in qualitative agreement with our extension of the WDT model,[8] which takes into account the anisotropy introduced by the TB's. However, at low fields, the sign reversal of the Hall resistivity is observed in the same temperature range for both current directions, in apparent contradiction with the predictions of the model.

ACKNOWLEDGMENTS

This work was supported by the PRAXIS XXI/JNICT program under Contract No. 2/2.1/QUI/410 and by the program ICCTI/Ambassade de France No. 105-B1. A. C. was supported by the PRAXIS XXI/JNICT program under Grant No. BD/5733/95.

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