Peak Effect as a Precursor to Vortex Lattice Melting in Single Crystal $YBa_2Cu_3O_{7-\delta}$

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We present direct evidence of a "peak effect" as a precursor to vortex lattice melting in a single crystal of $YBa_2Cu_3O_{7-\delta}$ containing only two twin planes. The peak effect occurs just below the vortex liquid to solid phase transition in a narrow field region between 0.3 and 1.5 T for $H \parallel \mathbf{c}$ and is clearly observed as a function of both magnetic field and temperature. We demonstrate that the peak effect is due to enhanced vortex pinning by the twin boundaries, indicative of lattice softening prior to melting. In addition, we show evidence for a non-Ohmic behavior in the vortex liquid state due to depinning of the vortices from the two twin boundaries with increasing Lorentz force.

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The complex magnetic phase diagram of the high temperature superconductors has been the topic of much interest. Among the most salient features of the phase diagram is the theoretically proposed existence of a vortex lattice melting line which separates a vortex liquid phase from a vortex solid phase [1–3]. Recently, transport measurements on $YBa_2Cu_3O_{7-\delta}$ have shown indication that the melting line is of first order at least in clean untwinned crystals where an extremely sharp drop in the magnetoresistivity has been observed in addition to a pronounced hysteresis at a characteristic vortex melting field H_m and temperature T_m [4–7]. The angular dependence of the melting temperature $T_m(\theta)$ in $YBa_2Cu_3O_{7-\delta}$ has been successfully fitted to a Lindemann criterion for melting [5,8]. Furthermore, recent measurements [9] on untwinned crystals with electron irradiation induced point defects demonstrate that this first order transition is an inherent property of clean untwinned $YBa_2Cu_3O_{7-\delta}$ crystals.

An important tool for the study of vortex melting when thermodynamic equilibrium measurements are unavailable is the investigation of the behavior of the vortex lattice shear modulus C_{66} at the melting transition. In conventional superconductors like niobium and in amorphous Nb_3Ge films, the occurrence of a "peak effect" [10] whereby a sudden increase in the critical current J_c is observed just below the upper critical field H_{c2} and the two-dimensional melting field H_m^{2D}, respectively, has been ascribed to the softening of the tilt and shear modulus [11–13]. More recently, in high temperature superconductors, such a peak effect has been inferred from a dip in the in-phase fundamental susceptibility $\chi'(T)$ [14] and from the resonance frequency enhancement in a vibrating reed experiment [15]. In this Letter, we report on the direct observation of the peak effect in J_c as a function of *both* field and temperature from magnetotransport measurements for $H \parallel \mathbf{c}$ in a $YBa_2Cu_3O_{7-\delta}$ single crystal with only two twin boundaries. We show that unlike conventional superconductors where the peak effect occurs near H_{c2} [10], but more similar to amorphous Nb_3Ge films [13] and 2H-$NbSe_2$ [16], the peak effect in $YBa_2Cu_3O_{7-\delta}$ as a function of temperature and magnetic field occurs just below the vortex liquid to solid phase transition at T_m and H_m, respectively, much below H_{c2}. We directly identify the enhancement of the critical current at the peak to be related to the pinning by twin boundaries (TB). The present data suggest a softening of the shear modulus near the melting transition, enabling the vortex lattice to better adjust to the pin sites thereby increasing the volume pinning force. Moreover, we speculate that the peak in J_c separates a region of elastic vortex flow below the peak from plastic flow above the peak, possibly coming from vortex line (VL) dislocations as the shear modulus drops sharply to zero at the melting transition. In addition, we observe that the depinning of vortices from the two twin boundaries is distinctly different in the liquid and solid states, reflecting the change in the vortex lattice structure at T_m.

