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Two-dimensional vortex dynamics in $YBa_2Cu_3O_7/PrBa_2Cu_3O_7$ multilayers

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We have measured the current-voltage characteristics of an $YBa_2Cu_3O_7/PrBa_2Cu_3O_7$ multilayer in perpendicular magnetic fields. A dislocation-mediated melting behavior of the two-dimensional vortex lattice (VL) is identified. Below the melting field, the vortex motion is found to undergo a crossover from elastic motion to plastic motion when the activation energy for the collective creep exceeds the formation energy of dislocation pairs in the VL at low currents. Above the melting field, the vortices are in a pinned liquid state with the I-V curves characterized by a linear behavior at small currents, changing to a nonlinear behavior at large currents.

It is well known that the high-temperature superconductors reveal much unusual behavior in the mixed state, resulting from their layered structures, high transition temperatures, and short coherence lengths. Due to the high operating temperature, the vortex lattice (VL) is thought to melt over a large region of the magnetic phase diagram and the thermally activated flux flow (TAFF) works in a large temperature region below T_c.[1] The vortex glass theory[2] predicts a power-law dependence of the activation energy U on the current density j with

$$U(j) \propto j^{-\mu}, \quad \mu > 0 , \tag{1}$$

which gives a vanishing linear resistivity in the limit of $j \rightarrow 0$ so that a truly superconducting state exists. Nevertheless, by analogy to the spin glass whose critical dimension is found to lie between two and three, the vortex glass is thought not to exist in the two-dimensional (2D) vortex system.[3] An experiment on the putative vortex glass was carried out by Koch *et al.*, who reported their observation of the scaling behaviors of the I-V curves in the critical region.[4] Dekker *et al.* found the 2D vortex glass correlation length diverging at zero temperature, thus confirming the absence of a vortex glass in the 2D vortex phase.[5]

Collective creep of flux lines has been considered by Feigel'man *et al.*[6] and Vinokur, Kes, and Koshelev[7] within the framework of elastic objects subjected to randomly distributed quenched disorders. Due to the elastic energy of the VL, when subjected to an external exerted force, the vortices will jump in bundles with a volume much larger than the collective pinning volume V_c considered by Larkin and Ovchinnikov.[8] The bundle size becomes larger as the applied force decreases. As a result, the activation energy becomes higher. The activation energy is found to show the same behavior as Eq. (1). Scaling theory for collective creep also reaches the same conclusion.[9] However, the above scenario is correct when only the elastic motion of the VL is considered. It is argued that for a 2D VL, when the activation energy exceeds the formation energy of dislocation pairs, plastic deformations will eventually come into play which can proceed by the motion of edge dislocation pairs. Hence the increase of the activation energy will be cut off. Each of these dislocation pairs is made up of two bounded-edge dislocations with opposite sign, i.e., with opposite Burgers vectors. These dislocation pairs carry net flux, and the plastic motion of these dislocation pairs will cause dissipation. It is this kind of plastic motion of dislocation pairs that prevents the occurrence of the 2D vortex glass.[6,7]

The thermal fluctuations can lead to melting of the VL. By analogy to the Kosterlitz-Thouless (KT) melting transition, a 2D disordered VL is found to be unstable upon the unbinding of the thermally created dislocation pairs.[10] The shear modulus c_{66} drops sharply to zero at the vortex melting temperature $T_m(B)$. A dislocation-mediated 2D VL melting behavior was observed by Berghuis, Van Slot, and Kes in thin films of Nb_3Ge by investigating the I-V response.[11] They also found that in the case of weak pinning, 2D dislocation-mediated melting takes place prior to thermal depinning resulting from the thermal fluctuations of the vortex positions.[12] Recently, another case of a vortex melting transition of KT type on short length scales in a disordered VL was reported by Yazdani *et al.*[13]

In this paper, we report our work on the 2D vortex dynamics on an $YBa_2Cu_3O_7/PrBa_2Cu_3O_7$ (YBCO/PCBO) multilayer by measuring the I-V characteristics at different temperatures and magnetic fields. We identified dislocation-mediated melting of the 2D VL. Below the melting point, a crossover from elastic to plastic motion of the 2D VL was observed.

