Size Effect in the Vortex-Glass Transition in Submicron $YBa_2Cu_3O_y$ Strips: Evidence for Softening of Vortex Matter

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The *I-V* curves of $YBa_2Cu_3O_y$ strips, with widths of 0.54 to 5.6 μm, were measured in magnetic fields. All the strips showed critical scaling behavior, and a clear decrease in the vortex-glass (VG) transition temperature with decreasing width was observed. This finding proves that the interaction range of vortices is relevant in characterizing the phase transition, and that softening of the vortex-matter elasticity occurs upon approaching this scale. Moreover, the results are not easily explained by the flux-creep picture and give strong support to the VG picture.

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High-temperature superconductors provide a new and rich field of physics in the mixed state, where anisotropy, short coherence length, and thermal fluctuations play significant roles. One of the most interesting things is the possibility of a second-order phase transition from vortex liquid to vortex solid. It is known that a flux-line lattice with a long-range crystalline order cannot be formed in the presence of microscopic disorder [1], and a "vortex glass" (VG) has been proposed for the possible low-temperature vortex-solid phase [2]. In this Letter, we call the interacting vortex system in general "vortex matter."

A scaling theory for the phase transition between the vortex liquid and the VG has been developed [2], with the first evidence for the transition given by Koch *et al.* [3] by confirming the scaling behavior in the current-voltage (*I-V*) characteristics. However, several authors claimed [4] that the observed change in the *I-V* curves can be explained within the framework of the conventional flux-creep (FC) theory or the thermally assisted flux-flow (TAFF) theory: They argued that the observed behavior is merely a crossover from an activated flux-creep regime to a viscous flux-flow regime. After these claims, support to the VG transition picture has been given by extending the voltage resolution to an extremely low region [5], and also by showing scaling behavior in the ac impedance [6]. Very recently, it was also shown that the low-temperature phase is not a vortex lattice but a vortex glass by examining the dissipation mechanism in that phase [7]. Although it has become rather clear that the VG transition does exist, much of the nature of the transition is yet to be solved: What is relevant in characterizing the vortex phase transition? What is the scale of the interaction between vortices in the transition?

In this Letter, we address these problems by introducing a new approach, namely, by looking at a size effect in the VG transition. The experiment consists of careful measurements of the *I-V* curves for five narrow strips with different widths made from the same film. The widths of the strips range from 0.54 to 5.6 μm. A clear decrease in the VG transition temperature T_g with decreasing widths below 2 μm was observed. We show that this finding can be understood to be a consequence of softening of the vortex-matter elasticity and that the interaction range of vortices is relevant in characterizing the phase transition. It was shown experimentally that the scale of interaction between vortices is given by the penetration depth.

Two kinds of size effects can be considered with regards to the VG transition in perpendicular fields; the effect of thickness and that of width. The former is related to the dimensionality of the vortex system: It has been shown [8] that, upon decreasing the thickness, a crossover from the 3D to the 2D regime occurs and that there is no finite-temperature VG transition in the 2D regime. For $YBa_2Cu_3O_y$ films thicker than 0.25 μm, only the 3D behavior has been reported [3,6,7], and therefore we chose the thickness of 0.3 μm to see solely the transverse size effect, the effect of the width, which is expected to be related to the scale of interaction between vortices. So far, strips with widths wider than 2 μm have been used [3,6,7], and no dependence of T_g on the width has been reported.

The samples studied here were made from a high-quality, *c*-axis-oriented $YBa_2Cu_3O_y$ film grown by laser ablation on a MgO(100) substrate. The film was first patterned by a standard photolithography technique with Ar-ion milling, into the shape of 8-μm-wide, 27-μm-long microbridges with 1-mm-wide contact pads on both ends. The five strips studied here were patterned on the same substrate at the same time. A focused ion beam (FIB) with Ga ions was subsequently used to mill the microbridges into strips with widths of 0.54, 0.79, 1.3, 1.8, and 5.6 μm. All the strips had a length of 10 μm except for the 5.6-μm-wide strips which were 27 μm long. The photoresist on the microbridges was left, so the FIB milled both the $YBa_2Cu_3O_y$ and the photoresist; this photoresist was useful in protecting the $YBa_2Cu_3O_y$ from suffering damage from the top surface. A standard dc four-probe method was used for the measurement. The voltage was read with a Keithley 182 nanovoltmeter, with an averaging time of 1.5 s for each current direction. The stability of the temperature during the I-V measurements was better than 0.03 K. The magnetic field was applied along the c axis by using a superconducting magnet. The temperature error due to the magnetoresistance of the thermometer was less than 0.5%.

