Direct Observation of Intrinsic Pinning in YBCO Thin Films

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The force-displacement response of vortices pinned in epitaxial YBCO thin films has been determined using an ac transport technique. The effective curvature of the pinning wells and the elastic limit of the displacement of the vortices before depinning are obtained. For magnetic fields parallel to the c axis the elastic limit is about a coherence length, consistent with core pinning. When the field is applied parallel to the ab planes structure appears in the force-displacement curve before the onset of flux flow. These "steps" appear at vortex displacements which are closely related to the spacing between the superconducting layers, providing direct evidence for intrinsic pinning.

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Most measurements of pinning effects in superconductors involve measuring the critical current density. However, it is also possible to measure two other parameters, the effective restoring force on the vortex lattice in the linear regime [1–3] and the interaction distance, or elastic limit, of reversible displacements of the vortex lattice [4]. Any theory should be consistent with measurements of these properties as well as the critical current density. Interpretation of the linear restoring force is as difficult as that of the critical current density in that it is dependent on the specific summation model used. However, the elastic limit is a distance which, although affected by collective pinning effects, should be directly related to some typical length scale in the sample. In particular, large elastic displacements are incompatible with closely spaced pinning centers, or intrinsic pinning. Although the idea of intrinsic pinning (by the pairs of CuO_2 planes making up the superconducting layer in the $YBa_2Cu_3O_{7-y}$ unit cell) is attractive and plausible, nearly all measurements show only a large increase in the critical current density, J_c, for fields parallel to the planes. The inherent anisotropy of the superconducting parameters will give a similar peak, but it is clear that intrinsic pinning must involve an elastic limit for vortex movement comparable to the superconducting plane spacing.

Measurements can be made either inductively from the susceptibility [3] or using a resistive type of measurement [5]. The former has the advantage of larger signals, and in the case of plane geometry, the possibility of measuring the complete force-displacement curve. However, since the flux can move in two directions, and will choose the easier, it is not possible to investigate intrinsic pinning by the layer structure. In other words, when a field is applied parallel to the ab planes, any ac modulation of the field will result in both in and out of plane movement of the vortices. The resistive geometry involves low signal levels and the interpretation is more difficult, but the flux can be forced to move across the atomic planes in the sample. This is required for the investigation of intrinsic pinning, which should be clearly indicated by a maximum reversible displacement of the order of the superconducting layer spacing.

Measurements on conventional superconductors have given displacements of the order of a quarter of the vortex spacing in many cases. This is predicted by simple strong pinning models [6,7], but the distance can be very variable and no general theory is available. However, measurements on Nb_3Al gave distances comparable to the coherence length [8]. The first measurements on high T_c materials were on $YBa_2Cu_3O_{7-y}$ (YBCO) powders using the susceptibility [9]. These showed reversible displacements of the order of 20 nm, which is much larger than the coherence length and is incompatible with the dense array of small pinning centers usually assumed in high T_c materials. The first resistive measurements were made by Tomlinson, Przyslupsky, and Evetts [10] on thin films of YBCO and showed very much smaller reversible displacements, comparable with the coherence length.

Epitaxial YBCO films were prepared on $LaAlO_3$ substrates using a high oxygen pressure dc sputtering technique [11]. The c axes are always normal to the film surfaces. As grown the films had a linear variation of normal state resistance with temperature and the intercept at 0 K was 2% of the room temperature value. The critical temperatures in the as-prepared state are always > 88.5 K with typical transition widths of less than 1.2 K. Appropriate postannealing in oxygen shifts the T_c to above 90 K and results in narrowing of the transition width [12]. Standard photolithography and wet etching techniques were used to pattern tracks 1 mm long and 20 μm wide in the films, with pads to provide voltage and current contacts in the standard four probe configuration. The voltage contacts were 1 mm apart.

Results on two films are reported. The first film, which hereafter will be referred to as A, had a thickness of 190 nm, a T_c ($\rho=0$) of 88.6 K, and a zero field J_c of 1.1×10^6 A/cm^2 at 77 K. The second, referred to as sample B, had a thickness of 250 nm, a T_c of 89.1 K, and a J_c of 0.63 $\times10^6$ A/cm^2 at 77 K in zero field. An ac current was passed through the sample and the voltage measured with a two phase lock-in amplifier. The frequency was chosen to be 3.3 kHz to maximize the sensitivity without encountering viscous effects in the sample or resonant or skin depth effects in the probe. Careful checks showed the results to be independent of frequency between 1 and 5 kHz.

