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Published in:
Physical Review. B, Condensed Matter

DOI:
10.1103/PhysRevB.48.6612

Anomalous flux pinning by twin boundaries in single-crystal $YBa_2Cu_3O_7$

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(Received 30 November 1992; revised manuscript received 20 May 1993)

Pinning by twin boundaries in single-crystalline $YBa_2Cu_3O_7$ has been investigated by measuring the field-induced resistivity for flux lines moving within twin boundaries, crossing twin boundaries in a perpendicular direction and crossing twin boundaries with an angle of about 45°. It is found that the strong pinning effect of the twin boundaries depresses the flux movement in the flux-creep regime for fields aligned along the twin boundary for all directions of the flux-line movement. For this field orientation the flux-creep regime persists to higher temperatures. In the flux-flow regime, the effect of the twin boundaries is not significant for flux lines crossing the twin boundaries, while for flux lines moving within the twin boundaries, the twin boundary seems to act as a "flux-flow channel" enhancing the flux movement.

Twinning is a prominent substructure which, in general, exists within $YBa_2Cu_3O_7$ grains and which is formed to accomodate the change in shape during the transformation from the tetragonal to the orthorhombic structure. The twin boundaries form {110}-type of plane defects and are considered to be important pinning sites in $YBa_2Cu_3O_7$.[1] The pinning behavior of the twin boundaries in $YBa_2Cu_3O_7$ has been investigated by many authors. Recent magnetic torque,[2] magnetization,[3] and resistivity[4,5] experiments show that the significant pinning by twin boundaries is only present for magnetic-field directions aligned within a small angle along the twin boundary. It should be noted that in the magnetic torque and magnetization experiments, the direction of the flux-line movement is not uniform. In penetrating the sample, flux lines move along twin boundaries for certain moving direction and cross twin boundaries for other directions. The results from the resistivity measurement in Refs. 4 and 5 are relevant for flux lines moving along twin boundaries. In this paper, we give some observations from resistivity measurements with various configurations of current and field directions with respect to the crystallographic axes. Pinning by twin boundaries is investigated in cases of flux lines moving within twin boundaries, crossing twin boundaries perpendicular and crossing twin boundaries with an angle of about 45°.

The two $YBa_2Cu_3O_7$ single-crystalline samples used in the present experiments are the same as in Ref. 6. Sample No. 1 is with the current direction within the *ab* plane and sample No. 2 is with the current direction along the *c* axis. The superconducting (zero-resistivity) transition temperatures are 93.4 and 92.6 K for samples No. 1 and No. 2, respectively.[6] For both samples, two directions of twin boundaries perpendicular to each other are observed with one dominant direction. The twin-boundary distance is about 0.5 μm. The ac resistivity was measured at a frequency of 90 Hz with a current density of about 1 A/cm^2 for sample No. 1 and about 0.1 A/cm^2 for sample No. 2. The experiments were performed inside a rotating horizontal superconducting magnet with a maximal magnetic field of about 5 T. The magnet was rotated with step of 0.2°. Temperatures were stabilized within 20 mK. The experimental results for the various configurations are the following.

(i) For the current along the *c* axis (sample No. 2) and the magnetic field rotating within the *ab* plane, the angle-dependent resistivity is shown in Fig. 1. In this configuration, flux lines prefer to lie in the plane between the two CuO_2 layers to minimize the condensation energy.[7] The Lorentz force is along the *ab* plane and flux lines move between the CuO_2 layers. The relatively flat resistivity curves are as expected because the Lorentz force is uniform during the field rotation. The small resistivity modulation may be due to the fact that the current is not really along the *c* axis or that there is a small misorientation of the sample. Sharp resistivity drops with a distance in angle of 90° appear for field directions parallel to the twin boundaries. In this case, the flux lines are parallel to the twin boundary (for example, field along the [110] direction), and move (due to the