The normal-state resistivity of the strips at 100 K was about 170 $\mu\Omega$cm and the difference between the strips was less than 10%. All the strips showed zero resistivity at 85.5 ± 0.1 K, except for the 0.54-μm strip which showed a slight broadening of 0.5 K, which can be observable only below 1 $\mu\Omega$cm. The critical current density J_c (the criterion was 4×10^{-5} V/cm) at 77 K in zero field was, starting from the narrowest strip, 1.7×10^6, 2.2×10^6, 0.9×10^6, 1.5×10^6, and 2.3×10^6 A/cm^2, respectively. These data support the conclusion that there is no substantial, systematic change in samples with varying width caused by our processing. We have also estimated the Larkin-Ovchinnikov pinning length $l_{\rm LO}$ [1], as in Ref. [7], to be $\sim a_0$ in all the strips, where a_0 is the vortex spacing: This indicates that our strips are in the "amorphous limit" and in the same regime as the earlier works [3,7].

One of the most common ways of localizing the VG transition is the measurement of the I-V curves with small temperature intervals [3,7]. Figure 1 shows the I-V curves in 1 T for the 0.54-μm- and 0.79-μm-wide strip; the plots are log$J$ vs log$E$ (J and E are the current density and the electric field, respectively). Similar curves were also taken in the magnetic fields of 2 and 3 T, and for the other strips. The general characteristic of the VG transition, namely, an abrupt change of the curvature from positive to negative upon decreasing T, was clearly seen in our strips. The VG transition temperature T_g was identified as the temperature at which the positive- and negative-curvature regions are separated. For example, the I-V curves of 0.79-μm strip in 1 T [Fig. 1(b)] show positive curvature at a lower current density above 77.8 K but show only negative curvature below 77.5 K, so we determined the T_g for this case to be 77.7 K. The VG scaling theory [2] predicts that the I-V curve shows power-law behavior $E\sim J^{(z+1)/2}$ at T_g, where z is the dynamical exponent. The dashed lines in Fig. 1 show this putative power-law I-V curve. The exponent z was calculated with the slope of this dashed line. At higher temperatures, the I-V characteristics are linear at small current densities; linear resistivity ρ_L is well defined here. This ρ_L should vanish as $\rho_L\sim(T-T_g)^{\nu(z-1)}$ at T_g. We calculated the static exponent ν with the slope of logρ_L vs log$(T-T_g)$. This exponent ν determines the behavior of the VG coherence length $\xi_g\sim|T-T_g|^{-\nu}$. Table I shows the measured exponents for the five strips. The changes in z for different fields were within errors bars. The 1-T data were used to obtain ν.

An important prediction of the theory [2] is that a scaling relation $E\approx J\xi_g^{1-z}\mathcal{E}_\pm(J\xi_g^2)$, where $\mathcal{E}_\pm(x)$ is an appropriate scaling function, holds near the VG transition. This means that all the I-V curves should collapse onto two universal curves above and below T_g, respectively, if scaled as $J_{\rm scl}\equiv J/|T-T_g|^{2\nu}$ and $(E/J)_{\rm scl}\equiv(E/J)/|T-T_g|^{\nu(z-1)}$. The insets in Fig. 1 show that our I-V data obey this scaling law: This gives us evidence that we are looking at the VG transition in our narrow strips.

