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2D-3D CROSSOVER EFFECTS ON THE VORTEX-GLASS PHASE TRANSITION IN THIN $YBa_2Cu_3O_{7-\delta}$ FILMS*

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Nonlinear current-voltage characteristics have been measured for ultrathin (16-400 Å) $YBa_2Cu_3O_{7-\delta}$ films in high magnetic fields. A scaling analysis of these data reveals deviations from the universal vortex-glass critical scaling behavior observed for thick films. This is argued to be a dimensionality effect: At large currents, one probes length scales smaller than the film thickness, i.e., the three-dimensional (3d) vortex-glass behavior, whereas at low currents the vortex excitations involve typical length scales which exceed the film thickness, hence the 2d behavior is exhibited. Further evidence for this picture is found from the 3d vortex-glass correlation length, which appears to be cut off by the film thickness.

The magnetic phase diagram of the oxide superconductors continues to be a very active area of research. A consensus seems to have been reached that a three-dimensional (3d) disordered superconductor in a magnetic field exhibits a phase transition into a truly superconducting vortex-glass (VG) phase.[1] Experimental evidence has in particular been obtained from the critical behavior of the nonlinear current-voltage (I-V) curves of $YBa_2Cu_3O_{7-\delta}$ films.[2] It has been predicted theoretically[1,3] that a VG phase transition will not occur in a 2d system however. In this paper, we present experimental data that support this notion. We find that the critical scaling behavior of the I-V curves – which signals the phase transition – deteriorates for ultrathin films which are in the 2d limit.

Epitaxial c-axis-up $YBa_2Cu_3O_{7-\delta}$ films of thickness between 16 and 400 Å were made by laser ablation. Details of the film fabrication and patterning have been given in Ref. 4. Magnetic fields were applied $\parallel \vec{c}$. The zero-resistance T_c in zero field ranged from 89.4 K for the 400 Å film to 13 K for the 16 Å film.

Figure 1 shows some I-V curves for a 100 Å

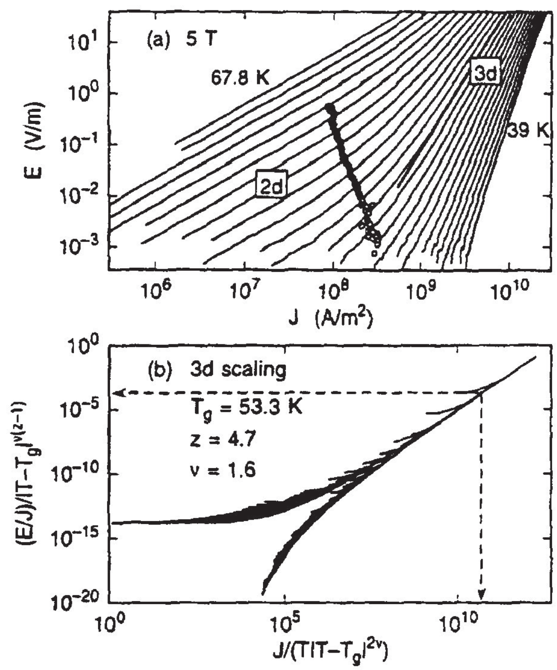

Figure 1. (a) Selected I-V isotherms for a 100 Å film. Curves are 1.2 K apart. Thick solid line denotes T_g. Open dots represent the crossover points where deviations from scaling occur. The data in the upper right corner (marked 3d) show the scaling behavior, whereas the data at lower left (2d) lead to deviations from scaling. (b) 3d scaling plot of the above data. Dashed lines illustrate the definition of points that characterize the crossover from 3d scaling to 2d deviations [open dots in (a)].

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film at 5 T. Results at other fields and for films with thickness between 32 and 400 Å are very similar. In order to fully appreciate these data, one should compare these to the results obtained for thick (~ 3500 Å) films such as reported in Ref.2. The *I-V* data for these thick films show the critical scaling behavior characteristic for a 3d continuous phase transition at a glass transition temperature T_g, viz., they obey $(E/J)/\rho_{\rm lin} = \mathcal{F}_\pm(J/J_{\rm nl})$, with $\mathcal{F}_\pm(x)$ a scaling function, $\rho_{\rm lin} = \rho_0|T-T_g|^{\nu(z-1)}$, $J_{\rm nl} = J_0 T|T-T_g|^{2\nu}$, and z and ν critical exponents.[1,2] Accordingly, one may replot the *I-V* data unto a single universal scaling curve.