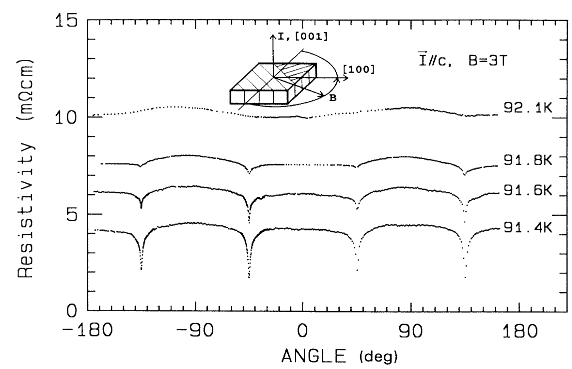

FIG. 1. Angle-dependent resistivity near the superconducting transition temperature with the current along the *c* axis and the field ($B=3$ T) rotating within the *ab* plane. The sharp resistivity drops correspond to a field direction parallel to the twin boundaries.

Lorentz force) perpendicular to the twin boundary (i.e., the flux lines move along the $[\bar{1}10]$ direction). The flux lines have to cross the twin boundaries at moving. The significant resistivity drops indicate that the twin boundary works as a strong pinning site for flux lines crossing it. This strong pinning effect becomes smaller when the temperature is increased, as illustrated clearly in Fig. 2(a) where ρ vs T curves were measured for three special field directions: the field direction parallel to the *ab* plane as well as parallel to the twin boundary, the field direction parallel to the *ab* plane but far from the twin boundary, and the direction 6° off from the *ab* plane (also far from the twin boundary). From Fig. 2(a) we learn that at high temperatures ($T > 92$ K) these three curves are identical and the special pinning by twin boundaries and by the layered structure is not effective. With decreasing temperature, we first find the pinning effect due to the twin boundary starting [as indicated by arrow (2)] and next the pinning effect due to the layered structure at a lower temperature [as indicated by arrow (1)]. It is noted that resistivity "kinks" are quite visible in the upper two curves in Fig. 2(a). These kinks are caused by the crossover from flux flow to flux creep.[6,8] Charalambous, Chaussy, and Lejay[9] also found kinks in their experiments with the same current field geometry as ours. They proposed that a vortex-melting transition occurs at the temperature where the kinks appear. The crossover from flux flow to flux creep was observed by them around the melting temperature in a narrow temperature interval.[9] For the lowest curve in Fig. 2(a) with the large twin-boundary effect, no obvious kink is found. However, an Arrhenius plot [$\log_{10}\rho$ vs $1/T$, as shown in Fig. 2(b)] for this curve shows that the resistive transition can be separated into two distinct regions below and above the temperature indicated by arrow (2). The region below arrow (2) is activated indicating that flux creep is dominant in this region. Apparently, in the presence of an extra pinning by a twin boundary, the flux-creep regime can persist to higher temperatures.

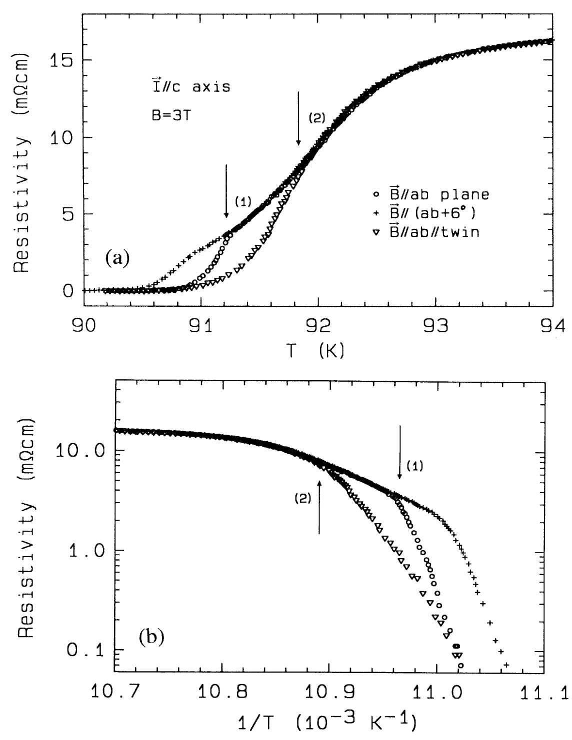

FIG. 2. (a) The ρ vs T curves with the current along the c axis and with the field direction at some special positions. The onset temperatures for the specific pinning by the layered structure (1) and by the twin boundary (2) are indicated by the arrows. (b) Arrhenius plots of $\log_{10}\rho$ vs $1/T$ for the data in (a).

