Bose-glass behavior of the vortex system in epitaxial $Bi_2Sr_2CaCu_2O_{8+\delta}$ films with columnar defects

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(Received 23 September 1994)

A continuous transition of the vortex ensemble into a Bose-glass state in epitaxial $Bi_2Sr_2CaCu_2O_{8+\delta}$ films with columnar defects along the c axis, induced by irradiation with 2.7 GeV ^{238}U ions was observed. The temperature variation of the resistivity, measured with the magnetic field $B=\mu_0 H$ applied parallel to the c axis, fits the expression $\rho(T)\sim(T-T_{BG})^{\nu(z-2)}$ at low levels, with a field-independent exponent up to $B\approx 2$ T. At very low fields, the magnetic-field dependence of the Bose-glass transition temperature T_{BG} is in good agreement with the predictions of theory of boson localization in the presence of correlated disorder, $1/T_{BG}-1/T_{c0}\sim B^{1/4}$. However, for applied field values significantly larger than the dose-equivalent field $B_\phi=1$ T, the vortex delocalization in our samples seems to proceed via melting, the magnetic-field exponent becoming very close to $\frac{1}{2}$. The occurrence of the Bose-glass transition in the case of intrinsically very anisotropic superconductors, as $Bi_2Sr_2CaCu_2O_{8+\delta}$, can be understood through an increase of the tilt modulus in the vortex ensemble in the presence of correlated disorder, which promotes vortex localization.

The occurrence of dissipation in transport-current-carrying high-T_c superconductors in the mixed state has been a subject of numerous recent experimental and theoretical investigations. The vortex fluctuations in highly anisotropic superconducting cuprates, such as Bi-based and Tl-based compounds, have important consequences on the form of the irreversibility line, which was found to lie well below the mean-field critical temperature T_{c0}.[1–4] In the case of random point disorder, a second-order phase transition of the vortex system into a vortex-glass state, with zero ohmic resistance in the limit of small transport currents, was predicted to occur at a vortex-glass temperature T_g,[5,6] whose magnetic field dependence close to T_{c0} can be expressed as $1-T_g(B)/T_{c0}\sim B^{3/4}$.

A conceptually different situation is expected to arise in the presence of correlated disorder, for example, twin boundaries, or columnar defects engineered by irradiation with heavy ions, which can have a stronger influence on the supercurrent transport properties, even in the case of intrinsically very anisotropic superconductors.[7] Nelson and Vinokur[8] investigated the response of a system of vortex lines to the presence of a columnar defect structure. By mapping the physics of flux lines onto the problem of localization of quantum-mechanical bosons in two dimensions,[9] they predicted a new Bose-glass phase at low temperatures, with the vortex lines localized on the columnar pins. Of particular interest is the transition at T_{BG} from the Bose glass to a vortex liquid. The critical behavior of this transition can be parametrized in terms of a scaling theory with two undetermined critical exponents, ν and z, and the resistivity ρ close to T_{BG} should then vanish as $T\to T_{BG}$ from above as

$$\rho(T)\sim(T-T_{BG})^{\nu(z-2)} . \tag{1}$$

An important point is the universality of the critical exponents, i.e., their independence of the applied magnetic field. The critical-exponent relations for a Bose-glass transition are very similar to those predicted by the vortex-glass theory,[5,6] but the Bose-glass phase and the vortex-glass phase have different underlying microscopic physics. In contrast to point disorder, which promotes vortex wandering and entanglement, the correlated disorder inhibits wandering and promotes localization.

Although a detailed theory of the Bose-glass transition is not yet available, it was shown in Ref. 8 that the flux liquids are stable to weak correlated disorder, provided $T>T_{BG}(B)$. At very low flux densities, $B<B_0=\Phi_0/\lambda_{ab}^2$, where Φ_0 is the magnetic flux quantum, and λ_{ab} is the in-plane component of the London penetration depth, the $T_{BG}(B)$ dependence can be written as

$$1/T_{BG}(B)-1/T_{c0}=a_1 B^{1/4} . \tag{2}$$

Up to a factor of the order unity,

$$a_i\approx B_\phi^{-1/4}[4\xi_{ab}(0)/c_0](\mathrm{Gi}/\ln\kappa)^{1/2}T_{c0}^{-1} ,$$

where B_ϕ is the dose equivalent field, $\xi_{ab}(0)$ is the coherence length in the (a,b) plane at 0 K, c_0 is the radius of the columnar pins, Gi is the Ginzburg number, and κ is the Ginzburg-Landau parameter. The instability at $T<T_{BG}(B)$ signals the onset of flux-line localization.

