Observation of a Field Induced Transition in the Vortex Solid of $DyBa_2Cu_3O_7/(Y_{1-x}Pr_x)Ba_2Cu_3O_7$ Superlattices

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We report on the observation of a change in the field dependence of the critical current density J_c of $DyBa_2Cu_3O_7/(Y_{0.45}Pr_{0.55})Ba_2Cu_3O_7$ superlattices at a characteristic magnetic field H_s^*. This change shows up as an abrupt transition when analyzing the current-voltage (I-V) characteristics in the framework of the vortex glass and collective flux creep theories. This behavior can be traced back to a sudden reduction in the collective pinning energy U_c above H_s^*, and may reflect a softening transition of the vortex lines in the vortex solid. H_s^* is very similar to the characteristic field H_l^* in the vortex liquid phase, which we interpreted to be due to entanglement.

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The high superconducting transition temperature T_c, the extreme type-II character, and strong anisotropies allow for a large variety of phenomena in the mixed state of high T_c materials [1]. It is now well established that one has to distinguish between two regimes in the mixed state: a high temperature vortex liquid with Ohmic resistivity down to the lowest currents and a low temperature vortex solid with a nonzero critical current density. The existence of a glass transition (pinned systems) or a melting transition (clean systems) between these phases has been revealed through extensive studies of single crystals and thin films of high temperature superconductors [2,3].

In addition, recent small angle neutron diffraction measurements [4] and muon-spin rotation experiments [5] on single crystals of $(Bi_{2.15}Sr_{1.85})CaCu_2O_8$ (BSCCO) have shown the existence of a field induced and temperature independent transition in the vortex solid. Above a characteristic magnetic field, $B \sim 50$ mT in this case, the vortex lattice loses its rigidity along the vortex line. Such a transition may theoretically be correlated to a decoupling of the vortex pancakes in neighboring superconducting layers [6] or alternatively to a transition into a supersolid state [7]. A change in the nature of the vortex solid state should, in principle, also result in a change of the vortex dynamics and in the flux creep behavior.

Most measurements of vortex dynamics so far have concerned pure superconducting compounds, restricting the studies to a specific material dependent anisotropy of the vortex lattice. Artificially made superlattices give, in principle, the possibility of changing the anisotropy almost arbitrarily. $YBa_2Cu_3O_7/PrBa_2Cu_3O_7$ (YBCO/PrBCO) superlattices have been extensively studied so far [8]. The coupling between the YBCO layers disappears, however, when the thickness of the insulating PrBCO layers exceeds a few unit cells [9]. On the other hand, by using a nonmetallic $(Y_{0.45}Pr_{0.55})Ba_2Cu_3O_7$ (YPrBCO) alloy, which has a much lower resistivity than PrBCO, a stronger coupling between the superconducting layers can be obtained [10]. Indeed, extensive measurements of thermally activated resistivity in the vortex liquid of DyBCO/YPrBCO superlattices has shown that the coupling along the vortex line persists up to distances of about 400 Å [11]. Furthermore, the coupling gives an effective anisotropy which is intermediate between the ones in YBCO and in BSCCO and these superlattices can thus be considered as a promising system for studying vortex dynamics.

Recently we have used I-V characteristics to determine the liquid-solid transition line in these materials [12]. In the present work, we concentrate on the I-V characteristics in the vortex solid phase. From these results we determine the critical current density J_c and fit the I-V characteristics using a vortex glass and collective flux creep relation. We observe a crossover in $J_c(H)$ at a field H_s^* which can be traced back to a sudden change in the collective pinning energy U_c. Furthermore, H_s^* is inversely proportional to the sample thickness and correlates with a characteristic field H_l^* in the vortex liquid at which we observed a change in the field dependence of the activation energy, U, of flux motion [10,11].

For the present study, we used samples consisting of N 24 Å (two unit cells) thick DyBCO layers separated by 96 Å (eight unit cells) thick YPrBCO layers and deposited onto a 230 Å thick YPrBCO buffer. We concentrate here on two samples: one consisting of $N = 15$ DyBCO layers and another one consisting of $N = 5$ layers. The preparation and characterization of the samples used in this work have been described in several publications [10,11,13].

