Crossover between Channeling and Pinning at Twin Boundaries in $YBa_2Cu_3O_7$ Thin Films

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The critical current (J_c) of highly twinned $YBa_2Cu_3O_7$ films has been measured as a function of temperature, magnetic field, and angle. For much of the parameter space we observe a strong suppression of J_c for fields in the twin boundary (TB) directions; this is quantitatively modeled as flux-cutting-mediated vortex channeling. For certain temperatures and fields a crossover occurs to a regime in which channeling is blocked and the TBs act as planar pinning centers so that TB pinning enhances the overall J_c. In this regime, intrinsic pinning along the TBs is comparable to that between the twins.

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Several explanations have been proposed for the high critical current densities ($J_c s$) found in $YBa_2Cu_3O_7$ (YBCO) thin films. These include dislocations [1], low-angle grain boundaries [2], intrinsic pinning by the $a-b$ planes [3,4], twin boundaries [5], stacking faults [4], and random defects [6]. Although different sources often contribute simultaneously, they can be distinguished through their different temperature, field, and anisotropy dependences [7,8]; here we use the fact that in epitaxial films TBs always occur in particular directions to study their contributions to the J_c.

The role of TBs has been extensively studied, but a full understanding of their influence on vortex pinning is still lacking. Theoretical calculations have variously predicted both an increase [9] and a decrease [10,11] of the superconducting order parameter at the TBs. Although both possibilities are expected to create effective pinning sites, the latter would be expected to give rise to channeling of vortices along the TBs, as at grain boundaries [12]. Gurevich and Cooley [13] discuss vortices interacting with planar defects and demonstrate theoretically that channeling should generally be favored because of the low longitudinal pinning force acting on vortices lying within such defects.

Previous experiments have found that twin planes can act as strong pinning centers [5,14–16] or as vortex channels [17–20]. In this Letter we present clear evidence from angular transport J_c measurements that TBs can act both as flux channels and as pinning centers, with a $T-H$ dependent crossover between these two regimes. In particular, we show that under certain circumstances the longitudinal pinning force within a TB is at least equal to that between the plains, thus blocking vortex channeling.

Epitaxial YBCO films 150 nm thick, with in-plane orientation spread <1° and zero-field $J_c(77\ \mathrm{K}) \sim 2 \times 10^{10}\ \mathrm{A\,m^{-2}}$, were grown on $LaAlO_3$ single crystal substrates using a trifluoroacetate (TFA) precursor route [21,22] and patterned to form 500 μm × 20 μm tracks running in different directions with respect to the YBCO crystallographic axes. In twinned films, both [100] and [010] directions in YBCO are parallel to those in the substrate plane. Thus we define the orientation of the track with respect to the [100] and [010] directions by α [see inset of Fig. 1(a)]. Tracks were patterned with $\alpha = 0°$ in samples A and B, and with $\alpha = 25°$ and $\alpha = 80°$ in samples C and D, respectively, in order to break the symmetry.

J_c data were obtained by rotating H in-plane (ϕ) and out-of-plane (θ) of the film surface, using a two-axis goniometer mounted in an 8 T magnet [23] and a voltage criterion of 0.5 μV. Figure 1(a) shows the $J_c(\phi)$ curves obtained at $\theta = 60°$, $T = 50$ K and $\mu_0 H = 5$ T for tracks A, C, and D. The broad peaks in J_c observed at $\phi = 0°$ and 180° are those expected in the minimum Lorentz force (LF) configuration, i.e., when the projection of H into the film plane is parallel to the current [see inset of Fig. 1(a)]. Superimposed on this there is a sharp suppression of J_c when H is oriented along the [110] and [$\bar{1}$10] directions.

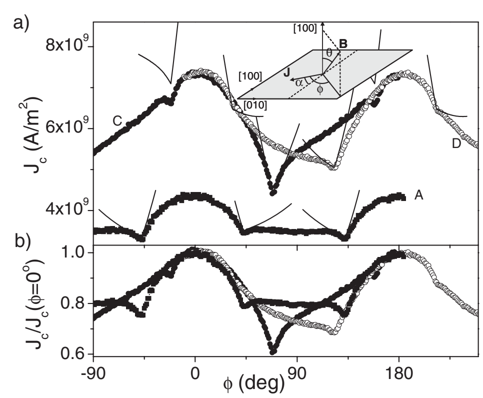

FIG. 1. $J_c(\phi)$ dependence measured at $\theta = 60°$, $T = 50$ K, and $\mu_0 H = 5$ T for samples with different angles α, A (0°), C (25°), and D (80°) (a). Solid lines are theoretical fits to the experimental data using Eq. (1). The same $J_c(\phi)$ curves normalized to $J_c(\phi = 0)$ are shown in (b). The inset shows the experimental geometry considered.