The occurrence of the Bose-glass transition in $YBa_2Cu_3O_7$ crystals[10] and epitaxial $Tl_2Ba_2CaCu_2O_8$ (Ref. 11) with continuous columnar defects was recently reported. By analyzing the flux-creep process in $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi-2:2:1:2) single crystals at low fields, in the regime of remanent magnetization, an irradiation-induced crossover from point defect to correlated disorder pinning was discussed in Ref. 12.

In the present work, we studied the temperature variation of the resistivity in the case of Bi-2:2:1:2 films with columnar defects along the c axis, for B parallel to the defects. We found that, at low resistivity levels, the $\rho(T)$ variation fits Eq. (1), with a field-independent exponent up to $B \approx 2$ T, and more importantly, the resulting $T_{BG}(B)$ dependence at very low fields is in agreement with Eq. (2). The applicability of the Bose-glass theory, which implies vortex lines, to intrinsically very anisotropic superconductors, such as Bi-2:2:1:2, in which the vortex lines may decompose into pancake vortices situated in the $(CuO_2)_2$ blocks,[6] is explained through an increase of the tilt modulus in the presence of correlated disorder.

Bi-2:2:1:2 films ($\approx$400 nm thick) with reproducible superconducting properties were prepared by an *in situ* sputtering method on (100) oriented $SrTiO_3$ substrates, as described in detail in Ref. 13. The strongly c-axis-oriented growth and in-plane epitaxy were confirmed by means of x-ray diffraction in a Bragg-Brentano and four-circle geometry. The stacking sequence was additionally investigated by transmission electron microscopy, which revealed a low density of stacking faults. The critical temperature of the two films investigated in this work was, after patterning and annealing of contacts, T_c (zero resistance) ≈ 87 K, and T_{c0} (inflection point) $=91.5$ K (Fig. 1). One of them was irradiated at 70 K with 2.7 GeV ^{238}U ions. The beam direction was perpendicular to the (a,b) plane. The dose of 4.8×10^{10} ions/cm^2 corresponds to a dose equivalent field $B_\phi = 1$ T. The electronic energy loss of the 2.7 GeV ^{238}U ions ($\approx$48 keV/nm) is well above the proposed threshold of 16 keV/nm for production of columnar defects.[14] The calculated depth is 2 orders of magnitude larger than the film thickness. The columnar defects in our sample have a radius $c_0 \approx 5$ nm. After irradiation, and thermal cycling between 77 K and room temperature, the critical-current density (at 5 μV/cm) was 0.937×10^9 A/m^2, for $B=0.7$ T and $T=57$ K. Upon irradiation, the normal-state resistivity $[\rho_n = \rho(120 \text{ K})]$ increased by $\approx 35\%$, and the critical-current density increased by a factor of 25. The critical temperature became $T_c \approx 80.5$ K, and $T_{c0} = 89$ K (Fig. 1).

We first compare the irreversibility temperature T_r determined with a low resistivity criterion $[\rho_c = 10^{-6}\rho(120 \text{ K})]$ for the unirradiated sample with that observed after irradiation. In Fig. 1 (inset), it can be seen that, after irradiation, the irreversibility line is shifted to higher temperatures, over the whole magnetic field domain under consideration. However, this effect, which is rather strong close to B_ϕ, diminishes at $B \gg B_\phi$.

The resistive transitions of the irradiated sample fit Eq. (1) very well at low levels $[\rho(T) < 10^{-4}\rho(120 \text{ K})]$, in a three-parameter fit (Fig. 2). The exponent is practically constant up to an applied field value $B \approx 2$ T, with an average value $v(z-2) \approx 9$ (Fig. 3, inset). Combining this with the estimation made in Ref. 15 for the dynamic critical exponent, $z = 6\pm0.5$, we obtain $\nu \approx 2$, in agreement with the value derived in Ref. 11. It is worth noting that including the resistive data at higher levels ($\rho \le 10^{-2}\rho_n$, for example), the fit becomes poor and the exponent decreases, due to the appearance of thermally assisted flux flow (TAFF) in the vortex fluid. The exponent resulting from the fit illustrated in Fig. 2 begins to decrease at higher fields (up to ≈ 5 at 5 T), indicating the failure of the Bose-glass transition model for $B \gg B_\phi$.