YBCO/PBCO multilayers were fabricated by *in situ* dc-rf sputtering method in an ultrahigh vacuum system.[14] The sample we used was a c-axis-oriented YBCO/PBCO (48 Å/100 Å) multilayer with 11 alternating periods. Some description about the properties of this sample can be found in Ref. 15 (sample YP-36). The sample was patterned by photolithograph into a microbridge with 100 μm in length and 80 μm in width. Four gold strips were evaporated onto the film and gold wires were used to make the contacts. To avoid possible sample heating by the applied current, the sample was immersed into the liquid nitrogen. The temperature was controlled by pumping with temperature stability better than 0.2 K during the measurement. A four-probe method was employed to measure the I-V characteristics. A programmable Keithley 220 current supplier was worked as the current source with the available current ranging from 1 nA to 100 mA. A Keithley 181 nanovoltmeter was used to detect the voltage signal with a resolution of 2 nV. In this measurement, the configuration was kept as $H \parallel c$ and $H \perp I$.

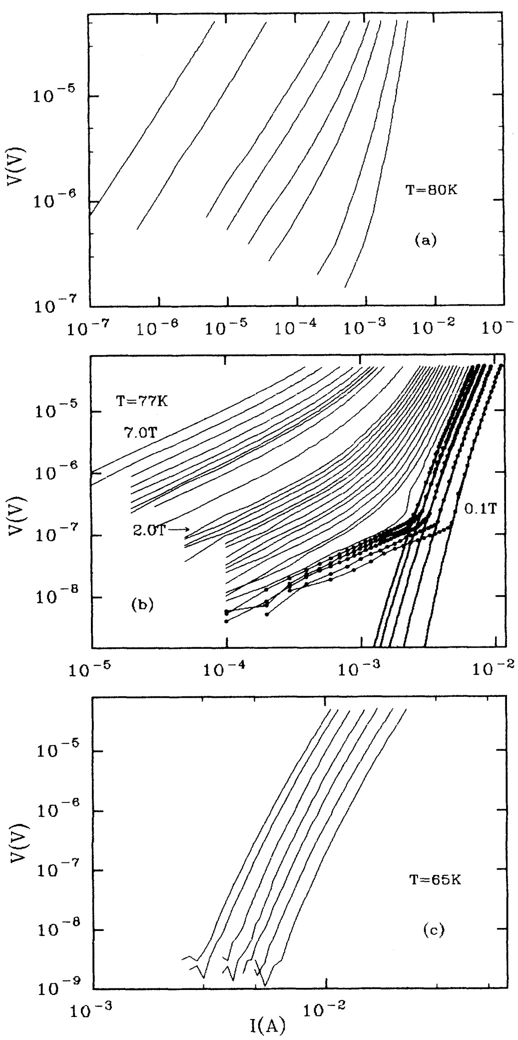

FIG. 1. Selected I-V curves at different temperatures. (a) At 80 K, B =0.2, 0.4, 0.7, 1.0, 1.5, 2.0, 4.0, and 7.0 T, respectively; (b) At 77 K, from 0.1 to 2.0 T, the field interval is 0.1 T; from 2.0 to 7.0 T, the field interval is 0.5 T. Below 0.6 T, the solid circles are experimental data and the bold lines are fitting results; (c) At 65 K, B ranges from 1.0 to 7.0 T with a 1 T interval.

Since the PBCO layer thickness of this sample is 100 Å, the Josephson coupling is presumed to vanish. The magnetic interaction of the vortices in different YBCO layers is much smaller than the magnetic interaction of those vortices in the same layer. Therefore, the VL's in different YBCO layers are essentially decoupled. In addition, the correlation length of the vortices in the c direction is found to be several hundred Å, which is longer than the YBCO layer thickness of 48 Å. Hence the VL in this sample can be considered as individual 2D VL.

Figure 1 presents the measured I-V curves at different temperatures of 80, 77, and 65 K in a double-logarithmic plot. At 80 K, the I-V curves demonstrate upward curvature with a crossover from linear behavior at small currents to nonlinear behavior at large currents. At 65 K, all the I-V curves show downward curvature. At 77 K, the I-V curves can be divided into two regimes, depending on the fields: (i) in the high-field region ($B > 0.6$ T), the I-V curves show the same characteristic as those at 80 K; (ii) in the low-field region ($B < 0.6$ T), the I-V curves exhibit downward curvature in the large-current region, and gradually change to linear behavior in the small-current region. Very similar I-V curves measured on proton-irradiated YBCO single crystals were also reported by Worthington *et al.*[16]

It is well known that such I-V curves with negative curvature are predicted by both the vortex glass theory and the collective creep theory. Both theories deduce that the I-V curves follow such forms as[2,4]

$$V = V_0 e^{-(U_c/kT)(I/I_0)^{-\mu}}, \quad (2)$$

where μ is related to the dimensionalities of the flux bundles and disorders in the sample, and U_c is the collective pinning energy. Here we fit the I-V curves which have negative curvature [those below 0.6 T in Fig. 1(b)] by Eq. (2) with V_0, μ, and $(U_c/kT)I_0^{\mu}$ as independent fitting parameters. The fitting results are listed in Table I; the fitting curves are shown as bold lines in Fig. 1(b). We found that the up-sloping parts of the I-V curves can be fitted satisfyingly with Eq. (2).

