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FLUX PINNING BEHAVIOR IN
TWIN BOUNDARIES OF SINGLE CRYSTAL YBa$_2$Cu$_3$O$_{7-x}$

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Flux Pinning Behavior in Twin Boundaries of Single Crystal YBa2Cu3O7.5

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ABSTRACT

We present magnetoresistance measurements up to H = 6 Tesla using a crossed magnetic field technique to demonstrate pinning by twin boundaries (TB) in YBa2Cu3O7.5. We investigate geometries for H \parallel c \parallel TB, H \parallel ab \parallel TB and for H rotated within a twin boundary plane. We find the critical angle \theta* for TB pinning to be field dependent and field independent for H \parallel c \parallel TB and H \parallel ab \parallel TB respectively in fields up to 6 Tesla and temperatures near T_C. In addition, we report on the full phase diagram for the onset of TB pinning. The TB pinning onset temperature coincides with the 'shoulder' feature observed in the resistive transition in magnetic fields in these crystals.

KEY WORDS: YBa2Cu3O7.5 superconductor, transport, pinning, twin boundaries

INTRODUCTION

The resistive transition in magnetic field of the high T_C superconductors displays a distinct 'fan shaped' broadening well below the onset of superconductivity [1]. This broadening has generally been attributed to large fluctuations [2] near the onset T_C and to dissipation by vortex motion [3] in the tail of the resistive transition. Defects in the crystalline structure or inhomogeneity in the material may inhibit this vortex motion, leading to zero resistance at lower temperatures. Among these defects, the most salient feature in YBa2Cu3O7.5 is twin boundaries which are formed in the <110> and <110> crystallographic directions to accommodate the strains induced as the material is cooled through its tetragonal to orthorhombic phase near 700°C during its synthesis. The twin boundaries are approximately 10-30Å wide [4] nonorthorhombic regions where oxygen atoms may be displaced from their ideal positions due to strain fields. The twin boundaries are probable locations of atomic defects such as oxygen vacancies and Cu atom displacements which may act as pinning centers. These boundaries separate regions of the crystal characterized by the alternation of the a/b axis in the basal plane of the crystal which can be clearly observed under a polarized light microscope. In this paper, we report on the direct measurement of the anisotropic flux pinning by twin boundaries in a high quality single crystal of YBa2Cu3O7.5. We employ a novel crossed magnetic field technique where the resultant magnetic field vector of two orthogonal superconducting magnets is rotated to obtain angular dependent magnetoresistance. We observe a critical angle \theta* for twin boundary pinning characterized by a sharp drop in resistance as the magnetic field is rotated across a twin boundary plane. In addition we also extract a phase diagram for the onset of anisotropic twin boundary pinning. For magnetic fields in the c-axis, we can correlate the onset of twin boundary pinning with the 'shoulder' feature commonly observed in the resistive transition curve in magnetic field.
EXPERIMENT

The sample was prepared by a self-flux method described elsewhere [5] which yielded platelet single crystals. From a large batch, a crystal with a single domain of twin boundaries oriented only in the <110> direction was selected. The crystal edge corresponded to either the a or b crystallographic axis such that twinned boundaries intersected the crystal edge at a 45° angle. The crystal was cleaved along the c-axis, such that the twin boundaries intersected the edge of the crystal at nearly 90°. The final dimensions of the crystal were 0.7 x 0.2 x 0.02 mm³. AC resistivity was measured by the standard four probe method with silver conducting pads sintered onto the crystal for low contact resistances. Typical measuring current density was -0.7 A/cm² at 17 Hz in the ab plane of the crystal, directed perpendicular to the twin boundaries. This particular crystal showed zero field critical temperature Tc of 90.3K with transition width ΔTc<200mK. The crystal was placed in the bore of two superconducting magnets: a 1.5 Tesla split coil magnet used to generate a transverse magnetic field (HT), which resided in the bore of an 8 Tesla solenoid magnet contributing a longitudinal magnetic field (HL). A resultant magnetic field at an arbitrary angle with respect to the sample is obtained by separately energizing these two orthogonal magnets. Extremely high angular resolution of Δθ<0.005° may be obtained by adjusting the two magnet currents. This technique was recently used to study intrinsic pinning in these materials [6].

