Superconducting phase of $YBa_2Cu_3O_{7-\delta}$ films in high magnetic fields: Vortex glass or Bose glass

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Nonlinear current-voltage (I-V) curves are measured in laser-ablated $YBa_2Cu_3O_{7-\delta}$ films deposited onto $SrTiO_3$. The measurements are performed near the glass phase transition in a magnetic field of 5 T at various angles from the c axis. From a critical scaling analysis, the angular dependencies of the glass transition temperature and the critical glass exponents are extracted. At small angles, these results distinguish between a vortex glass, caused by random pointlike disorder, and a Bose glass, caused by linelike disorder. The results can be understood in terms of the vortex-glass model only. No evidence is found for the existence of a Bose-glass phase.

The nature of the vortex state in the high-temperature superconductors has been extensively debated in the last few years. In 1989, Fisher[1] proposed the concept of a vortex glass (VG) for the description of disordered type-II superconductors. In the VG phase, the magnetic flux lines are thought to be frozen onto random positions dictated by random disorder, i.e., uncorrelated disorder, such as originating from oxygen vacancies, impurities, and precipitates. Experiments on the nonlinear transport characteristics of $YBa_2Cu_3O_{7-\delta}$ indeed provided evidence for the existence of a phase transition to a superconducting glassy state.[2–6] Recently, however, Nelson and Vinokur[7] developed a somewhat different model for the glassy state of the flux lines, named the Bose glass (BG). This model differs from the VG model in that it considers pinning by correlated, or *line*like, defects rather than *point*like defects. Correlation of the disorder along the pinning lines leads to a different dynamics of the flux-line excitations in the glass phase as well as to a different critical behavior near the phase transition. The BG model is particularly appropriate for the description of samples in which columnar defects have been artificially introduced, such as by heavy-ion irradiation.[8] It has, however, been suggested[7] that the BG model is more generally valid because of the natural occurrence of extended pinning defects like screw dislocations and twin planes. If extended defects indeed are the dominant pinning centers, many of the experiments to date on the glassy state of the flux lines[2–6] have in fact probed BG rather than VG characteristics.

In this paper, we examine to what extent the two models are appropriate to $YBa_2Cu_3O_{7-\delta}$ films. This is accomplished by examining the critical scaling behavior of the nonlinear current-voltage (I-V) curves (Fig. 1) near the glass phase transition as a function of the angle between an external magnetic field $\mathbf{H}$ and the film normal. Correlated disorder, such as associated with screw dislocations and twin planes, is anticipated to be oriented along the c axis, i.e., the film normal. In the presence of sufficiently strong linelike disorder, therefore, a BG phase will develop for $\mathbf{H} \parallel \mathbf{c}$. Line pinning, however, becomes less effective when the magnetic field is tilted away from the c axis. This results in a lowering of the BG transition temperature, until the point where the pointlike disorder takes over and a VG phase develops (cf. the inset of Fig. 2). With further increase in the field angle, the VG phase will persist, and the VG transition temperature will rise because of the anisotropy of $YBa_2Cu_3O_{7-\delta}$. In summary, in case linelike disorder is present, a transition from the BG to the VG phase is expected to occur with increasing angle of the magnetic field with the c axis. As it turns out, however, our results can be understood consistently in terms of the VG model only. No indications are found for the existence of a BG phase.

The sample we studied was an epitaxial c-axis-up 3500-Å $YBa_2Cu_3O_{7-\delta}$ film grown by laser ablation on a $SrTiO_3$ substrate, similar to the samples used in Refs. 2, 5, and 6. Details of the film fabrication are given in Ref. 9. The sample was photolithographically patterned to a four-probe structure with strip dimensions of