Random impurities destroy the long-range correlation of the translational order of the VL, but nevertheless, an ordered VL can exist locally in a region of radius L_p, the Larkin correlation length.[17] The presence of the disorders renormalizes the shear modulus of the VL at large distance to a small but finite value, therefore, the elasticity of the VL is thought to be preserved in the presence of disorders.[18] It is this elasticity that is crucial for the application of the collective creep theory. For 2D collective

TABLE I. Some fitting results for the I-V curves in Fig. 1(b) by Eq. (2). I_d is defined in the text.

Field (T)	I_d (A)	μ	$\frac{U_c}{kT}I_0^{\mu}$	$\frac{U_c}{kT}\left[\frac{I_d}{I_0}\right]^{-\mu}$
0.1	4.8E −3	0.50	1.66	24.0
0.2	3.2E −3	0.31	4.10	24.4
0.3	2.9E −3	0.27	5.18	25.1
0.4	2.1E −3	0.26	5.07	25.2
0.5	2.2E −3	0.26	5.16	25.3

creep, the value of μ has been calculated by Vinokur, Kes, and Koshelev[7] who found that μ shows several values, depending on the vortex bundle size during one concurrent jump.

When the probing current density is smaller than $j_2=j_c(a_0/\lambda)^{8/5}$, where j_c is the critical current density, a_0 is the vortex spacing, and λ is the penetration depth, the bundle size will be larger than λ, and then the local elastic modulus c_{11} should be used. In this case $\mu=0.5$ is roughly consistent with our fitting values of μ. There is some scattering in the fitting results, but considering the complexity of the vortex system and the uncertainty in our fitting, we think the experiment fits the theory well. The characteristic current scale j_2 can be estimated by employing those typical values for YBCO. Here, we use $j_c=5\times10^{10}$ A/m^2, $\lambda=1400$ Å, with $a_0\sim1000$ Å, and we obtain $j_2\sim2.4\times10^{10}$ A/m^2 which lies well above the current density we used at this temperature.

However, as stated in the introductory part, the elastic motion of the 2D VL will eventually be replaced by the plastic deformations of the VL when U exceeds the formation energy of dislocation pairs. Then, the 2D collective creep theory is no long applicable. The motion of the dislocation pairs can be well described by the TAFF theory with activation energy nearly independent of the current. Therefore, a linear I-V curve is expected when the plastic motion of dislocation pairs begins to dominate. This is clearly observed in Fig. 1(b). The crossover from elastic motion to plastic motion is determined by the activation energy of the elastic motion of the VL and the characteristic energy for the dislocation pairs. The smallest dislocation pairs are those with the distance between the dislocations approximately equal to a_0, and they can be visualized as interstitials or vacancies in the VL. The typical energy for such a dislocation pair is

$$U_d=\Phi_0^2 d/4\pi^2\mu_0\lambda^2 . \tag{3}$$

If we take $d=48$ Å and $\lambda=1400$ Å, we obtain $U_d\approx1700$ K. Here, we define the crossover points I_d by the values of I where $dV/dI=1.1$. Those values are listed in Table I. The activation energies at I_d were calculated by $U(I_d)=U_c(I_0/I_d)^\mu$. We find that $U(I_d)$ and U_d are roughly equal, and they are nearly independent of the current, which is just what we expect.

The above result is qualitatively consistent with Monte Carlo simulations of the VL in a random field under an exerted force.[19] It is found that at large driving force, the vortex motion is elastic. As the driving force decreases, the VL becomes defective, and the plastic motion dominates the dissipation.

The picture discussed above can be understood in an alternative way, i.e., excitation of vortex loops (here vortex pairs) in the VL by an applied Lorentz force.[2] Applying a current, a vortex pair with size L_J will be excited. The current probes the physical quantities in a length scale of L_J. The typical vortex pair size is larger for smaller applied current densities. When J is large, L_J will be smaller than L_p. Therefore, the I-V curves can be well described by the collective creep theory. As J decreases, L_J will eventually be larger than L_p, and then, the physics encountered will be governed by the plastic properties of the vortex system, hence a linear I-V resistivity will appear.