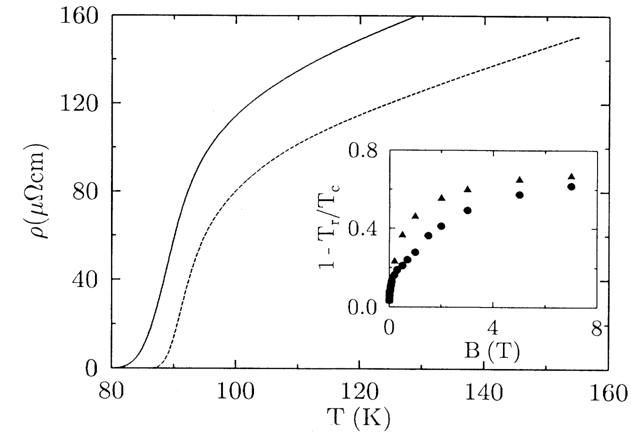

FIG. 1. Characteristic resistive transition in zero applied magnetic for the unirradiated samples (- - -). The zero-field resistive transition of the sample irradiated with 2.7 GeV ^{238}U ions (——). The inset represents the irreversibility line determined with a low resistivity criterion, $\rho_c = 10^{-6}\rho(120 \text{ K})$: (▲) unirradiated sample; (●) irradiated sample. In order to avoid the influence of the larger transition width resulting after irradiation, we used here T_c (zero resistance) as critical temperature.

Further, we analyze the $T_{BG}(B)$ dependence resulting from the fit of the resistive transitions. This is shown in Fig. 3. We considered the mean-field critical temperature T_{c0} equal to the temperature value corresponding to the inflection point in the zero-field resistive transition (Fig. 1). At very low fields, the $T_{BG}(B)$ variation is clearly different from that proposed for the transition to a vortex glass dominated by point disorder, but is in very good agreement with Eq. (2). The one-parameter fit of the low field data gives $a_1 = 1.01\times10^{-2}$ K^{-1}T$^{-1/4}$ (Fig. 3). With $\xi_{ab}(0) = 3$ nm (Ref. 16) for Bi-2:2:1:2,

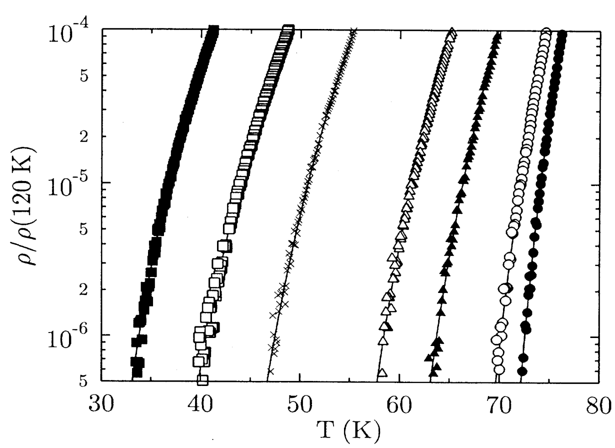

FIG. 2. Temperature dependence of the resistivity for B parallel to the c axis [$B=0.05$ T (●); 0.1 T (○), 0.5 T (▲); 1 T (Δ); 2 T (×); 3 T (□); 5 T (■)]. The solid lines represent the fits of the $\rho(T)$ data $[\rho(T) < 10^{-4}\rho \text{ (120 K)}]$ with Eq. (1).