We investigated three geometries of the magnetic field orientation with respect to the twin boundaries with this setup as shown in Fig. 1. In the first geometry, the sample was first mounted such that the transverse magnetic field was parallel to the ab plane of the crystal. The sample was then rotated mechanically about the c-axis. The angular dependence of the resistance for H=1.5 Tesla and T=89.44K is shown in Fig. 2. We see a clear sin²θ modulation of the resistance due to

Fig. 1 Orientation of magnetic field and twin boundary for three geometries (a) H || ab and (b) H || c and (c) H rotated within a twin boundary plane. The measuring current is in the ab plane of the crystal.

flux flow effects originating from the Lorentz force induced flux motion as reported in our earlier work [7]. A very sharp drop in resistivity is observed close to θ~0° when the magnetic field is aligned parallel to the twin boundaries. For as-grown crystals in our previous studies, this drop in resistivity was observed at θ~45°. However, due to the orientation of the twins in this sample, the drop occurs near the point of maximum Lorentz force. This makes the comparison of the anisotropy of twin boundary pinning for H || ab and H || c more consistent since in both geometries we consider the case for H ⊥ I (ie. maximum Lorentz force). The Lorentz force for H || ab is directed in the twin boundary plane along the crystallographic c-axis. The sharp drop in resistance may be analyzed in terms of a critical angle θ⁺ for twin boundary pinning, which describes the field misalignment which
can be tolerated without causing the twin boundary pinning to disappear. For slightly misaligned fields, the vortex can take advantage of the pinning energy $\Delta \varepsilon$ at the cost $1/2\varepsilon_1 \theta^2$ of bending away from the field direction by an angle $\theta$ where $\varepsilon_1$ is the tilt modulus for a single vortex line. The critical angle $\theta^*$ will then be proportional to $\sqrt{2\Delta \varepsilon/\varepsilon_1}$. With estimates for the pinning energy, twin density, and vortex-vortex interaction, Blatter, Rhyner and Vinokur [8] obtained a critical angle of $-50^\circ$ at $H=1$ T, in close agreement with our measured critical angle of $\theta^*\approx3.5^\circ$.

Using the crossed magnetic field technique, we investigated the temperature dependence of the critical angle and the sharp drop in resistance. We remounted the crystal such that the longitudinal magnetic field was in the $ab$ plane, parallel to the twin boundaries but perpendicular to the measuring current, and the transverse magnetic field $H_L$ was also in the $ab$ plane but parallel with the measuring current. By energizing both magnets separately, the resultant magnetic field was swept through small angles about the twin boundary plane. Angular dependent magnetoresistance plotted as $\log R$ versus the angle $\theta$ between the applied magnetic field and the twin boundary for $H=3T$ in the $ab$ plane for various temperatures is shown in Fig. 3. At temperatures just below $T_c=90.3\,K$, we do not observe any pinning by twin boundaries. However, with gradually decreasing temperatures, we see the onset of twin boundary pinning for temperatures below $T=89.19\,K$. The critical angle $\theta^*$ defined as half the angular distance between the two shoulders on either side of the sharp resistance drop, remains virtually constant. However, the strength of the pinning increases with decreasing temperatures quite rapidly, as shown by the rapid growth of the valley at $\theta=90^\circ$. With this method we determined the onset of twin boundary pinning for $H \parallel ab \parallel TB$.

An alternate method to determine the onset point is to measure the temperature dependence of the resistivity at fixed field and angle at $H \parallel TB$ ($\theta=49^\circ$ in Fig. 2) and at $H$ misaligned from the twin boundary by more than the critical angle $\theta^*(\theta=0^\circ$ in Fig. 2) and determine the temperature at which the resistive curves deviate. This point is shown in Fig. 4 where we have expanded the region of the tail of the resistive transition in a field of 3 Tesla. The onset temperature of twin boundary pinning determined with this method is approximately 89.2K, in close agreement with the value obtained using the crossed magnetic field technique.

For the second geometry of Fig. 1, the crystal was mounted such that $H_L \parallel c \parallel TB$ and $H_T \parallel ab \parallel l$. By energizing the two magnets, the resultant magnetic field was tilted from the $c$ axis parallel to TB towards the $ab$ plane. The angular dependence of the resistance at $H=3T$ for several fixed temperatures is shown in Fig. 5. We observe a much larger critical angle $\theta^*$ for this field direction in addition to a weaker temperature dependence $R(TB)/R(\theta^*)$. We also note a large critical angle dependence on the magnetic field for this field direction as demonstrated in Fig. 6, where the angular
Fig. 4 Resistance versus temperature near the foot of the transition for H=3T, for two different geometries, H II twin boundary and H L I (max. resistance point in Fig. 2, θ=0°).