The crystal was grown at Argonne National Laboratory using the self-flux method [17]. The crystal dimensions are $0.45(l) \times 0.46(w) \times 0.016(t)$ mm^3 with $T_c(0) \sim 93.03$ K and width $\Delta T_c(0)$ (10%–90%) < 300 mK. The crystal had two twin boundaries parallel to each other oriented 45 deg from the crystal edge and separated by $d \sim 140$ μm as determined by polarized light microscopy. Four conductive silver pads were sintered onto the crystal at 400 °C for about six hours. Gold wires were attached to these pads with silver epoxy and cured for one hour at 120 °C, resulting in a contact resistance of less than 1 Ω. ac resistivity was measured using the standard four probe method with a measuring current density I_S between 1 and 100 A/cm^2 at 17 Hz directed parallel to the **ab** plane of the crystal. dc voltage-current characteristics were obtained with a nanovoltmeter while reversing the direction of the dc current to minimize thermal voltages.

The temperature dependence of the resistivity for magnetic fields parallel to the crystallographic **c** axis is shown in Fig. 1 for $I_S = 1$ A/cm^2. For $H \leq 0.5$ T, a single sharp "kink" is observed near $\rho = 10$ $\mu\Omega$ cm. This kink in the resistivity has been associated with a first order vortex freezing transition from a vortex liquid to

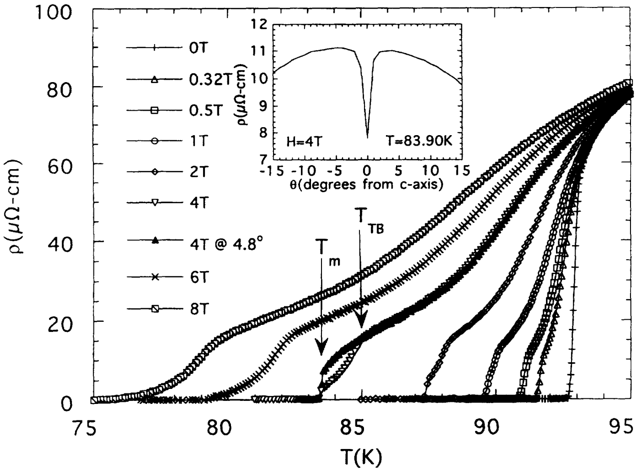

FIG. 1. Resistivity versus temperature of $YBa_2Cu_3O_{7-\delta}$ with two twin boundaries at several different magnetic fields. Also shown is the $H = 4$ T curve for magnetic field tilted at 4.8° from the **c** axis and the twin planes in a plane perpendicular to the current. Inset: Angular dependence of twin boundary pinning at $H = 4$ T and $T = 83.90$ K.

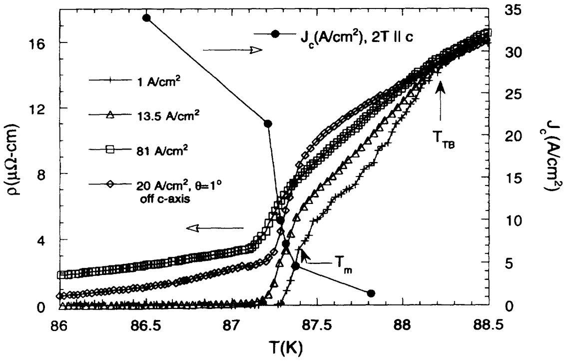

FIG. 2. Temperature dependence of the resistivity and the critical current at $H = 2$ T || **c** for different measuring currents. Also shown is the resistivity curve for a 1° tilt of the magnetic field off the **c** axis and the twin planes.

a vortex solid [4–7]. With increasing magnetic field, $H > 0.5$ T, the resistive height of this kink decreases, and a "shoulder" develops near $\rho = 15$ $\mu\Omega$ cm. The shoulder is fully developed by $H \geq 2$ T and remains constant in height while the kink is completely absent beyond $H = 6$ T. The shoulder corresponds to the onset of twin boundary pinning in the vortex liquid state [18] as shown by the comparison of the $H = 4$ T curves for $\theta = 0°$ and 4.8°, where θ is the angle between the **c** axis and the applied magnetic field in a plane perpendicular to the current. Tilting the magnetic field by 4.8° removes the shoulder at $T_{\rm TB}$ and recovers the kink at T_m. The inset to Fig. 1 shows the angular dependence of twin boundary pinning for $H = 4$ T at 83.90 K and demonstrates that for $\theta > 4°$ twin boundary pinning is absent, consistent with the resistivity curve for $\theta = 4.8°$. Figure 1 demonstrates that with increasing field the kink associated with the first order vortex liquid to solid transition is suppressed, as twin boundary pinning in the liquid state becomes established.