The rapid increase of $J_c(\phi)$ on either side of the minima resembles that previously observed [12,24] where vortex channeling occurs along grain boundaries. For sample A, with $\alpha = 0°$, the minima occur at $\phi = -45°$, 45°, 135°, etc., while for the samples C and D, the minima are correspondingly shifted according to the value of $\phi - \alpha$. The suppression of J_c is larger when the twin direction is close to the maximum LF orientation ($\phi = 90°$) and is less pronounced when the twin orientation is near the minimum LF angle ($\phi = 0°$ and 180°). Figure 1(b) shows the same $J_c(\phi)$ curves normalized to $J_c(\phi = 0)$ to demonstrate that the channeling modifies an angular J_c variation which is similar for all α.

Figure 2 shows the effect of changing θ on the $J_c(\phi)$ behavior for sample C at $\mu_0 H = 5$ T for two different T. At 50 K [Fig. 2(a)] channeling minima appear along the [110] and $[\bar{1}10]$ orientations for all the curves, although their depths decrease at high values of θ. The inset to Fig. 2(a) shows several $J_c(\phi)$ curves measured at different θ ($\theta > 60°$) for sample A at 50 K and $\mu_0 H = 7$ T. The channeling minimum is reduced as the value of θ is increased and no channeling at all can be detected for $\theta = 90°$ (H parallel to the film plane). In contrast, at 77 K [Fig. 2(b)] the $J_c(\phi)$ curves for $\theta = 20°$ and $\theta = 30°$ show broad peaks instead of the minima at the same ϕ orientations. In fact, such peaks can also be observed for the other values of $\theta < 90°$, although for $\theta > 40°$ they are *superimposed* on the channeling minima and merge into the minimum LF peak as $\theta \rightarrow 90°$. The appearance of broad J_c peaks implies that at high T, the planes that induced vortex channeling along the [110] and $[\bar{1}10]$ orientations also generate directional vortex pinning. The maximum J_c peaks are observed at low θ values when a large component of the LF is normal to the twin plane and a correspondingly small component lies along the channel.

Figure 2(c) shows several $J_c(\phi)$ curves measured at different T for sample C at $\mu_0 H = 5$ T and $\theta = 60°$. Dashed lines correspond to H oriented along the [110] and $[\bar{1}10]$ directions. At low T (20 K and 50 K) we only observe the channeling minima whereas at higher T (77 K) small broad peaks superimposed on the minima can be distinguished, especially near the maximum LF ($\phi = 70°$). At 80 K the J_c peaks are clearly visible at $\phi = -20°$, $\phi = 70°$ and $\phi = 160°$. The inset to Fig. 2(c) shows several $J_c(\phi)$ curves measured at 50 K and $\theta = 60°$ for sample A at different H. The channeling effect appears for $\mu_0 H > 2$ T and the minimum becomes more prominent with increasing H. The presence of J_c peaks observed at lower temperatures has also been observed for $\mu_0 H > 2$ T.

Figure 3 shows a TEM planar view image of a typical YBCO film grown by TFA which reveals the existence of a high biaxial twin density with typical domain spacing of 50 nm, containing either [110] or $[\bar{1}10]$ TBs. Both directional vortex pinning and channeling effects occur along