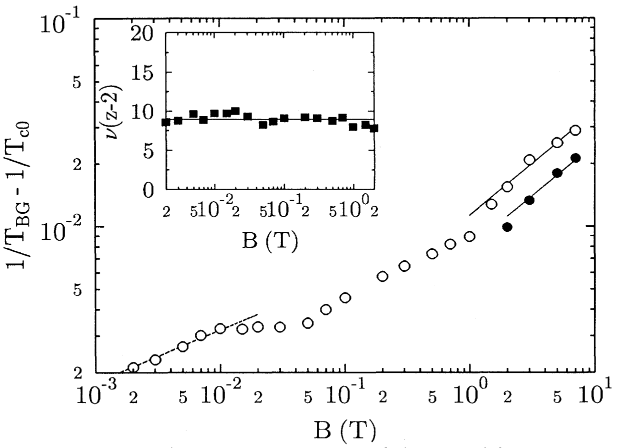

FIG. 3. Magnetic-field dependence of the transition temperature resulting from the fit of the resistive data (Fig. 2) (○), and the field dependence of the high field T_r values from Fig. 1 (●). The dashed line represents the fit of the low field data ($B \leq 10$ mT) with Eq. (2) (one-parameter fit). The solid lines represent the fit of the high field data ($B \geq 2$ T) with Eq. (3) (one-parameter fit). The inset: magnetic-field variation of the exponent $\nu(z-2)$ (see text). The line in the inset represents the mean value for $B \leq 2$ T.

$\kappa \approx 10^2$, $c_0 \approx 5$ nm, and $T_{c0} = 89$ K, the theoretical estimation[8] (see above) leads to $a_1 \approx 0.35 \times 10^{-2}$ $\mathrm{K}^{-1}\mathrm{T}^{-1/4}$ The difference is understandable, taking into account the transport-current density $J_p = 10^7$ $\mathrm{A/m}^2$, imposed by the sensitivity of our measurements. In the limit $J_p \to 0$, the $T_{\mathrm{BG}}(B)$ values are expected to be higher, leading to a lower a_1. The deviation from Eq. (2) appears at $\approx 10^{-2}$ T. We have $T_{\mathrm{BG}}(10^{-2}\,\mathrm{T}) = 69$ K. By considering the temperature dependence of the penetration depth for B parallel to the c axis, $\lambda_{ab}(T) = \lambda(0)(1 - T/T_{c0})^{-1/2}$, with $\lambda_{ab}(0) \approx 250$ nm for Bi-2:2:1:2,[17] it can be seen that this is exactly the field $B_0 = \Phi_0/\lambda_{ab}^2$, below which the vortices interact only via a short-range potential. At $B > B_0$, the interactions between vortices restrict the growth of the localization length before the transition to a vortex liquid occurs, and $T_{\mathrm{BG}}(B)$ will be shifted to higher temperatures (see Fig. 3), in agreement with the estimation of the Bose-glass transition temperature made for this magnetic field domain.[8]

The field value above which the interactions between vortices modify the columnar pinning in an important way is the matching field B_ϕ, provided the temperature is lower than a crossover temperature T_0, defined through the relation[8] $c_0 = \sqrt{2}\xi_{ab}(T_0)$. With $\xi_{ab}(T) = \xi_{ab}(0)(1 - T/T_{c0})^{-1/2}$, and $\xi_{ab}(0) \approx 3$ nm, the mean radius of the columnar defects in our samples leads to a $T_0 \approx 57$ K. The observed influence of the columnar defect structure at fields slightly higher than B_ϕ can be understood by taking into account that, for $B \geq B_\phi$, although all the columnar defects are occupied, the excess vortices, which go into the interstitial space, will still be localized by interactions with vortices trapped on the pinning structure. The spatial distribution of the density of columnar defects in the sample has a similar effect.

At $B \gg B_\phi$, the vortex configuration at low temperatures will be composed from domains of crystalline order interrupted by the correlated pinning potential. This highly inhomogeneous structure is responsible for the broadening of the transition at high fields (Fig. 2). Although the point disorder may become important at low temperatures, for $B \gg B_\phi$, the vortex delocalization in our sample seems to proceed via melting. The magnetic field dependence of the melting temperature T_m would be[1,8,18]

$$1/T_m(B) - 1/T_{c0} = a_2 B^{1/2} \tag{3}$$

with $a_2 \approx 2\sqrt{2}[\xi_{ab}(0)/c_L^2 T_{c0}](\mathrm{Gi}/\Phi_0 \ln\kappa)^{1/2}$ (up to a factor of the order unity), where c_L is the Lindemann constant. If the fit from Fig. 2, for $B > B_\phi$, is considered as an extrapolation of the resistive data to lower levels, the resulting $T_{\mathrm{BG}}(B)$ data at high fields ($B \geq 2$ T) fit Eq. (3) (in a one-parameter fit), with $a_2 = 1.13 \times 10^{-2}$ $\mathrm{K}^{-1}\mathrm{T}^{-1/2}$ (Fig. 3). This is in very good agreement with the above theoretical estimation, which gives, with $\xi_{ab}(0) \approx 3$ nm, $c_L \approx 0.2$,[8] $\mathrm{Gi} \approx 0.1$,[8,19] $\kappa \approx 100$,[8] and $T_{c0} = 89$ K, $a_2 \approx 10^{-2}$ $\mathrm{K}^{-1}\mathrm{T}^{-1/2}$. If we take the high-field T_r data from Fig. 1 (inset) instead of T_{BG}, the magnetic-field exponent remains $\frac{1}{2}$, but the constant a_2 becomes lower $[0.88 \times 10^{-2}\,\mathrm{K}^{-1}\mathrm{T}^{-1/2}]$.