The I-V characteristics were measured using a conventional four-probe technique. Bridges for the I-V measurements were made by a diamond scratcher giving a typical width of about 100 μm and a length of about 1 mm. Comparison between I-V characteristics measured in liquid He and in He gas confirmed that the current-induced heating of the sample was negligible in He gas. J_c was determined by an electric field criterion, $E \sim 2$ μV/cm. The observed magnetic field dependencies of J_c did not depend on the choice of a specific criterion. However, it is important to keep in mind that the experimental J_c, defined as the onset of dissipation, is different from the theoretical one because the thermally activated flux creep may lead to a nonzero resistivity even if the applied current is much lower than the theoretical critical current.

The magnetic field dependence of J_c for the $N = 15$ superlattice is shown in Fig. 1. $J_c(H)$ can be described by a logarithmic law for fields lower than a characteristic field $\mu_0 H_s^* \approx 1$ T. Above H_s^*, $J_c(B)$ is better described by an exponential magnetic field dependence as shown in the inset of Fig. 1. Although the change in the magnetic field dependence of J_c is less obvious above 20 K, our data indicate that H_s^* is nearly temperature independent.

We now turn to a more careful description of the I-V characteristics. Since the films have high J_c, implying efficient pinning, the vortex system is most likely in a glassy state. According to the collective flux creep theory [14], the I-V characteristics should then be described by

$$E/J = \rho_0 \exp\left[-\frac{U_c}{kT}\{(J_c/J)^\mu - 1\}\right], \tag{1}$$

where U_c is the collective pinning energy, k is the Boltzmann constant, and T is the temperature. The exponent μ depends on the different regimes of collective creep, and $\rho_0 \approx \rho_f$, the flux flow resistivity. The -1 in the exponent is included to reproduce the Anderson-Kim result, i.e., the effective activation energy should vanish at $J = J_c$. This expression is formally equivalent to the vortex glass relation [1],

$$E/J = \rho_0' \exp[-(J_0/J)^\mu], \tag{2}$$

where ρ_0' and J_0 are fitting parameters (the relationship between ρ_0 and ρ_0' is discussed later). Since Eq. (2) has a simpler form and gives a more straightforward analysis, we start by using it to describe our data. From Eq. (2), one can easily get

$$\frac{d\ln(E/J)}{dJ} = J_0^\mu \mu J^{-(\mu+1)}. \tag{3}$$

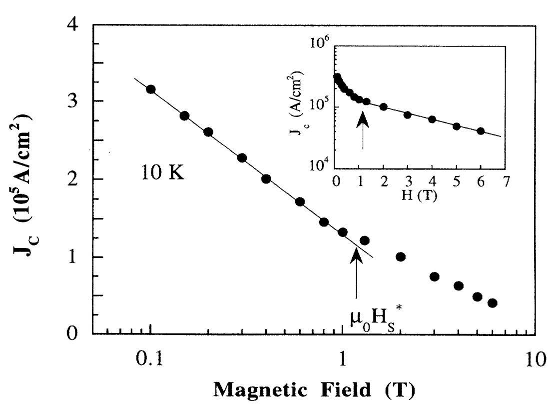

FIG. 1. Magnetic field dependence of J_c at 10 K. The arrow indicates the magnetic field H_s^* when J_c changes its magnetic field dependence. The solid line represents the logarithmic field dependence of J_c. The inset shows the observed exponential field dependence of J_c above H_s^*.

By plotting $d\ln(E/J)/dJ$ vs J, as shown in the inset of Fig. 2, one can now *uniquely* determine the parameters μ and J_0. The observed straight lines in the double logarithmic plot of $d\ln(E/J)/dJ$ vs J prove successful fitting and suggest glassy behavior in our I-V characteristics.

As shown in Fig. 2, there is an abrupt change in J_0. The end of the transition is almost temperature independent and corresponds to H_s^* as defined above from the critical current. However, the onset field H_{on} of the transition is temperature dependent so that the width of the transition increases with increasing temperature. On the other hand, as shown in Fig. 3(a), the exponent μ decreases with increasing magnetic field, a plateau appears when μ equals 1.5, and μ decreases again above the characteristic field H_s^*. Large values of μ (>1.5) as observed at low magnetic fields have not been predicted from the collective creep theory [14].