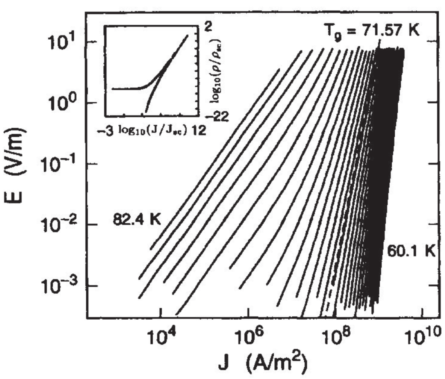

FIG. 1. Log-log plot of some selected I-V isotherms for $H = 5$ T and $\theta = 30°$. The field is directed perpendicular to the current. The I-V curves differ by a temperature interval of 0.8 K. The inset shows the scaling collapse of these data for $T_g = 71.57$ K, $z = 5.85$, and $\nu = 1.70$. In the scaling procedure J is scaled by $J_{sc} \propto T|T - T_g|^{2\nu}$, and ρ by $\rho_{sc} \propto |T - T_g|^{\nu(z-1)}$.

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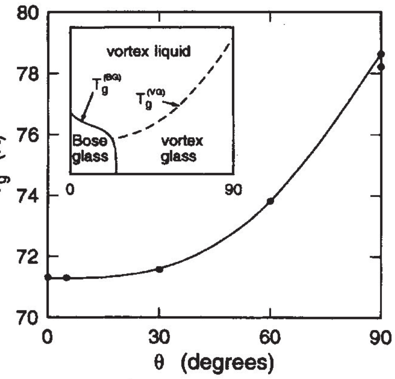

FIG. 2. Angular dependence of the glass transition temperature T_g, derived from data such as in Fig. 1. The two data points at $\theta = 90°$ refer to the $\mathbf{H} \perp \mathbf{I}$ and $\mathbf{H} \parallel \mathbf{I}$ configurations. The solid line through the data points is a guide to the eye. The inset shows the angular phase diagram as predicted by the BG model (after Ref. 7).

$200 \times 20\ \mu m^2$. A gold layer on top of a titanium interface layer was deposited onto the contact pads, yielding a contact resistance of much less than 1 Ω. In the absence of a magnetic field, the film exhibited zero resistance near 87 K.

The I-V measurements were carried out in a magnetic field of 5 T at angles θ from the c axis ranging from 0° to 90°. The current **I** was applied in the (a, b) plane. For $\theta = 90°$, the I-V curves were observed to be virtually identical for $\mathbf{H} \perp \mathbf{I}$ and $\mathbf{H} \parallel \mathbf{I}$, which is consistent with previous reports.[10,11] For $\theta < 90°$, the measurements were done in the $\mathbf{H} \perp \mathbf{I}$ configuration. For each field orientation, a set of nonlinear I-V curves was measured at equidistant temperatures around the glass phase transition. These data were taken by the use of an ac method,[2] where the sample was biased with a low-frequency current (~ 10 Hz). By means of a digital oscilloscope the time traces of current and voltage were sampled, and averaged over typically 5000 periods to reduce noise and interference.

Figure 1 shows a typical set of I-V curves, which exhibit the standard critical behavior.[2–6] With decreasing temperature, the I-V curves are seen to develop from ohmic ($V \propto I$) to a power-law behavior ($V \propto I^x$) at the glass transition temperature T_g. Upon further decrease of the temperature, the I-V curves display a gradually more pronounced exponential dependence ($V/I \propto \exp[-(I_0/I)^x]$).

The analysis of the I-V data is based on critical scaling behavior near the glass phase transition. Both for the VG and the BG model the nonlinear I-V curves near T_g can be cast into the scaling form

$$\frac{\rho}{\xi_\parallel \xi_\perp^{-z}} = \mathcal{F}_\pm\left(\frac{J\xi_\parallel\xi_\perp}{T}\right), \qquad (1)$$

where ρ is the resistivity and $\mathcal{F}_\pm$ is a scaling function, which differs for temperatures above (+) and below (−) T_g. The resistivity is defined by $\rho = E/J$, with E the electric field and J the current density. The quantities $\xi_\parallel$ and $\xi_\perp$ are the glass correlation lengths parallel and perpendicular to the c axis, respectively. For the VG $\xi_\parallel \propto \xi_\perp$, whereas for the BG $\xi_\parallel \propto \xi_\perp^2$. The temperature dependence of $\xi_\perp$ is assumed to have the critical form $\xi_\perp = \xi_{\perp 0}/|T - T_g|^\nu$. From a comparison of the scaling equation (1) for the two models it follows that the critical exponents for the VG and the BG are related simply by