(ii) For the current within the *ab* plane (sample No. 1) and the field rotating from the *ab* plane to the c axis, strong pinning by twin boundaries is observed for a field direction parallel to the c axis, which field direction is also parallel to the twin boundary, as shown in Fig. 3. For the field parallel to the c axis, the direction of the Lorentz force on the flux lines is along the *ab* plane making an angle of about 45° to the twin boundary (sample No. 1 is with the current direction along the a/b axis with few degrees deviation as will be seen later). The sharp dropping down in resistivity indicates that a strong pinning by twin boundaries is also present for a configuration of the flux line crossing the twin boundary with an angle about 45°. This strong pinning is only effective at lower temperatures. A ρ vs T measurement with the field direction parallel to the c axis and with the field direction 10° off from the c axis is shown in Fig. 4. It shows that a clear resistive kink appears around 88.5 K for the field parallel to the c axis. For temperatures above this temperature, the strong pinning effect by twin boundaries vanishes. As mentioned before, there are two directions of twin boundaries in our single-crystalline samples. In a separate experiment we remounted the sample with a small misorientation by which the c axis deviates a few degrees from the plane in which the field rotates. In this case, at approaching the c direction, the field will be parallel to the (110) plane and the $(\bar{1}10)$ plane at separate positions rather than at the same position as in the case of no misorientation. The results are shown in Fig. 5, in which a double resistivity drop indicates the pinning by the two different directions of twin boundaries. An interesting observation is that we can get a

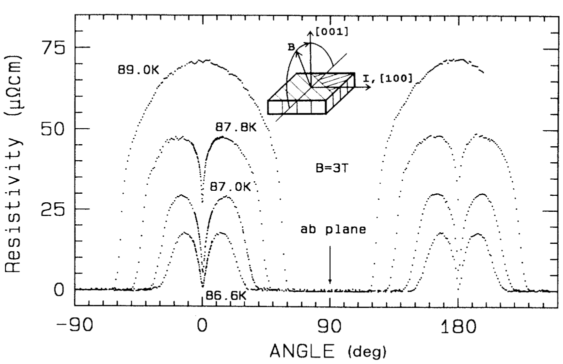

FIG. 3. Angle-dependent resistivity with the current within the *ab* plane and the field rotating from the *ab* plane (90°) to the c axis (0°, 180°) at temperatures indicated.

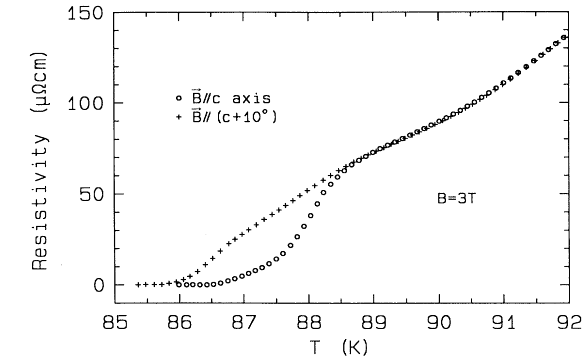

FIG. 4. The ρ vs T curves with the current along the *ab* plane, and with the field direction parallel to the *c* axis (parallel to the twin boundaries) and with the field direction shifted over 10°.