Having determined J_0 and μ from Eq. (3), we can now obtain ρ_0' from Eq. (2). The result is shown in Fig. 3(b), and we notice the striking nonmonotonous behavior of ρ_0'. The dramatic behavior of J_0 and ρ_0' clearly suggests a change in the mixed state or in the vortex dynamics at the transition. We now show that both variations can be understood as resulting from an abrupt reduction of the collective pinning energy U_c. From Eqs. (1) and (2), one expects that the experimentally determined ρ_0' using Eq. (2) includes a term $\exp(U_c/kT)$ due to the additional term -1 in the exponent in Eq. (1), whereas $\rho_0 \approx \rho_f$. The experimentally determined ρ_0' is thus given by

$$\rho_0' \approx \rho_f \exp\left\{\frac{U_c}{kT}\right\}. \tag{4}$$

The jump of ρ_0' is interpreted as resulting from a rapid decrease of the collective pinning energy U_c because the exponential term in Eq. (4) is dominant. To confirm the rapid decrease of U_c, we calculate U_c from a second and independent relation,

$$\frac{U_c}{kT} = \left\{\frac{J_0}{J_c}\right\}^\mu, \tag{5}$$

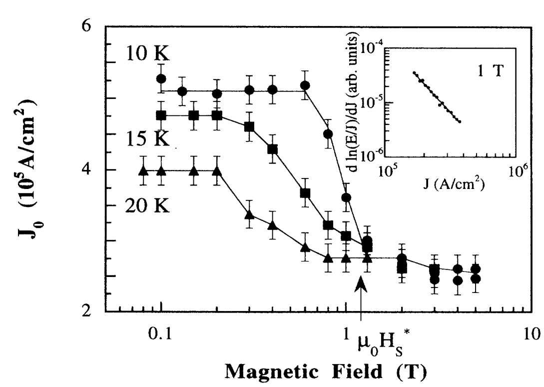

FIG. 2. Magnetic field dependence of the scaling current density J_0 at several temperatures. The inset shows the fitting of the I-V characteristics (see text). The solid lines are guides for the eye.

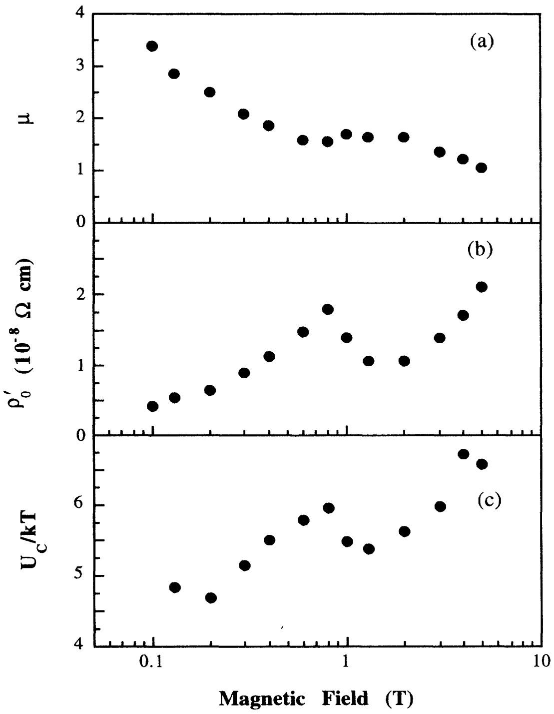

FIG. 3. Magnetic field dependence at 10 K of the exponent μ (a), the resistivity ρ_0' (b), and the activation energy U_c (c).

obtained from Eqs. (1) and (2). Here we use values of J_0 and μ determined from the $d\ln(E/J)/dJ$ vs J plot together with the experimental J_c. The magnetic field dependence of U_c/kT calculated from J_c and J_0 using Eq. (2) is shown in Fig. 3(c). This $U_c(H)$, determined independently of ρ_0', also shows an anomaly at a field corresponding to the transition in J_0. The consistency between the two analyses is clear evidence for the rapid change of U_c. Moreover, the magnitude of the jump in ρ_0' can be quantitatively explained by the jump of U_c and Eq. (4).