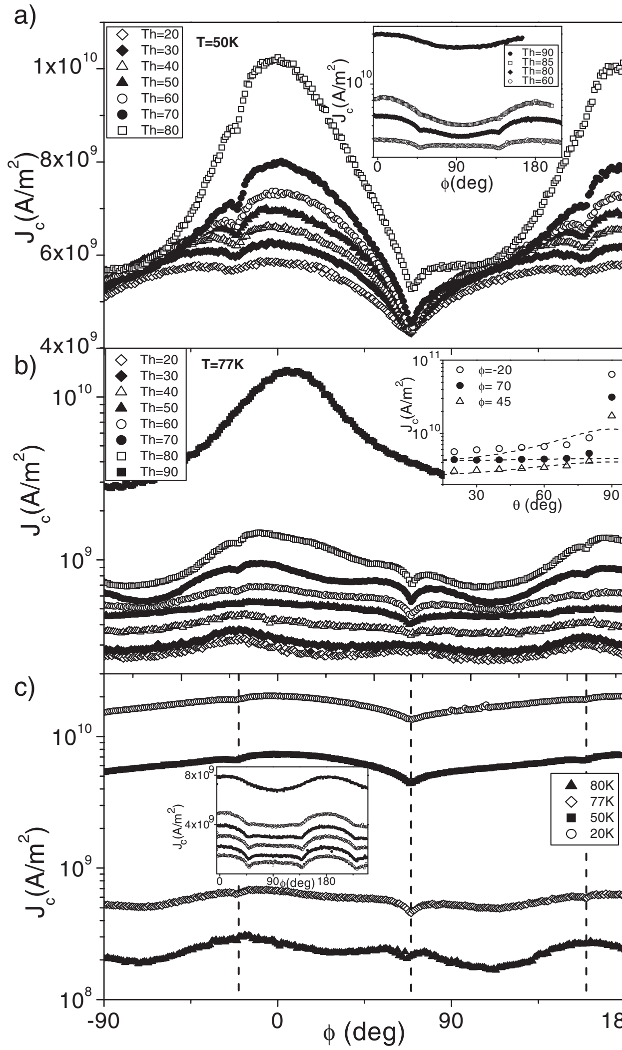

FIG. 2. $J_c(\phi)$ dependence obtained for sample C at various θ for $\mu_0 H = 5$ T at $T = 50$ K (a) and 77 K (b). $J_c(\phi)$ curves measured at different T for sample C at 5 T and $\theta = 60°$ (c). The inset to Fig. 2(a) shows several $J_c(\phi)$ curves measured at 50 K and 7 T for sample A, varying θ with $\theta > 60°$. The inset to Fig. 2(b) shows the θ dependence of the J_c in the channeling minima at $T = 50$ K and $\mu_0 H = 5$ T, for sample A at $\phi = 45°$ (△) and for sample C at $\phi = -20°$ (○) and $\phi = 70°$ (●). The inset to Fig. 2(c) shows the $J_c(\phi)$ dependence obtained for sample A for various H (from top to bottom 2, 4, 5, 6, 7, and 8 T) at 50 K and $\theta = 60°$.

these directions, depending on T, H or θ, and these effects can be associated with the high density of TBs. This behavior is also seen in YBCO thin films grown on $SrTiO_3$ substrates by pulsed laser deposition (PLD), such films also exhibit a high density of TBs [25]. Thus, the effects reported here can be treated as a general result which occurs for all the twinned films.

For channeling to be observable, (1) vortices must be confined to planar defects by a lower local value of the order parameter, (2) these defects must be preferentially aligned within the sample, and (3) the longitudinal pinning

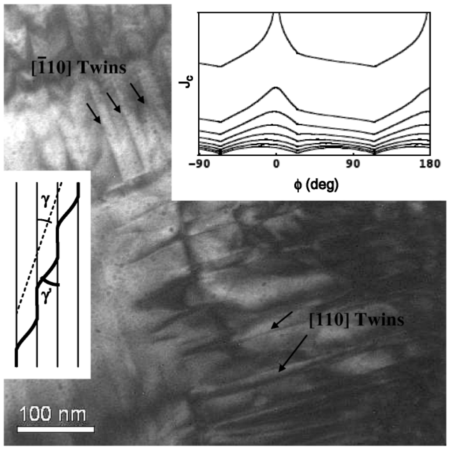

FIG. 3. TEM planar view image of a typical YBCO film grown by TFA where a high density of TBs along the 110 and [1̄10] directions can be observed. The inset graph shows $J_c s$ arising from TB pinning for the range of angles in Fig. 2(b) simulated using the model described in the text and illustrated by the inset diagram.

along the boundary must be lower than that outside the boundary. For (3) we make the important qualification that, in general, the longitudinal pinning force is actually the sum of the longitudinal elementary pinning force $f_{\|}$ introduced by Gurevich and Cooley [13] and the cutting force, $f_{\rm cut}$, required for vortices at an arbitrary angle to the defect to flow along it. It is the increase in $f_{\rm cut}$ and hence in the total longitudinal pinning with increasing angle between the vortices and the defect which gives rise to the crossover previously observed in grain boundaries where, for larger angles, flux flow occurs within the grains rather than by channeling down the grain boundaries [12].