As the field increases, dislocation-mediated vortex melting will occur when the following condition is fulfilled:[10]

$$Ac_{66}a_0^2 d/kT=4\pi , \tag{4}$$

where A is a parameter which is used to account for the renormalization of c_{66} due to the defects in the VL and the nonlinear lattice vibrations. Fisher estimated that $0.4<A<0.75$, and several experiments found $A\sim0.5$.[11,20] Here we identify the field at which the I-V curves at large currents change from positive to negative curvature as the melting point. To test this choice, we use the expression for c_{66} given by Brandt[21]

$$c_{66}=[B_c^2(t)/4\mu_0]b(1-0.29b)(1-b)^2 , \tag{5}$$

where $B_c(t)=B_c(0)(1-t^2)$ is the thermodynamic critical field, $t=T/T_c$, and $b=B/B_{c2}(t)$. Inserting the typical values of B_c and B_{c2} for YBCO with $B_c(0)\approx1$ T and $B_{c2}(0)\approx100$ T, together with $B=0.6$ T, $T=77$ K, and $T_c=82.5$ K,[15] we obtain $A\approx0.47$, which agrees well with the previously obtained value.

Extracting the linear resistance R_L from the I-V curves at low current, we find a small step near $B=0.6$ T as shown in Fig. 2. The reason for the step is the existence of vortex translational correlation over a distance L_p below the melting point. This is consistent with the Worthington *et al.* observation.[16] They found that R_L in the vortex slush (which is characterized as a VL with short-range translational order but no long-range phase order) is many orders of magnitude lower than R_L in the vortex liquid above T_m.

Thus, the above result means that at 77 K, the VL is melted by the thermal unbinding of dislocation pairs at 0.6 T. However, since in the presence of disorders, a VL with long-range translational order is not present, our results would rather suggest dislocation-mediated melting of a locally ordered VL with a characteristic length scale of L_p. In the field region with $B>0.6$ T, the VL is in a flux liquid state. As argued by Nelson and Halperin,[22] the VL just above the melting point is not an isotropic liquid, but a hexatic phase. In this state, the VL loses its elasticity but still feels some pinning force, or we say this is a pinned flux liquid state.

The I-V curves of the pinned liquid are characterized

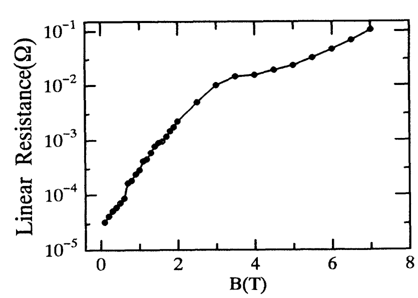

FIG. 2. The linear resistance extracted from the I-V curves of Fig. 1(b) at low currents.

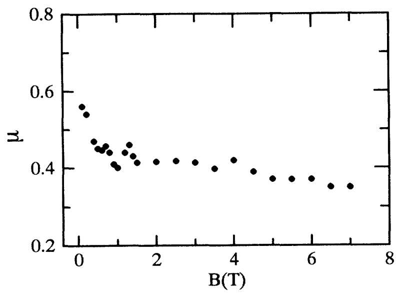

FIG. 3. Field dependence of μ at $T=65$ K.

by two Ohmic regimes at both low and high current densities.[23] Here, we only observed the Ohmic regime in the small-current-density regime. To avoid possible damage to the sample by a large current, we set up a cutoff for the upper voltage, so that a second Ohmic region in the high-current regime was not observed.

Very similar behaviors were observed by Berghuis, Van Slot, and Kes[11] who also regarded this as vortex melting. However, they did not observe the crossover from elastic to plastic motions of the 2D VL below the melting transition. As is shown by Eq. (3), the smaller the thickness of the YBCO layers, the smaller the energy for the generation of the dislocation pairs. Therefore, it is easier to observe such crossover behavior in samples with smaller thickness. Here, the thickness of the YBCO layers of our sample is 48 Å, while the thicknesses of their samples were several thousands Å. Therefore, it is likely that the crossover would lie well below the experimentally observable voltage range of Berghuis, Van Slot, and Kes.