Figure 2 shows the expanded view of the resistive transition at $H = 2$ T || **c** near the TB pinning shoulder for several different measuring currents. We have chosen this field since the effects of both the onset of twin boundary pinning (shoulder at $T_{\rm TB} \sim 88.20$ K) and of vortex melting (kink at $T_m \sim 87.40$ K) are observed in the resistivity curve for $I_S = 1.0$ A/cm^2. Also plotted on the same figure is the corresponding temperature dependence of the critical current obtained from dc voltage-current characteristic measurements using a voltage criterion of 0.1 μV. Unlike previous measurements in densely twinned crystals where the stronger pinning in this temperature and field region have shown only Ohmic behavior [18] near $T_{\rm TB}$, the resistivity here is distinctly non-Ohmic just below $T_{\rm TB}$, due to the depinning of the vortex liquid from the two twin boundaries in the sample. At $I_S = 81.0$ A/cm^2, weak twin boundary pinning still remains in the vortex liquid state. When the magnetic field is tilted $\theta = 1°$ from the twin planes, twin boundary pinning is reduced, and the resistivity between $T_{\rm TB}$ and T_m is higher than when $\theta = 0°$, even for a lower transport current of 20 A/cm^2. At T_m, the two curves cross, as the shear modulus develops, leading to pinning of the entire vortex lattice and a consequent sharp rise in the critical current. This is consistent with the association of the kink in the resistivity at T_m with a vortex liquid to solid phase transition.

The temperature dependence of the resistivity at $H = 0.5$ T in the region just below the kink at $T_m = 91.43$ K, which here also corresponds to $T_{\rm TB}$, for different tilt angles of the magnetic field with respect to the **c** axis is shown in Fig. 3(a) for a measuring current of $I_S = 40$ A/cm^2. At $\theta = 0°$ (H || **c**), the vortices are aligned with the two twin boundaries and the resistivity goes to zero at $T = 90.71$ K. However, at $T \sim 90.60$ K, we observe a sharp increase in the resistivity, followed by a gradually decreasing monotonic behavior at lower temperature. With increasing tilt angle, the strong pinning due to twin boundaries just below T_m decreases rapidly, leading to a substantial rise in the resistivity value at $T \sim 90.70$ K. At $\theta = 3°$, the "dip" in the resistivity is almost negligible, and at 10° the dip altogether disappears. This behavior corresponds to the critical angle of twin boundary pinning shown in the inset of Fig. 1 where pinning disappears beyond $\theta_c = 4°$.

The central result of the Letter is shown in Fig. 3(b) where we plot the critical current as a function of temperature for different tilt angles of the magnetic field with respect to the **c** axis and the twin planes. As before, the critical current was determined from dc voltage-current measurements using a criterion of 0.1 μV. The critical current density shows a clear peak for all angles

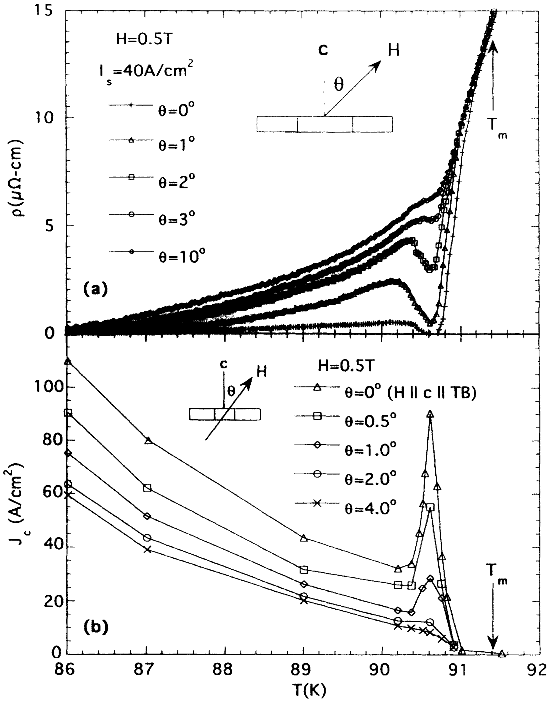

FIG. 3. (a) Temperature dependence of the resistivity below T_m at different angles of the magnetic field with respect to the **c** axis and the twin planes. (b) Temperature dependence of the critical current for different orientations of the magnetic field with respect to the twin boundaries, showing the peak effect just below T_m.