However, extreme care had to be taken with minimizing spurious signals arising both from inductive coupling in the leads and from common mode rejection problems. These were removed using a passive ac bridge circuit. The phase was set so that "in phase" implies a voltage in phase with the current, i.e., a pure resistance. This was determined using a standard resistance in series with the sample. Confirmation of the correct setting could be obtained by seeing that there was no in-phase signal at low amplitudes (viscous effects will be negligible at these frequencies, a fact which was confirmed by the lack of frequency dependence in the results). Background signals were nulled out with the sample in the Meissner state at low currents.

The sample itself was mounted on a brass block which could be rotated through 360° from outside the cryostat using a stepper motor with 0.01° control. The temperature was controlled to better than 50 mK. A magnetic field of up to 8 T was applied using a superconducting solenoid in the persistent mode. The measurement sensitivity was slightly less than 1 nV using a time constant of 3 s on the lock-in amplifier.

The measurement temperature was chosen to be 68 K where intrinsic pinning effects are known to exist in YBCO [13] in order first to avoid significant thermal activation effects, but second to be at sufficiently high temperatures that the critical current may easily be passed while maintaining thermal equilibrium between the sample and the thermometers. The I-V characteristic for the sample is obtained from the resistive (in-phase) signal. Control experiments showed that these results were identical to those obtained with a dc current. A criterion of 30 nV/mm was used in defining J_c. (All amplitudes in this report have been converted from rms to half peak-to-peak amplitudes.)

In most previous measurements [3,5,10], the maximum information is obtained by setting the lock-in with a wide band filter so that all harmonics are included. In these circumstances the signal is directly proportional to the flux passing the contacts and therefore to the distance moved by the vortex lattice. The sensitivities required for this study made wide band measurements extremely difficult without enormous averaging, so in these experiments we used a narrow filter and measured the amplitude of the fundamental only. Since our conclusions are

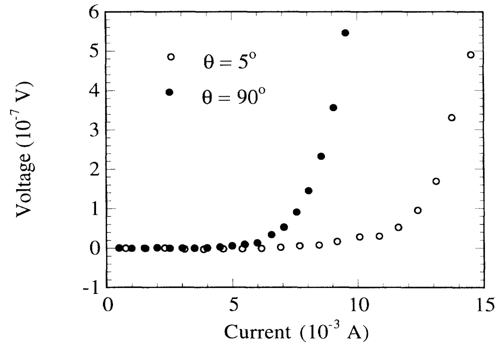

FIG. 1. The I-V characteristics of sample A at 68 K and 4 T with the magnetic field aligned at 90° and 5° to the ab planes.

drawn only from the linear region and its limit, this procedure does not cause any problems. It was in fact found that the response was very linear until close to the point at which flux flow started.

Force-displacement curves are obtained from the inductive (out-of-phase) signal. In the linear low amplitude region with a magnetic field B, vortices oscillating as $d_0\sin(\omega t)$ generate an electric field $\omega B d_0\cos(\omega t)$. Here d_0 is the displacement of the vortex and ω is the frequency. Hence the inductive voltage gives a direct measurement of the vortex displacement. A sensitivity of 1 nV at 1 T and 3.3 kHz with contacts 1 mm apart means that we can measure movements of 0.05 nm. The force driving the oscillation is the Lorentz force, $\mathbf{B}\times\mathbf{J}$, per unit volume.

Figure 1 shows the resistive I-V characteristics for sample A at 68 K with 4 T applied 90° and 5° away, respectively, from the ab planes of the sample. The force-displacement curves for the film under the same conditions are shown in Fig. 2. The arrows show the point at which the critical current is reached. It is apparent that the form of the curves is as expected, a linear regime is exhibited before the displacement starts to grow as depin-