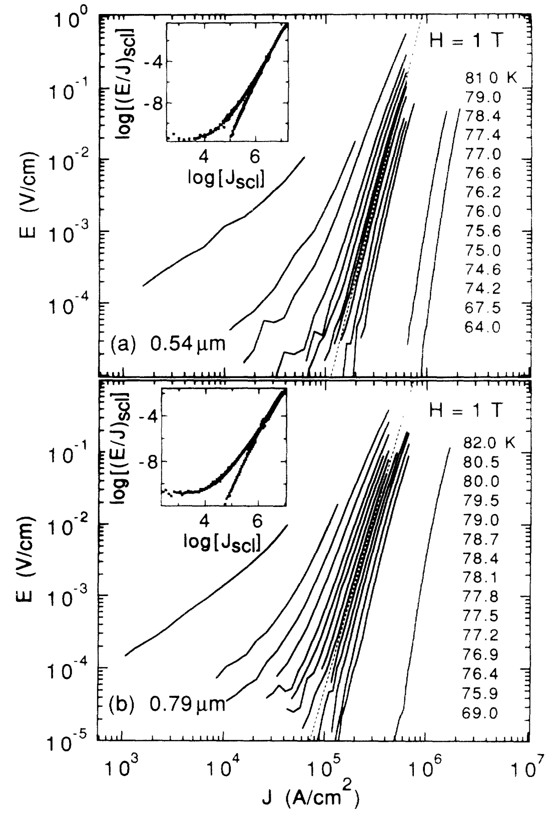

FIG. 1. I-V curves at $H=1$ T for the strips with the widths of (a) 0.54 μm and (b) 0.79 μm. The I-V curve moves to the right with decreasing temperatures, which are listed in the figure. Insets: Collapsed data plots of the I-V curves at temperatures (a) from 74.2 to 79.0 K and (b) from 75.9 to 80.5 K. The scaled parameters are $J_{\rm scl}\equiv J/|T-T_g|^{2\nu}$ and $(E/J)_{\rm scl}\equiv(E/J)/|T-T_g|^{\nu(z-1)}$.

In the VG state, dissipation with an applied current is supposed to occur by expansion of thermally activated vortex loops [2], which leads to the I-V curve of the form $E\sim J\exp[-(J_0/J)^\mu]$ below T_g. Recently, Dekker, Eidelloth, and Koch have shown [7] that the exponent μ is not universal but only current-density dependent. We have also analyzed our data and confirmed that our results agree with those of Ref. [7]. The value of μ changed from 0.1 to 0.95 with increasing current density. All the data from different strips collapsed onto a single line similar to the one in Fig. 3 of Ref. [7].

Figure 2 is our main result. The strip-width dependence of T_g is shown in this figure. A decrease in T_g with decreasing strip width is clearly seen. The fact that there is essential similarity between our narrow strips and wid-

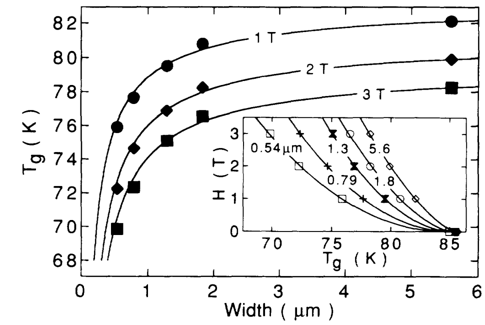

FIG. 2. The strip-width dependence of T_g at $H=1$, 2, and 3 T. The solid lines are theoretical fits to the data with Eq. (1). Inset: VG transition lines for the five strips. The solid lines are fits to the data with $H \cong (T_c - T)^{2\nu_0}$.

er ones studied in earlier experiments [3,7] proves that we are looking at the same phenomenon as in the earlier works and that we have obtained dimensional information relevant to this phenomenon. It should be emphasized that the VG transition occurs as sharply in the narrowest strip as in wider ones, which proves that the observed phenomenon comes not from the superposition of both the behavior of a bulk and that of the edge but from the behavior of the vortices in the system *as a whole*.