except $\theta = 4°$. The largest value of the critical current ~ 90 A/cm^2 occurs at $\theta = 0°$. The peak temperature $T_p \sim 90.60$ K remains constant for all angles and is situated just below the vortex lattice melting temperature $T_m = 91.43$ K. Using a larger voltage criteria of 1.0 μV did not change the qualitative features of the peak. This result demonstrates directly that this peak effect in $YBa_2Cu_3O_{7-\delta}$ is a precursor to melting and can be attributed to pinning by the two twin boundaries in the sample. (We have also observed a peak effect just below the melting transition in untwinned crystals [19]. In this case, the peak effect arises from pinning due to point defects since, unlike twin boundaries, no angular correlation with the peak was observed.) As the melting transition is approached from below, the softening of the shear modulus enables the lattice to adjust into a more favorably pinned configuration, pinning in this case being supplied by the twin boundaries. As the shear modulus weakens further, it can no longer prevent shear due to the competition of the pinning force and the Lorentz force, causing plastic deformation of the lattice as parts of the lattice begin to move independently. This accounts for the rapid decrease in J_c above $T_p = 90.60$ K. At T_m, the shear modulus finally goes to zero, and the critical current vanishes altogether. In this picture the peak in J_c separates two regimes of vortex flow: elastic flow below the peak and plastic flow above the peak. If plastic flow occurred below the peak, J_c would monotonically decrease as the shear modulus weakens in approaching T_m, contrary to our results.

The behavior of the critical current and the corresponding resistivity at $T = 90.20$ K as a function of magnetic field $H \parallel \mathbf{c}$ is presented in Fig. 4 for three different measuring currents. At $I_S = 6.6$ A/cm^2, the resistivity remains zero up to 0.7 T, followed by a sharp increase as one approaches the melting field $H_m \sim 0.82$ T for this temperature. With increasing measuring current (i.e., $I_S = 20$ and 40 A/cm^2), we observe a finite resistivity in the range of magnetic fields between 0.3 and 0.7 T. In this field range, the resistivity is characterized by a sharp jump at 0.32 T, followed by a gradual increase up to 0.5 T beyond which the resistivity decreases. At 0.68 and 0.7 T, the resistivity rises very sharply again for $I_S = 40$ and 20 A/cm^2, respectively, at the onset of plastic deformation prior to melting at $H_m = 0.82$ T. Also shown in Fig. 4 is the corresponding critical current as a function of magnetic field for the same temperature $T = 90.20$ K. The critical current drops sharply between $H = 0.28$ and 0.32 T, corresponding to the sudden jump in the resistivity at $H = 0.32$ T for $I_S = 40$ A/cm^2 where the measuring current is approximately equal to J_c. This jump is accompanied by a hysteresis of about 200 Oe. Between 0.32 and 0.6 T the critical current density decreases monotonically, whereupon it rises beginning at 0.6 T to a maximum at 0.68 T corresponding to the sharp drop in resistivity. Beyond 0.69 T, the critical current decreases rapidly towards zero, as the resistivity sharply increases. Thus the field dependence of the critical current and the resistivity near the melting field display the same peak effect as the temperature de-

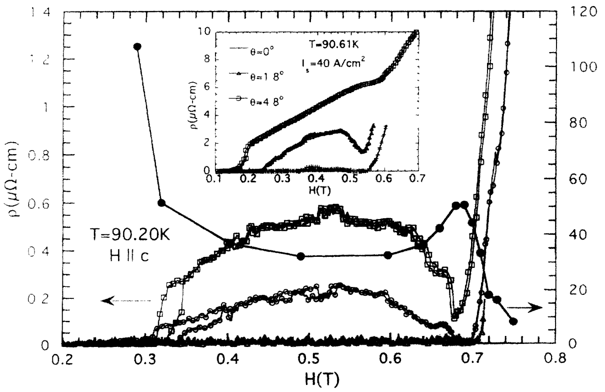

FIG. 4. Resistivity versus field for $H \parallel \mathbf{c}$ at $T = 90.20$ K for $I_S = 40$ (□), 20 (○), and 6.6 A/cm^2 (△) and the field dependence of the critical current (●). Inset: Field dependence of the resistivity at $T = 90.61$ K for field orientations of $\theta =$ 0°, 1.8°, and 4.8°, with respect to the **c** axis and the twin boundaries.

pendence near the melting temperature presented earlier in Fig. 3.