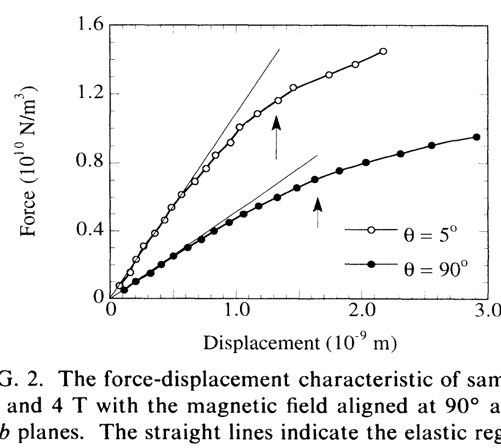

FIG. 2. The force-displacement characteristic of sample A at 68 K and 4 T with the magnetic field aligned at 90° and 5° to the ab planes. The straight lines indicate the elastic regime, the arrows indicate the points at which the critical current is reached, and the solid curves are guides for the eye.

ning begins, and the driving force approaches the maximum pinning force. Note that this is only strictly the force-displacement curve of the pinning centers in the linear region. Above J_c the signal will increase with the current even if the pinning force remains constant and a detailed analysis of the Fourier components expected is required.

Figure 3 shows the force-displacement behavior of film *A* at 4 T when the applied field is aligned with the *ab* planes. Structure is apparent at regular intervals in the displacement. In order to preclude spurious sample or field dependent effects, the measurement was repeated on sample *B* at 2 T and this result is also presented in Fig. 3. The fact that the steps occur at the same displacements and that they only appeared in a narrow range of angles within about 2° of the parallel configuration is strong evidence that the steps are directly related to a characteristic distance in the sample. It is evident from the figure (which shows half peak-to-peak displacements) that "steps" occur in the voltage at multiples of a peak-to-peak displacement of 1.0 ± 0.1 nm for both samples. This distance is very close to the *c*-axis lattice parameter for the unit cell in YBCO [14]. The "apparent" poor quality of these data results not from lack of resolution, but from the small signal levels in these measurements. Figure 4 shows the resistive *I*-*V* curve for sample *B* corresponding to the data presented in Fig. 3. At the first two of the steps in the force-displacement curve, there is a small feature in the *I*-*V* characteristic indicating an increase in the dissipation as shown by the arrows in the figure. The feature corresponding to the third step may have been washed out by the flux flow voltage. This curve is representative of the behavior of both samples but is clearer for sample *B*.

We begin a discussion of these results with the case of the field parallel to the *c* axis. First, the results in Fig. 2 show displacements at the onset of dissipation which are comparable in size to the coherence length. We emphasize here that at 3.3 kHz and 4 T, a displacement of 1 nm will generate a voltage of 19 nV along a 1 mm track. Our resolution is better than this and results in the smooth curves in Fig. 2 which are representative of all data we have measured when the magnetic field is not carefully aligned ($\theta > 1°$–$2°$) with the *ab* planes. This precludes the possibility that the "steps" in Fig. 3 are a result of either the experimental resolution or the measurement technique. Similar small values for the elastic limit of the displacement were also found by Tomlinson, Przyslupsky, and Evetts [10]. This is consistent with core pinning by closely spaced pinning centers and not consistent with strong widely spaced centers which the flux lattice could bend between. These distances are much less than those measured magnetically in YBCO powder [9]. This can be attributed to the much lower critical current density in the powder, implying a much wider spacing between pinning centers. It is interesting to see that the results are very similar to those [8] on Nb_3Al, which has similar superconducting parameters to YBCO in this orientation.

The restoring force for reversible displacements may be calculated from the slope of the volume pinning force versus displacement curve. The value obtained from Fig. 2 is 1.1×10^{19} N/m^4 for the case of field parallel to the *c* axis. This is lower than that reported by Tomlinson, Przyslupsky, and Evetts [10] at 4 T and 15 K but this can be explained by the fact that we are working at a higher temperature. The force is larger than that of Esquinazi [15] which is to be expected because of the much higher critical currents of films as compared to single crystals. It leads to a pinning penetration depth of about 0.3 μm which is not much larger than the London penetration depth, again consistent with a dense array of pinning centers.