The data for the ultrathin films show deviations from such 3d critical scaling behavior, as illustrated in Fig.1b. It is *not* possible to adjust the scaling parameters T_g, z, and ν such that a full data collapse without deviations is obtained. However, it *is* possible to do so for the high-current parts of the *I-V* data only. The low-currents parts then show deviations which appear as the horizontal lines in Fig.1b. We may define a crossover point at the crossing of these lines with the scaling curve. The result, the dots in Fig.1a, visualize the crossover from ohmic resistivity in the 2d regime to scaling behavior in 3d.

These findings are consistent with a finite-size effect. With an applied current, one creates vortex excitations with a typical length scale that is inversionally proportional to the current.[1] Accordingly, at large I one probes length scales smaller than the film thickness, i.e., the three-dimensional (3d) VG behavior, whereas at small I the length scales of the excitations exceeds the film thickness, hence the 2d behavior is exhibited.

This picture is corroborated with explicit estimates for ξ_c, the VG correlation length along $\vec{c}$. This may be obtained[1] from $\xi_c = \sqrt{c\gamma k_B T/\phi_0 J_{\rm nl}}$, with c a constant of order unity, $\gamma \approx 0.2$ the anisotropy parameter for $YBa_2Cu_3O_{7-\delta}$, ϕ_0 the flux quantum, and $J_{\rm nl}$ the current density where nonlinearity of the *I-V* curve sets in. The result is shown in Fig.2. The 3d critical divergence $\xi_c \propto (T-T_g)^{-\nu}$ (solid lines) appears to level off to a constant plateau (dashed lines) upon approaching T_g. The plateau value appears to roughly scale with the film thickness (see inset). These findings indicate that the growth of the 3d VG correlation length is cut off by the film thickness.

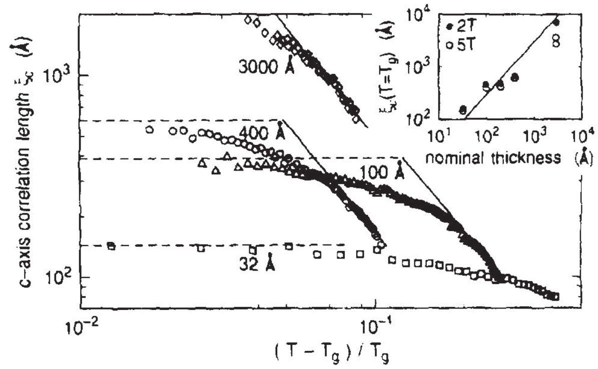

Figure 2. c-axis correlation length at 5 T vs reduced temperature for films of various thickness. Solid lines denote the critical behavior $\xi \propto (T-T_g)^{1.7}$. Dashed lines indicate the leveling off at lower T. Inset shows ξ_c vs nominal film thickness. Solid line denotes a linear relationship.

Finally we note that for the thinnest film of 16 Å at low ($\leq$ 10 K) temperatures, one may observe the nonlinear transport characteristics associated with the critical behavior of a zero-temperature 2d VG transition. These results have been presented in Ref. 4.

In conclusion, the nonlinear transport characteristics of ultrathin (2d) $YBa_2Cu_3O_{7-\delta}$ films in a high magnetic field appear to be different from those in a bulk (3d) system. This may be understood to be a finite-size effect. The results indicate that a VG phase transition does occur at 3d, but not at 2d.

References

[1] D. S. Fisher *et al.*, Phys. Rev. B **43**, 130 (1991).

[2] R. H. Koch *et al.*, Phys. Rev. Lett. **63**, 1511 (1989); P. L. Gammel *et al.*, *ibid.* **66**, 953 (1991); C. Dekker *et al.*, *ibid.* **68**, 3347 (1992).

[3] M. P. A. Fisher *et al.*, Phys.Rev.Lett. **66**, 2931 (1991); J. D. Reger *et al.*, Phys.Rev. B **44**, 7147 (1991); M. J. P. Gingras, *ibid.* **45**, 7547 (1992).

[4] C. Dekker *et al.*, Phys. Rev. Lett. **69**, 2717 (1992); P. J. M. Wöltgens *et al.*, unpublished.