In order to probe the total thickness dependence of the described results, we performed an identical analysis for the $N = 5$ sample. The qualitative behavior of J_c and the fitting parameters for this sample are the same as that of the $N = 15$ sample. However, J_c is enhanced by a factor of $1.5-2$ in the thinner sample, and $\mu_0 H_s^* \sim 3$ T; this result points to a proportionality of H_s^* to the inverse of the total thickness, $H_s^* \sim 1/N$. On the other hand, the onset of the transition H_{on} seems to be thickness independent, suggesting a different origin of both $H_{\text{on}}(T)$ and H_s^*.

The sudden decrease of U_c at H_{on} can be related to a collapse of the correlation volume of vortices. This decrease might correspond to the quasi-2D crossover at a field $H_{2\text{D}}$ in the vortex solid observed recently by Ryu *et al.* from computer simulations of the three- to two-dimensional decoupling in BSCCO [15]. According to these authors, the decoupling is not complete but results in a softening of the flux lines, which can account for the recent results from neutron data in BSCCO [4]. The identification of H_{on} with this crossover is further supported by its thickness independence and its decrease with increasing temperature. In fact, an increase in temperature should cause a reduction of the interlayer coupling and thus lower the crossover field.

Recently, we found that the field dependence of the activation energy for flux motion in the liquid phase changed at a characteristic field H_l^*, and it was discussed that this field might correspond to the onset of entanglement of the vortex liquid [16]. Remarkably, the characteristic fields H_l^* in the vortex liquid and H_s^* in the vortex solid have the same thickness dependence and correlate very well. These results are summarized in the phase diagram shown in Fig. 4, where we have also indicated the vortex glass transition temperature $T_g(H)$ as determined from the change in curvature in the I-V characteristics [12].

From the description of Ryu *et al.* [15], above $H_{2\text{D}}(T)$ the vortices remain essentially 3D but are able to wander over distances of about a tenth of the vortex lattice constant, from layer to layer, to better accommodate the pinning potential. Consequently, as H is further increased an entangled solid might appear, in some sense similar to the supersolid phase predicted for clean systems [7]. Our results suggest that H_s^* correspond to this second transition, which should be thickness dependent.

It is interesting to note that the characteristics of our samples (small thickness and intermediate anisotropy) allow the separation of the two transitions, which in bulk samples and/or materials with extreme anisotropies might not be distinguished. It is obvious that if the observed thickness dependence of H_s^* also applies to much thicker samples than ours, H_s^* will become much smaller, so that one will only see one transition when H_{on} becomes larger than H_s^*. In fact, above H_s^* we find the observed bulk behavior of both J_c in the vortex solid, $J_c \sim \exp(H)$, and the activation energy U for flux motion in the vortex liquid, $U \sim 1/\sqrt{H}$.

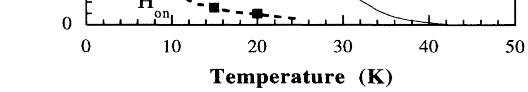

FIG. 4. Possible H-T phase diagram of the $N = 15$ superlattice. The closed circles are H_s^* in the vortex solid state and the hatched area is H_l^* in the vortex liquid state determined from activation energy measurements. The curvature of the I-V characteristics change at the solid line which is considered to be a vortex glass transition line, T_g. Full squares are $H_{\text{on}}(T)$ of the J_0 transition. The dashed lines are guides for the eye.

Another possible explanation of the observed change of the *I-V* characteristics might simply be a crossover of the creep in the solid state, predicted from the collective flux creep theory [14]. However, the thickness dependence of the observed transition and the correlation to the liquid phase do not find a straightforward explanation from this point of view.

In summary, we have observed an abrupt change in the *I-V* characteristics of DyBCO/YPrBCO superlattices characterized by two fields, H_{on} and H_s^*. Fitting these *I-V* characteristics using the vortex glass and the collective flux creep theories reveals a rapid change of the collective pinning energy U_c, suggesting that an abrupt softening of the vortices occurs in the vortex solid. Our measurements are in agreement with the behavior predicted by Ryu *et al.* [15] and the observed transition might be similar in nature to the one observed by Cubitt *et al.* [4] from neutron diffraction.

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