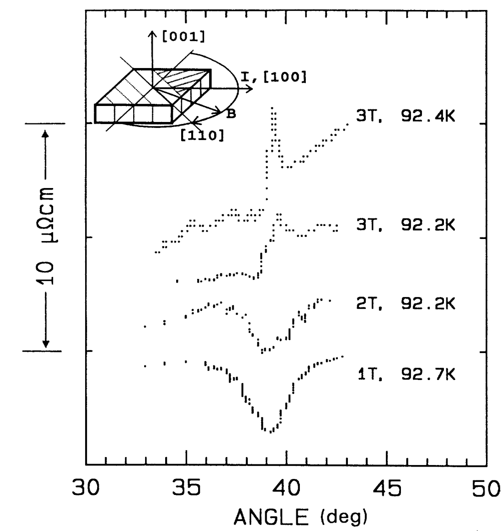

FIG. 6. The resistivity anomalies due to a twin boundary at various values of temperature and field with the current in the *ab* plane and the field rotating within the *ab* plane.

double structure with a distance between the two dips more than about 6°. The double structure is not observed for angles between the two dips less than 6°. This result implies a lock-in phenomenon.

(iii) Experiments for the current along the *c* axis (sample No. 2) and the field rotating from the *ab* plane to the *c* axis show a similar result as that in the configuration (ii) for the field approaching the *c* axis, even though the direction of flux-line movement is uncertain for this case. The double resistivity drop can also be observed by remounting the sample with a small misorientation. In this configuration too, the strong pinning by twin boundaries is only effective at lower temperature.

(iv) For current along the *ab* plane (sample No. 1) and field rotating within the *ab* plane, a 180° modulation of the angle-dependent resistivity is found,[10] which is caused by the periodical change of the Lorentz force at rotating the field. The resistivity anomalies in the modulation curves correspond to a field direction parallel to the twin boundary and the details are shown in Fig. 6. The angle in Fig. 6 is between current and field (i.e., $\theta=0°$ for $B \| I$) and the fact that the field is parallel to the twin boundary at about 40° indicates that our current direction deviates by about 5° from the a/b axis due to difficulties in making the electrical contacts exactly along the crystallographic axis. In the present configuration, flux lines lie within the *ab* plane and the Lorentz force on the flux lines is along the *c* direction. For the field parallel to the twin boundary, the flux lines which are attracted by the twin boundaries will move within the twin boundaries. In similar experiments by Kwok *et al.*,[4] only sharp drops in resistivity were found. However, we find that these phenomena are more complex: The resistivity anomalies sometimes reveal a minimum and sometimes a maximum, depending on field and temperature. The anomalous region is very narrow and is about 3° in width for minimum like anomalies and about 1° for maximumlike anomalies. To see clearly the temperature and field effects on the anomalies, we performed magnetoresistivity measurements at various temperatures for the field direction exactly parallel to the twin boundary and for a field direction 3° off from the twin boundary as shown in Fig. 7. It turns out that the ρ vs B behavior for the field parallel to

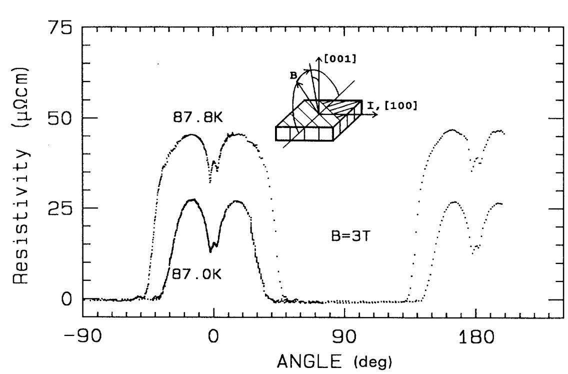

FIG. 5. A similar measurement as in Fig. 3 but with the sample having a small misorientation of a few degrees.