Dependent resistance curves for H=1T and 4T normalized to their values at θ=120° are shown. This can qualitatively be explained due to the increase in tilt modulus ε₁ with magnetic field strength at a fixed angle while the pinning energy remains constant, at least in the narrow temperature range near Tc under consideration and hence the critical angle decreases accordingly. The larger critical angle for H L c may be qualitatively understood in light of the difference in the tilt modulus of the vortices for H L ab and H L c. For an anisotropic effective mass tensor, the angular dependence of the vortex line energy for a single vortex is given by [10]:

$$\varepsilon(\phi) = \varepsilon_{0} \left( \frac{\sin^{2}(\phi)}{1} + \cos^{2}(\phi) \right)^{1/2}$$

(1)

where $\varepsilon_{0}=[(\Phi^{2}/(4\pi\lambda)^{2}) \ln \kappa]$, $\Gamma$ is the effective mass ratio, and $\phi$ is the angle tilted from the c axis.

For H L ab, $\phi=\pi/2$ and $\varepsilon(\pi/2) = \varepsilon_{0}\sqrt{\Gamma}$. The energy to tilt a single vortex line within the ab plane can be expressed as:

$$\frac{1}{2} \varepsilon_{1} \theta^{2} = \varepsilon(\phi)(1-\theta^{2})^{1/2} - \varepsilon(\phi)$$

(2)

Using $(1+\theta^{2})^{1/2} - 1 = \theta^{2}/2$, we obtain $\varepsilon_{1} = \varepsilon_{0}/\sqrt{\Gamma}$. On the other hand, for H L c, a Taylor expansion about $\phi=0$ yields $\varepsilon_{0}(1 - \theta^{2}/2 + \theta^{2}/2\Gamma)$. Substituting into equation (2), we obtain $\varepsilon_{1} = \varepsilon_{0}/\Gamma$ for a small angle tilt about the c axis. Thus if we assume from our simple model, $\theta^*$ is proportional to $\sqrt{2\Delta\epsilon/\varepsilon_{1}}$, then we would expect a smaller critical angle for H L ab compared with H L c. However, the absence of the field dependence of the critical angle for H L ab suggest that vortex-vortex interaction energy may also have to be taken into consideration due to the anisotropy of the penetration depth $\lambda$, which is larger for H L ab than H L c, and to the rapid change in the ratio $a_{0}/d$ with magnetic field. Further refinement of the model is required to explain these results.

In the third geometry (see Fig. 1), the sample was mounted such that H L c II TB and H T L ab II TB. The resultant magnetic field was rotated within a twin boundary plane as shown in Fig. 7 for H=4T and T=80.23K. The angular sweep for H crossing perpendicular with the twin boundary at H L c is also shown for reference. For magnetic field rotations in the twin boundary plane, the resistance always remains lower than field rotations crossing a twin boundary, suggesting that the vortices remain pinned as long as the entire length of the vortex lies within the twin boundary plane regardless of the orientation.
Using the crossed magnetic field technique as shown above in Figs. 4 - 6, we determined the phase diagram for the onset of twin boundary pinning for the two geometries, H \parallel ab \parallel TB and H \parallel c \parallel TB as shown in Fig. 8. The zero resistance points of the resistive transition at fixed fields for H \parallel c which have been associated with the irreversibility or depinning line are also shown for comparison and lie much below the twin boundary pinning onset curve. In high quality single crystals of YBa$_2$Cu$_3$O$_{7.8}$, several unique features in the resistive transition in magnetic field have been reported. Among them, a shoulder near the tail of the resistive transition characterized by a nearly universal behavior above this shoulder and different resistive behavior below the shoulder between twinned and untwinned crystals has been observed [11]. Remarkably, the onset of twin boundary pinning can be correlated with the inflection point in the resistance versus temperature curve occurring at the 'shoulder' observed in all high quality single crystals of YBa$_2$Cu$_3$O$_{7.8}$. These points are shown as arrows in Fig. 9.

In summary, we have shown evidence of strong twin boundary pinning close to $T_c$ in YBa$_2$Cu$_3$O$_{7.8}$ whenever the magnetic field is aligned within a critical angle $\theta^*$ of the twin boundary plane. The
critical angle for twin boundary pinning is larger for $H \parallel c$ than for $H \parallel ab$, and field dependence was observed only in the former case. Using a crossed magnetic field technique, we determined the phase diagram for the onset of twin boundary pinning. For $H \parallel c$, the onset temperature coincides with the downturn at the 'shoulder' observed in the resistive transition in magnetic field, suggesting that vortex pinning mechanisms set in at temperatures above the irreversibility line.

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