$$z' = \tfrac{1}{2}(3z + 1)\ , \qquad (2)$$

$$\nu' = \tfrac{2}{3}\nu\ , \qquad (3)$$

where the nonprimed exponents refer to the VG and the primed ones to the BG. For a determination of the critical exponents, therefore, it is sufficient to perform the scaling analysis for the VG model only; the equivalent results for the BG model can subsequently be derived with the aid of Eqs. (2) and (3).

In the scaling analysis of the I-V data, which includes the criterion of a pure power-law dependence at the transition temperature, the quantities T_g, z, and ν were, for each orientation, adjusted so as to achieve optimum collapse. Figure 1 shows, as an example, a selection of the I-V curves at $\theta = 30°$, and in the inset the scaling collapse of all I-V curves for this angle. The results of the scaling analysis for all configurations are presented in Table I.

The most important result is the angular dependence found for T_g. From Fig. 2, it is apparent that T_g does not show an initial decline, but increases monotonically with the angle starting from $\theta = 0°$. A cusp near $\theta = 0°$ appears to be absent. It is noted that the above analysis permits one to compare the T_g's at the various angles with an uncertainty of ±0.1 K. We thus find no indication

TABLE I. Scaling results for all orientations. Typical error bars are ±0.10 K for T_g, ±0.10 for z, ±0.10 for ν, ±0.02 for μ, ±6% for $J_0(\theta)/J_0(0)$ and $\rho_0(\theta)/\rho_0(0)$, and ±12% for $\xi_{\parallel 0}(\theta)/\xi_{\parallel 0}(0)$ and $\xi_{\perp 0}(\theta)/\xi_{\perp 0}(0)$.

θ		T_g (K)	z	ν	μ	$J_0(\theta)/J_0(0)$	$\rho_0(\theta)/\rho_0(0)$	$\xi_{\parallel 0}(\theta)/\xi_{\parallel 0}(0)$	$\xi_{\perp 0}(\theta)/\xi_{\perp 0}(0)$
0°	($\mathbf{H} \perp \mathbf{I}$)	71.31	5.70	1.70	0.23	1	1	1	1
5°	($\mathbf{H} \perp \mathbf{I}$)	71.29	5.70	1.75	0.22	1.03	0.95	0.97	1.00
30°	($\mathbf{H} \perp \mathbf{I}$)	71.57	5.85	1.70	0.25	1.04	0.91	0.96	1.01
60°	($\mathbf{H} \perp \mathbf{I}$)	73.82	5.90	1.65	0.22	1.08	1.96	1.04	0.90
90°	($\mathbf{H} \perp \mathbf{I}$)	78.64	5.72	1.60	0.25	1.76	43.2	1.07	0.53
90°	($\mathbf{H} \parallel \mathbf{I}$)	78.21	5.92	1.70	0.20	2.46	13.34	0.68	0.60

for the existence of a BG phase, i.e., line pinning is not dominating the glass transition near $\theta = 0°$. The overall increase in T_g with θ may be understood simply in terms of the VG model, and to result from the anisotropy in $YBa_2Cu_3O_{7-\delta}$.