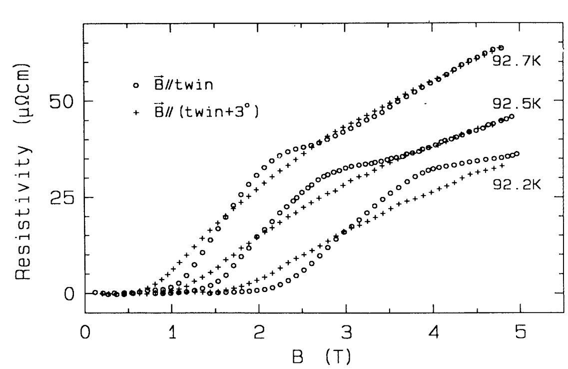

FIG. 7. Magnetoresistivity with the current in the *ab* plane at various temperatures for the field parallel to the twin boundary and for a field direction shifted over 3° within the *ab* plane.

the twin boundary (noted as the center position) is quite different from that for an angle shifted by 3° (noted as the shifted position). The ρ vs B curves show a significant S shape for the center position whereas only smooth ρ vs B curves are found for the shifted position. For the low-field range (the bottom of the S shape), the resistivity at the center position is lower than that at the shifted position, which corresponds to the minimumlike anomalies in Fig. 6. In an intermediate-field range (the top of the S shape), the resistivity at the center position is higher than that at the shifted position, which corresponds to the maximumlike anomalies in Fig. 6. For even higher field, the curves for both positions go together and the anomalous resistivity disappears. By comparing the kinks in the ρ vs T curves at different fields of Fig. 2(b) in Ref. 6 with the data of Fig. 7 of this paper, it turns out that the tops of the S shape in the ρ vs B curves of Fig. 7 correspond to the kink area in the ρ vs T curves of Ref. 6. By remembering that the kink is formed by the crossover from flux-flow regime to flux-creep regime, it seems that in the flux-creep regime, the movement of flux lines is depressed by the pinning effect due to the twin boundary for the field parallel to it. While in the crossover regime, the movement of flux lines seems to be enhanced for the field parallel to the twin boundary.

For all of the above configurations, the pinning effect due to the twin boundaries is significant only for flux lines that are aligned parallel to the twin boundary within a small angle. For the cases of flux lines crossing the twin boundary the pinning effect originates from the lowering of the free energy for flux lines staying in the twin-boundary area;[11] for the case of flux lines moving within the twin boundary, the pinning effect comes from inhomogeneities, such as arising from structural disorder inside the twin boundary.[12] The larger the part is of the flux line that is in contact with the twin boundary, the larger pinning effect is expected. Blatter, Rhyner, and Vinokur[13] have calculated the interaction between a tilted flux line and a twin boundary and proposed that for a flux line making a small angle with a twin boundary, the flux line will bend and form kinks to set part of itself into the twin boundary. The smaller the angle between the field and the twin boundary is, the larger the part of the flux line is within the twin boundary resulting in a larger effect. If the angle is larger than a certain critical angle, the flux line will keep straight and only a small fraction of the flux line is in contact with the twin boundary. This critical angle is approximately equal to the half width of the resistivity anomaly as shown in Figs. 1, 3, and 6. For a flux line moving along the twin boundary [configuration (iv), Fig. 6], the critical angle is very small ($1° \sim 3°$) as the theoretical model expects.[13] However, for flux lines crossing the twin boundary [configurations (i) and (ii), Figs. 1 and 3], the critical angle is not too small ($\sim 10°$). It seems that in these configurations, the Lorentz force on the flux line can assist the flux line to bend and to form kinks with an even larger angle between the field direction and the twin boundary.

We also noted that for all configurations, the strong pinning due to twin boundaries only is effective in the flux-creep regime. At lower temperatures, the pinning from both the host material and the twin boundary is larger than the Lorentz force and flux creep is the dominant process process for flux movement. The pinning force decreases with increasing temperature. Once the pinning force from the host material is less than the Lorentz force, flux lines can flow in the host material but still could be pinned by twin boundaries. In this way the flux-creep regime persists to a higher temperature. The limiting process for flux movement in this case is that flux lines overcome the attraction by twin boundaries. If the pinning force arising from the twin boundaries is also smaller than the Lorentz force at further increasing the temperature, flux flow becomes the dominant process for the flux movement. For flux lines crossing the twin boundary, they go through the same twin-boundary area for fields parallel to the twin boundary as well as for fields making a certain angle with the twin boundary. Therefore, in this situation the anomalies in the angle-dependent resistivity disappear as seen in Figs. 1 and 3 (in Figs. 2 and 4 the ρ vs T curves go together).