Rotating the field to within 5° of the *ab* planes leads to

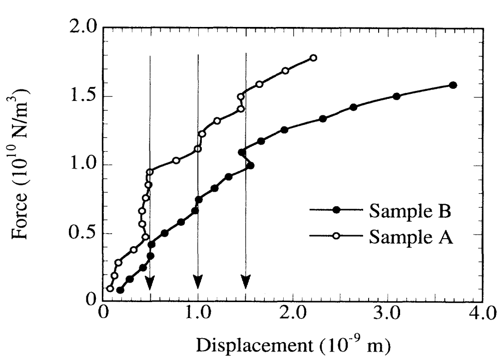

FIG. 3. Force-displacement curves for samples *A* and *B* at 68 K and 4 and 2 T, respectively, when the field is accurately aligned along the *ab* planes of the samples. The arrows indicate the positions of the steps in the curves. The solid curves are again for clarity.

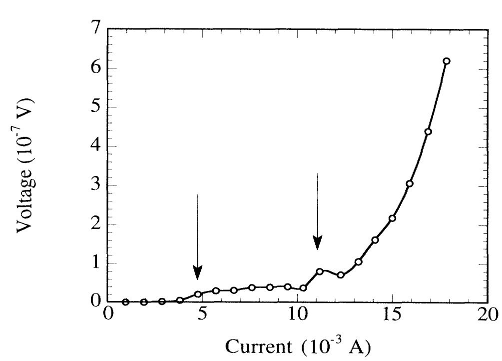

FIG. 4. The *I*-*V* characteristic of sample *B* at 68 K and 2 T when the field is aligned along the *ab* planes of the sample. Note that dissipation increases at points corresponding to two of the steps in Fig. 3, as marked by the arrows. The solid curve is a guide for the eye.

an increase in the effective curvature consistent with the increase in the critical current. The elastic limit of displacement gets smaller as expected and is approximately consistent with the decrease in coherence length. It seems less consistent with a model in which kinks in the vortices move in the planes. If the displacement of the sections normal to the planes remains constant then the observed displacements would be expected to drop by a factor $1/\sin\theta$, i.e., about 11 instead of the factor of 2 observed when the field is moved from parallel to perpendicular to the c axis.

For fields nearly parallel to the planes we expect any kinks to slide out and a "lock-in" transition to take place, with the flux line cores lying between the superconducting planes. The short elastic limit found when the field is parallel to the *ab* planes is not on its own sufficient evidence for intrinsic pinning since a rather short limit is also found when the magnetic field is parallel to the c axis. However, the features in Fig. 3 provide stronger evidence. For film B, the applied field is 2 T and an isotropic vortex spacing at this field would be 34 nm. For sample A, at 4 T, the spacing is 24 nm. The anisotropic predictions [16] would suggest, for an assumed [17] anisotropy ratio γ of 8 for YBCO, vortex spacings in the c direction of 10 and 7 nm at 2 and 4 T, respectively. Thus there are expected to be between 5 and 25 vortices threading the film thickness depending on the choice of γ.

The following picture would account for a step in the force-displacement curve. The flux moves relatively freely between the planes, but when the core comes up against a superconducting layer it experiences a stiffening of the pinning force. The amplitude does not increase until a significantly larger current is applied, when it is pushed passed the barrier causing a sudden increase in loss. Thus the observed features occur at displacements which almost correspond to the periodicity of the condensation energy, or the c axis unit cell dimension. The fact that the value measured is slightly smaller than the c axis unit cell parameter may be explained by the finite vortex core radius.

It is less easy to see why there should be more than one step. If the (intrinsic) potential wells are all identical, then when a sufficiently large force is applied a pinned vortex should depin and move into the flux flow state, having enough energy not to be trapped in any of the other wells. However, it seems to us reasonable to assume that these films are not absolutely uniform through their thickness. Imperfect epitaxy at the substrate would result in lattice distortion and internal stresses. The exposed surface will also have modified superconducting properties. Finally, it may be plausible that the properties of the films change slightly and continuously through their thickness during fabrication. It is not clear what determines the precise number of steps. It is likely that they would be washed out in large samples so that the number of steps seen will depend on the sample thickness and the number of vortices in the sample.

In conclusion, measurements of the force-displacement curves of the vortex lattice are a useful technique which is complementary to the usual dc measurements for investigating pinning effects. The elastic limits found for in plane movements are very small and suggest pinning by a dense array of small pinning centers acting by core pinning. The curves for vortices moving perpendicular to the planes show steps at displacements corresponding to the modulation distance of the order parameter along the c axis. These can be explained as an effect of intrinsic pinning by the copper oxide layers.

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