When the temperature decreases, the current scale involved increases, the length scale probed by the current becomes smaller, while the formation energy of dislocation pairs increases, so the nucleation of dislocation pairs will be beyond our voltage resolution, and only the elastic motion can be detected. Again, we find the I-V curves can be well fitted by Eq. (2). The fitted values of μ are shown in Fig. 3. As seen in Fig. 3, the μ values are larger in the low fields, and then tend to 0.4 in the high fields. The value 0.4 agrees well with the prediction of the 2D collective creep theory for the large bundle size. There exists an interesting possibility. As temperature decreases, the effect of thermal fluctuations becomes small, and the remanant magnetic interaction between the vortices in different YBCO layers will make it possible for these vortices to form a stacked 2D vortex glass.[3] This system shows the same dynamic response as a 3D vortex glass system which is characterized by a vanishing linear resistivity. This possibility can be tested by extending the sensitivity of the voltage detection or by comparing the I-V curves of an ultrathin film and multilayer system. In this case, the observation of a vortex glass scaling behavior in the I-V curves will depend on the strength of the disorders and on how far we are from the critical regime of the stacked vortex glass.

Here, we summarize our results. For a 2D disordered vortex system, the VL can be locally melted by the unbinding of thermally generated dislocation pairs. Below the melting field, elasticity is preserved to a certain length scale. The response of the VL to an applied Lorentz force will be elastic when the current is large enough. At low currents, the dissipation is dominated by the TAFF of edge dislocation pairs. The associated plastic motion will destroy the vortex glass state in the 2D VL. Above the melting field, the vortex is in a pinned liquid state whose I-V curves are characterized by a linear resistivity in the low and high currents. The I-V curves in the low-temperature region can be well described by the 2D collective creep theory.

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[1]D. R. Nelson, in *Phenomenology and Applications of High Temperature Superconductors*, edited by K. Bedell *et al.* (Addison-Wesley, New york, 1992).

[2]M. P. A. Fisher, Phys. Rev. Lett. **62**, 1415 (1989); D. S. Fisher, M. P. A. Fisher, and D. A. Huse, Phys. Rev. B **43**, 130 (1991).

[3]D. S. Fisher, in *Phenomenology and Applications of High Temperature Superconductors* (Ref. 1).

[4]R. H. Koch *et al.*, Phys. Rev. Lett. **63**, 1511 (1989).

[5]C. Dekker *et al.*, Phys. Rev. Lett. **69**, 2717 (1992).

[6]M. V. Feigel'man *et al.*, Phys. Rev. Lett. **63**, 2303 (1989); M. V. Feigel'man, V. B. Geshkenbein, and A. L. Larkin, Physica C **167**, 177 (1990).

[7]V. M. Vinokur, P. H. Kes, and A. E. Koshelev, Physica C **168**, 29 (1990).

[8]A. I. Larkin and Y. N. Ovchinnikov, J. Low Temp. Phys. **34**, 409 (1979).

[9]K. H. Fischer and T. Nattermann, Phys. Rev. B **43**, 10 372 (1991).

[10]B. A. Huberman and S. Doniach, Phys. Rev. Lett. **43**, 950 (1979); D. S. Fisher, Phys. Rev. B **22**, 1190 (1980).

[11]P. Berghuis, A. L. F. van Slot, and P. H. Kes, Phys. Rev. Lett. **65**, 2583 (1990).

[12]P. Berghuis and P. H. Kes, Phys. Rev. B **47**, 262 (1993).

[13]A. Yazdani *et al.*, Phys. Rev. Lett. **70**, 505 (1993).

[14]X. G. Qiu *et al.*, J. Appl. Phys. **72**, 2072 (1992).

[15]X. G. Qiu *et al.*, Phys. Rev. B **47**, 14 519 (1993).

[16]T. K. Worthington *et al.*, Phys. Rev. B **46**, 11 854 (1992).

[17]A. I. Larkin, Zh. Eksp. Teor. Fiz. **58**, 1466 (1970) [Sov. Phys. JETP **31**, 784 (1970)].

[18]G. Blatter *et al.* (unpublished).

[19]H. J. Hensen *et al.*, Phys. Rev. B **38**, 9235 (1988); A. C. Shi and A. J. Berlinsky, Phys. Rev. Lett. **67**, 1926 (1991).

[20]A. Hebard and A. T. Fiory, Physica B **109&110**, 1637 (1982); P. L. Gammel, A. F. Hebard, and D. J. Bishop, Phys. Rev. Lett. **60**, 144 (1988).

[21]E. H. Brandt, Phys. Status Solidi B **77**, 551 (1976); Int. J. Mod. Phys. B **5**, 751 (1991).

[22]D. R. Nelson and B. I. Halperin, Phys. Rev. B **19**, 2457 (1979).

[23]V. M. Vinokur *et al.*, Phys. Rev. Lett. **65**, 259 (1990).