For flux lines moving along twin boundaries, at least part of them move within the twin boundaries. The twin boundary can be considered as a weak superconducting plane defect (the upper critical field B_{c2} is supposed to be smaller) with a large structural disorder inside (with the implication of a larger normal-state resistivity ρ_n). The flux-flow viscous drag coefficient η in the twin boundary may be smaller than that in the host material ($\eta = \Phi_0 B_{c2}/\rho_n$). It looks as though the twin boundary acts as a "flux-flow channel" and flux lines move easily within it in the flux-flow regime. That gives the explanation for the maximumlike anomalies in Fig. 6 and the top of the S shape in Fig. 7, where flux flow just starts to become the dominant process. At even higher temperatures, a larger flux flow is expected and the effect of the channel may be smeared out. As a good analogy for the above situation, we consider the results shown in Fig. 8, where the current direction is along the c axis (sample No. 2) and where the field is rotating from the c axis to the ab plane [in fact, this is configuration (iii), but here we focus at a position shifted by 90°]. If the field is parallel to the ab plane, the flux lines lie within a layer (the plane of the CuO chain) between two superconducting CuO_2

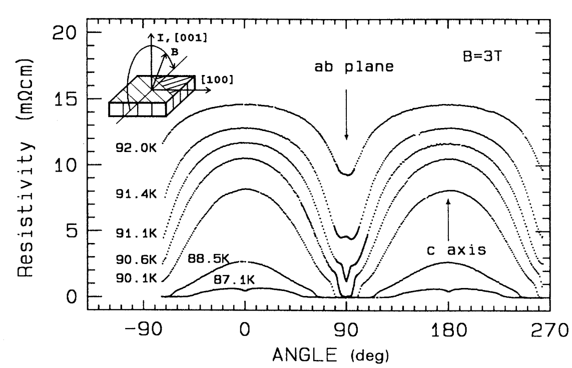

FIG. 8. Angle-dependent resistivity with the current along the c axis and the field rotating from the c axis to the ab plane.

planes and move within this layer, which we compare with the situation of flux lines moving within the twin boundary. In the flux-creep regime [curves at 91.1 K and at lower temperatures in Fig. 8 and in fact the curves in Fig. 2 in the temperature range lower than that indicated by the arrow (1)] a strong pinning effect is found for the field parallel to the layer (it is noted that the situation here is different from that of "intrinsic pinning"[7] due to the layered structure where flux lines cross the layers). At higher temperature in the flux-flow regime, however, the pinning effect around 90° vanishes and a small resistivity peak is found for the field parallel to the layer as shown by the curve at 91.4 K in Fig. 8. This observation shows a behavior similar to that of flux-flow channel.

In summary, we measured the resistivity in single-crystalline $YBa_2Cu_3O_7$ for various configurations of flux-line-moving directions with respect to the twin boundaries and found that a strong pinning effect due to twin boundaries is present only for fields aligned along the twin boundaries within a small angle. This effect depresses the flux movement for all moving directions in the flux-creep regime. The flux-creep regime persists for these field directions to a higher temperature than that in the absence of the twin-boundary effect. In the flux-flow regime, the effect of twin boundaries is not significant for flux lines crossing the twin boundaries, while for flux lines moving with the twin boundary, the twin boundary seems to act as a flux-flow channel enhancing the flux movement.

This work is part of the research program of FOM-ALMOS (Amsterdam-Leiden Material Research Cooperation) supported by the "Stichting FOM" (Foundation for Fundamental Research on Matter) and by the NOP-HTS (National Research Program for High-Temperature Superconductors).

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