Now we show that the observed decrease in T_g can be understood in the context of the VG theory. It is expected [9] that T_g is close to the vortex-lattice (VL) melting temperature T_m of a clean system when $l_{\text{LO}} \sim a_0$, which is the case for our film; therefore, the size effect on T_g is expected to be the same as that on T_m. We discuss the change in T_m by using the theory of elasticity of VL [10]. In an infinite system, the energy of an elastic mode $\mathbf{k}$ is given by $\langle u_\alpha(\mathbf{k})\Phi_{\alpha\beta}\mu_\beta(\mathbf{k})\rangle/2 = k_B T/2$, where $\Phi_{\alpha\beta}$ is the elastic matrix. (We follow the notation used by Brandt [10].) Assuming that the interaction range of vortices is given by the penetration depth λ, we suppose that, for all the elastic modes $\mathbf{k}$, the interaction energy density of vortices within the depth λ from the surface of a strip is reduced by a factor of ζ, on average, compared to that of the vortices far apart from the surface, because they have no counterpart for interaction outside the strip. This leads to the reduction of the total elastic energy of the system by the factor of $[(W-2\lambda)+\zeta 2\lambda]/W$, where W is the strip width. Then, by using the Lindemann criterion, a straightforward calculation gives the reduction of T_m, which is equivalent to the reduction of T_g. The result is

$$T_g = T_g^0[1 - 2\lambda(1-\zeta)/W], \tag{1}$$

where T_g^0 is the transition temperature of a bulk system. We use $\lambda = 0.14$ μm at zero temperature and assume two-fluid temperature dependence.

The solid lines in Fig. 2 are theoretical fits to the data with Eq. (1). The parameters used are $T_g^0 = 83.1$, 81.0, and 79.4 K and $\zeta = 0.80$, 0.73, and 0.68 for $H=1$, 2, and 3 T, respectively. This magnetic field dependence of ζ may come from the effects neglected in our model, such as the $\mathbf{k}$ dependence of ζ, the discreteness of VL ignored in the continuum approximation used here, or the effect of the surface shielding current. However, our simple model describes the physics in our narrow strips fairly well, since the fit of the data by Eq. (1) is very good.

TABLE I. Measured exponents for the five strips.

Strip width (μm)	z	ν	ν_0
0.54	9.7 ± 0.7	0.70 ± 0.2	1.07 ± 0.1
0.79	8.3 ± 1.2	0.77 ± 0.4	1.06 ± 0.1
1.3	7.2 ± 1.0	0.76 ± 0.3	0.99 ± 0.1
1.8	6.9 ± 1.2	0.73 ± 0.4	0.84 ± 0.1
5.6	5.6 ± 1.0	1.2 ± 0.6	0.75 ± 0.1

The inset of Fig. 2 shows the shift of the VG transition line with the strip width. The solid lines are the theoretical line $H \cong (T_c - T)^{2\nu_0}$ fitted to the data. The fits are very good. The values of ν_0 are listed in Table I. The theoretical prediction for ν_0 is $\frac{2}{3}$ for the zero-field critical region [2]. Our results are somewhat larger than this value and show an increase with decreasing width. As shown in Table I, the dynamical exponent z also shows an increase with decreasing width. On the other hand, the critical exponent ν does not show a dependence on the width within our experimental resolution. This nonuniversality of the critical exponents should not be considered as disproving the existence of the phase transition, because our systems are so small that some breakdown of the universality of the scaling is expected. Note that universality is expected only in an infinite system. The apparent increase in z, which means a faster critical slowing down, may be related to the softening of the system.

Can our results also be explained by the FC or TAFF theory? Since it is difficult to formulate the "crossover temperature" which is the substitute for T_g, we will not discuss its size effect but concentrate on the accompanying effect. In the context of these theories, the activation barrier $U(T)$ for a vortex bundle is approximately given by $d(\ln\rho_L)/d(1/T)$. Although the relation $\rho_L \sim (T - T_g)^{\nu(z-1)}$ actually holds near T_g and U is, strictly speaking, not well defined, we have calculated this *apparent* U around 82 K, which is shown in Fig. 3. This *apparent* U increases with width. However, as shown in the inset of Fig. 3, J_c in magnetic fields at 77 K shows little systematic correlation with the width. In the TAFF theory, J_c is determined by $E_0 = w_h B f_0 \exp(-U/kT) \times \sinh(J_c B V_c w_h/kT)$, where E_0 is the criterion electric field, w_h is the hopping distance, f_0 is the attempt frequency, and V_c is the correlation volume. With this formula, it is very difficult to explain that a size effect in J_c is roughly absent, when U shows a clear size effect. Note that our strips are in the amorphous limit where no significant change in V_c and w_h with width is expected.