We interpret the hysteric jump in the resistivity at 0.32 T as the transition from a region where *most* vortices are stationary and pinned by the twin boundaries to a region where the vortex lattice moves as a whole. This can be seen from the angular and the current dependence of the field at which the hysteric jump in the resistivity occurs and can be correlated to the behavior of J_c. For example, at $T = 90.61$ K, when the magnetic field is tilted away from the twin planes (i.e., θ is increased), J_c decreases, and the field where finite resistivity occurs decreases concomitantly (inset to Fig. 4). It is surprising that only two twin boundaries suffice to pin the entire vortex lattice at low fields. The total force on a row of vortices for a measuring current of 40 A/cm^2 and a field of 0.32 T is $f_p = jBdt = 2 \times 10^{-4}$ N/m and has to be balanced by the pinning force of the twins. This is in agreement with the estimate of the twin boundary pinning force from the lock-in transition angle [20], giving a pinning force per unit length $f_p \sim 6 \times 10^{-6}$ N/m at $H =$ 58 Oe and $T = 85$ K, which when adjusted for our field difference (3200/58 Oe) yields $f_p \sim 3.4 \times 10^{-4}$ N/m at 0.32 T. It is also comparable with the calculations of Kes *et al.* [21], yielding a small effective scattering probability $p_{\mathrm{tr}} \sim 0.01$ for the twin boundary. A possible explanation for the rapid increase of J_c below 0.32 T is the dispersive nature of C_{44} [12]. As noted in Fig. 3 for $J_c(T)$, an increase in θ causes the peak effect in $J_c(H)$ to disappear (inset Fig. 4): While the resistivity goes to zero near 0.55 T for $\theta = 0°$, a finite resistivity is clearly observed for $\theta = 1.8°$ and the dip in the resistivity disappears completely at $\theta = 4.8°$. The resistivity between 0.2 and 0.55 T at $\theta = 4.8°$ shows linear behavior reminiscent of the Bardeen-Stephen model for flux flow [22].

Investigation of the peak effect at different fields and temperatures shows that its appearance is limited to low fields between $H = 0.35$ and 1.5 T in this crystal. A recent theoretical investigation [23] using the perturbation theory approach to evaluate the mean velocity of a moving vortex array pinned by twin boundaries yields an exponential dependence of the critical current J_c on C_{66} at intermediate fields in the region where the dispersion of the tilt modulus C_{44} is important. This may account for the narrow field region where the peak effect is observed in this crystal.

In summary, we have shown direct evidence of a peak effect in a single crystal of $YBa_2Cu_3O_{7-\delta}$ for $H \parallel \mathbf{c}$ as a function of both temperature and magnetic field. Unlike the peak effect in conventional superconductors, the peak effect in $YBa_2Cu_3O_{7-\delta}$ occurs just below the vortex liquid to solid phase transition as a precursor to vortex melting. We demonstrate conclusive evidence that the peak effect arises from pinning due to the two twin boundaries in this sample. Our results suggest that the shear modulus is considerably softened near the vortex melting transition, thus enhancing the pinning effect of the twin boundaries on the vortices. Beyond the peak, the Lorentz force induced by the field and the transport current, and the rapid drop of the shear modulus as the melting transition is approached from below, lead to plastic deformation of the vortex lattice probably through the creation of vortex line dislocations. In this interpretation, the peak separates the region of elastic flow from plastic flow. In addition, we showed for the first time the depinning of a vortex liquid from two twin boundaries. A change in the pinning behavior due to twin boundaries is observed at T_m, consistent with the earlier claim of a melting transition in the vortex system.

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