We write the LF balance equation as $\mathbf{J_c} \times \mathbf{B} = \mathbf{F}_{\|} + \mathbf{F}_{\rm cut}$, where $\mathbf{F}_{\|}$ is the pinning force density of the vortex segments within the TB and $\mathbf{F}_{\rm cut}$ is a summation of the flux cutting force over all vortices intersecting the TB. $\mathbf{F}_{\|}$ can be written in terms of the pinning force per unit length within the TB, $f_{\|}$, and the vortex spacing, a_0, as $|\mathbf{F}_{\|}| = (f_{\|}/{a_0}^2)$. Similarly $\mathbf{F}_{\rm cut}$ can be written in terms of the force required to cut and cross-join [26] a single vortex, $f_{\rm cut}$, and the density of points where vortices cross into the TB, $|\mathbf{F}_{\rm cut}| = (f_{\rm cut}/L{a_0}^2)$, where L is the length of each vortex segment in the TB, given by $L = d_{\rm tb}/|\cos(\phi - \alpha \pm 45°)|$ and $d_{\rm tb}$ is the TB width. In the experimental geometry employed $|\mathbf{J}_c \times \mathbf{B}| = J_c B\sqrt{\sin^2\phi + \cos^2\phi\cos^2\theta}$, and thus the J_c behavior close the channeling minima can be written as

$$J_c = \frac{f_{\|} + (f_{\rm cut}|\cos(\phi - \alpha \pm 45°)|/d_{tb})}{\Phi_0\sqrt{\sin^2\phi + \cos^2\phi\cos^2\theta}}. \quad (1)$$

Equation (1) has been used for fitting the experimental $J_c(\phi)$ data in Fig. 1(a) near the channeling minima. We have taken a value of $d_{\rm tb} = 5$ nm, typical for YBCO [27], and left $f_{\|}$ and $f_{\rm cut}$ as fitting parameters. Solid lines in Fig. 1(a) shows the fit obtained with $f_{\|} = 5.4 \times 10^{-6}$ N/m, 8.4×10^{-6} N/m, and 8.9×10^{-6} N/m and $f_{\rm cut} = 2.1 \times 10^{-14}$ N, 4.8×10^{-14} N, 2.7×10^{-14} N for samples A, C, and D, respectively. The slightly lower value of $f_{\|}$ value for sample A is consistent with its lower overall J_c. The $f_{\rm cut}$ values found are very similar to the values obtained in vicinal YBCO films [24]. The minor variations observed may be associated with different $d_{\rm tb}$. Using the optimum values of $f_{\|}$ and $f_{\rm cut}$, the theoretical equation accurately reproduces the shape of the channeling minima, including the increased depth of the J_c minima close to the maximum LF. The same equation has been used to fit the evolution of the J_c channeling minima with θ. The inset to Fig. 2(b) shows the experimental values of the J_c minima obtained at $T = 50$ K and $\mu_0 H = 5$ T, for samples A and C at different ϕ. Dashed lines show the $J_c(\theta)$ dependence determined by using Eq. (1) at the different ϕ considered; the results taking the $f_{\|}$ and $f_{\rm cut}$ parameters obtained in Fig. 1(a) fit the experimental data well for $\theta \leq 80°$. For $\theta = 90°$, i.e., H parallel to the film plane, the effect of intrinsic pinning in the $a - b$ planes is to increase the pinning force significantly and so the experimental J_c is much higher than that predicted by Eq. (1).