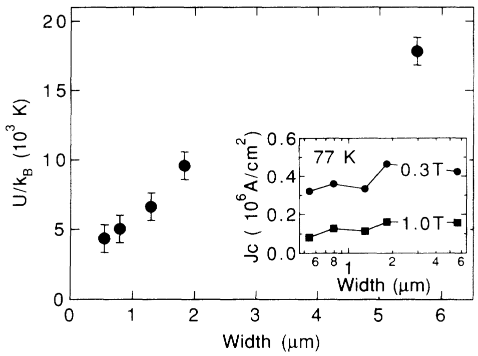

FIG. 3. The strip-width dependence of the apparent activation energy in 1 T. Inset: The strip-width dependence of J_c in 0.3 and 1 T at 77 K.

On the other hand, in the VG theory, J_c in the VG state is determined by $E_0 \simeq J_c \xi_g^{1-z} \mathcal{E} - (J_c \xi_g^2)$. At 77 K ($< T_g$), the increasing ξ_g for narrower strips (because of decreasing T_g) tends to lead to a decrease in J_c, but at the same time the increasing z (which makes ξ_g^{1-z} even smaller) tends to lead to an increase in J_c. This trend qualitatively explains the rough irrelevance of J_c on width.

It is worthwhile to note the essential difference between our results and the other transverse size effect observed in the depinning line measured by a vibrating-reed technique [11]. The latter is a natural consequence of the diffusive nature of TAFF, and is expected to occur in the region above T_g. The depinning line is a line in the H-T plane defined by $D(H,T)=$const, where $D(H,T)$ is the diffusivity of the vortex liquid. A vibrating-reed technique detects the line where the resonance frequency equals the reciprocal diffusion time $\tau^{-1} = \pi^2 D(H,T)/R^2$, where R is a characteristic sample width [11]. Therefore, the depinning-line shift with decreasing R, which was reported in Ref. [11], just corresponds to the change of the criterion of $D(H,T)=$const; namely, the change in the nature of the vortex liquid itself was not observed in this experiment.

In conclusion, we have measured the VG transition for five narrow strips with the widths ranging from 0.54 to 5.6 μm, and found a clear decrease in T_g with decreasing strip width. This finding proves that the vortex-vortex interaction range is relevant in characterizing the vortex phase transition and that the scale of interaction is given by the penetration depth. The observed size effect in T_g can be understood to be a consequence of softening of the vortex matter elasticity and, together with the behavior of J_c, can consistently be explained within the context of the VG theory. On the other hand, it is difficult for the FC or TAFF theory to consistently explain the results: Our observation gives strong support to the VG picture.

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[1] A. I. Larkin and Yu. N. Ovchinnikov, J. Low Temp. Phys. **34**, 409 (1979).
[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] R. H. Koch *et al.*, Phys. Rev. Lett. **63**, 1511 (1989).
[4] S. N. Coppersmith, M. Inui, and P. B. Littlewood, Phys. Rev. Lett. **64**, 2585 (1990); R. Griessen, Phys. Rev. Lett. **64**, 1674 (1990); P. Esquinazi, Solid State Commun. **74**, 75 (1990).
[5] P. L. Gammel, L. F. Schneemeyer, and D. J. Bishop, Phys. Rev. Lett. **66**, 953 (1991).
[6] H. K. Olsson *et al.*, Phys. Rev. Lett. **66**, 2661 (1991).
[7] C. Dekker, W. Eidelloth, and R. H. Koch, Phys. Rev. Lett. **68**, 3347 (1992).
[8] C. Dekker *et al.*, Physica (Amsterdam) **185-189C**, 1799 (1991).
[9] T. K. Worthington *et al.* (to be published).
[10] E. H. Brandt, Int. J. Mod. Phys. B **5**, 751 (1991).
[11] J. Kober *et al.*, Phys. Rev. Lett. **66**, 2507 (1991).