Another argument that the VG model applies over the whole range of angles is that the critical exponents z and ν are independent of θ (cf. Table I). We find, averaged over θ, the results $z = 5.8$ and $\nu = 1.7$. There is no *a priori* reason why the BG and VG should have identical exponents, so a marked change is anticipated at a transition from the BG to the VG phase in the presence of linelike disorder. Furthermore, we examined in detail the *I-V* curves below the glass phase transition, where they are adequately described by the exponential relation $\rho \propto \exp[-(J_0/J)^{\mu}]$. The exponent μ was determined from the $T < T_g$ branch of the scaling plot using the method of Ref. 6. It was found to have a value of $\mu = 0.23 \pm 0.03$, again independent of the angle, and in good agreement with $\mu = 0.19 \pm 0.05$ from previous measurements at $T \ll T_g$.[6] This experimental result contradicts the BG model, for which $\mu = \frac{1}{3}$.[7]

We have seen that the *I-V* curves can be made to collapse onto a single scaling curve for each individual θ. The resulting critical exponents z and ν were, within errors, found to be independent of θ. In order to compare the associated scaling functions for the various angles, we have plotted the scaling curves in a single graph using single, averaged, values for z and ν. In such a plot, the scaling curves appear to have identical shapes for the various θ, yet do not exactly coincide. Closer inspection shows that the curves, when plotted in a log-log plot, differ from one another by simple shifts along both the ordinate and the abscissa. At this point, it should be realized that the proportionality constants appearing in J and ρ are not necessarily universal constants, as distinct from the critical exponents. In other terms, if we rewrite Eq. (1) to $\rho/\rho_{sc} = \mathcal{F}_{\pm}(J/J_{sc})$, with $\rho_{sc} = \rho_0|T-T_g|^{\nu(z-1)}$ and $J_{sc} = J_0 T|T-T_g|^{2\nu}$, the proportionality constants J_0 and ρ_0 may very well depend on θ. If we adopt the reasonable assumption that the scaling is indeed universal, as the above results indicate, the scaling curves for the various θ can be shifted to coincidence with the $\theta = 0°$ curve by taking $J_0(\theta)/J_0(0)$ and $\rho_0(\theta)/\rho_0(0)$ as specified in Table I. The full scaling collapse of the data at all angles is shown in Fig. 3. This collapse clearly shows that the scaling function itself is independent of the angle. This once more indicates that only a single model applies for all angles. It is finally of interest to note that

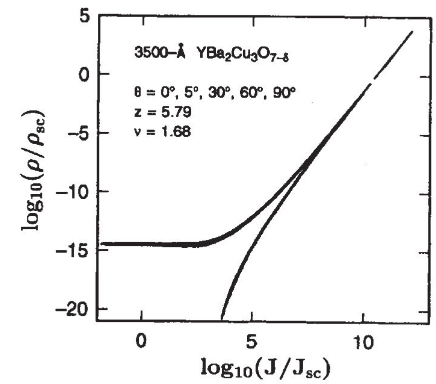

FIG. 3. Scaling collapse of the *I-V* curves for *all* angles.

it is possible to decompose the θ dependencies of ρ_0 and J_0 into the proportionality constants $\xi_{\parallel 0}$ and $\xi_{\perp 0}$ appearing in the critical forms of $\xi_{\parallel}$ and $\xi_{\perp}$. This may be done via the relations $\rho_0 = \xi_{\parallel 0}\xi_{\perp 0}^{-z}$ and $J_0 = (\xi_{\parallel 0}\xi_{\perp 0})^{-1}$. The results are given in Table I. The remarkable finding is that $\xi_{\parallel 0}$ is virtually independent of the angle for $\mathbf{H} \perp \mathbf{I}$, while $\xi_{\perp 0}$ is roughly halved in going from $\theta = 0°$ to $90°$.

After completion of this work, we learned that Silver *et al.*[12] have performed a similar experiment on $YBa_2Cu_3O_{7-\delta}$ films sputtered onto MgO. Surprisingly, these authors find an increase in T_g towards $\theta = 0°$, which is indicative of the occurrence of a BG phase, i.e., linelike disorder. The discrepancy with the present results is presumably related to the different materials parameters, such as the substrate or the deposition method. The question, therefore, remains to what extent the presence of a BG phase is related to the materials parameters.

In summary, we have found no evidence for linelike disorder in a typical laser-ablated $YBa_2Cu_3O_{7-\delta}$ film deposited on $SrTiO_3$, i.e., we have found no indications for a BG phase at small field angles. All our experimental results are in good agreement with the VG model only.

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