The complete absence of channeling minima for $\theta = 90°$ [see Fig. 2(b) and the inset to Fig. 2(a)] indicates that intrinsic pinning by the $a - b$ planes blocks the vortex channeling. This is very different to the behavior observed in GBs [12] and is presumably a consequence of a near-perfect structural order of the YBCO within the TBs. We observe TB channeling for a wide range of conditions and so requirements (1) and (2) are clearly satisfied in our experiments. Condition (3) has been considered previously by Gurevich and Cooley [13], and they conclude that for general planar structures in which modified Abrikosov-Josephson (AJ) vortices lie within the defect, $f_{\|} \ll f_A$ where f_A is the bulk pinning force per unit length of the superconductor, implying that channeling should be generally observed. Since, for $\theta \sim 90°$, channeling is blocked, we can conclude that the order parameter is not homogeneously low within the TB, but rather preserves a similar spatial variation associated with the layered crystal structure to that in defect-free material. This is consistent with the model of Belzig *et al.* [10], in which an ideal TB is nonpair breaking but has a suppressed order parameter over a distance much less than the coherence length. Thus, the energy of a vortex would be reduced at a TB, but would still be modulated by the periodic potential associated with the layered crystal structure within the material surrounding the boundary. This further implies that TBs cannot be considered to be "weak links" under any circumstances and that the vortices remain Abrikosov in nature.

Additionally there are more general conditions of field strength and orientation (i.e., $\theta \neq 90°$,) under which channeling is superimposed on a J_c enhancement and may be completely blocked. This is most apparent at high T and low θ [see Fig. 2(b)]. This is a consequence of the particular symmetry of TBs: although components of the LF act both along and normal to both planes defining the TB directions, except in the special case of $\theta = 0$ vortices will only interact significantly with the TB plane to which they are more nearly parallel.

Where $f_{\parallel} < f_A$, channeling will determine J_c for the material as a whole since vortices away from the TB experiencing the same LF will be more strongly pinned. If $f_{\parallel} > f_A$ then the channel is invisible since vortex flow within untwinned material will occur, as described above for the special case of $\theta = 90°$. The situation is different for LF components normal to the TB; here the 2D nature of the defect means that there is no short-circuit pathway for vortex flow and so any pinning associated with TBs which exceeds that of the intervening material will enhance the overall J_c.

The inset diagram to Fig. 3 shows schematically a vortex interacting with a set of parallel planar defects. We discuss this interaction using a simplified version of the model of Blatter *et al.* [28]. Here, the fraction p of each vortex lying within the planar defect and hence able to interact with it is $p = |\cos\gamma| - |\sin\gamma/\tan\gamma'|$ and the energy per unit length is given by

$$E = \sin\gamma\left\{\frac{F}{\sin\gamma'} + (F - Z)|\cot\gamma - \cot\gamma'|\right\}, \qquad (2)$$

where F is the vortex energy per unit length (which can be held to include general elasticity terms for the lattice as a whole), Z is the energy reduction per unit length for a vortex within the planar defect (physically $F > Z$). Minimizing E with respect to γ' gives $\cos\gamma' = 1 - Z/F$. Thus, as Z tends to F (i.e., the strong pinning limit), p tends to the geometrical limit of $\cos\gamma$. As Z decreases, p declines increasingly rapidly with γ and is zero, contributing no extra pinning, for $\gamma > \cos^{-1}(1 - Z/F)$.

Taking the dependence of the planar pinning as $|\cos\gamma|$, the behavior given by equating the in-plane component of the LF to p is shown in the inset to Fig. 3. The same angles as Fig. 2(b) have been used and, without being a quantitative fit, the results reproduce well the general shapes and trends observed in the experimental data. Since, the characteristic angular dependence of the channeling means that a depressed J_c occurs only within a few degrees of the TB, where it occurs simultaneously with enhanced TB pinning, this is observed as a sharp dip within a broad pinning peak. It is therefore possible for TBs to act simultaneously as vortex channels and centers for enhanced 2D pinning. Significantly, there is a regime at high T [for example, in Fig. 2(b)], when bulk pinning is relatively weak, in which both the perpendicular and longitudinal pinning due to TBs exceeds that of the bulk and hence determines the overall J_c of the material irrespective of field orientation.

In conclusion, we have investigated the $J_c(\phi)$ dependence in YBCO thin films at different T and H. By reducing the symmetry of the experiment, we have shown that TBs may act both as pinning sites or flux channels depending on the temperature and magnetic field orientation. The $J_c(\phi)$ dependence in the channeling minima resembles the one observed in low-angle grain boundaries [12] and vicinal films [24] and can be described by a flux cutting model. The disappearance of channeling for $\theta = 90°$ implies that vortices within TBs, unlike other planar defects retain their Abrikosov nature.

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