The applicability of the theory of Bose-glass transition in the case of Bi-2:2:1:2 is puzzling, taking into consideration the large intrinsic anisotropy of this compound. In some experiments, the material appears to be magnetically transparent for fields perpendicular to the c axis.[20] However, detailed analyses of the magnetic field and temperature dependence of the activation energy in the TAFF regime[21–23] have revealed an excellent quantitative agreement with the model of plastic TAFF with double vortex-kink formation.[24] This model, extended in Ref. 25 for a vortex liquid, describes both the linear temperature decrease of the activation energy U with increasing temperature, and the field dependence $U(B) \sim B^{-1/2}$, observed experimentally in the case of Bi-2:2:1:2 films,[22,23] over an extended magnetic-field–temperature domain. This means that the $(\mathrm{CuO_2})_2$ blocks cannot be considered completely decoupled, even in fields as high as 7 T.

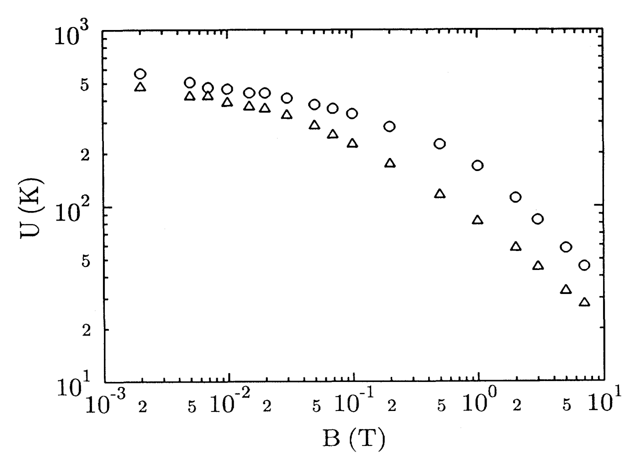

FIG. 4. The activation energy in the TAFF regime vs applied magnetic field, at $T/T_{c0} \approx 0.9$: (Δ) unirradiated sample; (○) irradiated sample.

After irradiation, significant modifications were observed. In Fig. 4, we illustrated the change of the magnetic-field dependence of the activation energy in the TAFF regime at $T/T_{c0} \approx 0.9$, induced by the presence of the columnar defect structure. The $U(T,B)$ values were determined directly from the $\rho(T)$ data,[22,23]

$$U(T,B)=T[\ln\rho(T_{c0},B)-\ln\rho(T,B)] \quad (k_B=1) .$$

The change in the $U(B)$ variation at $B_{cr}=30-40$ mT, observed for the unirradiated sample, was attributed[23,26] to the appearance of vortex strings with three-dimensional fluctuations, due to the increase of the tilt modulus at $B < B_{cr}$, when the intervortex spacing is higher than the Josephson bending length.[2,27] In the case of the sample without columnar defects, at $B > B_{cr}$, the $B^{-1/2}$ dependence of the activation energy (resulting from the double vortex-link formation) is seen, whereas this is shifted to higher fields for the irradiated sample (Fig. 4). [Moreover, the linear $U(T)$ dependence, which is characteristic for samples without columnar defects for $B > B_{cr}$, transforms into an upcurved $U(T)$ variation at low temperatures.] This behavior can be interpreted through an increase of the tilt modulus (even for large field values) in the presence of the columnar defects, which promote vortex localization.

In conclusion, the temperature dependence of the resistivity of epitaxial Bi-2:2:1:2 films with columnar defects along the c axis, for applied fields parallel to the defects, indicates the occurrence of the Bose-glass transition at low temperatures, with vortices localized on the columnar pins. The magnetic-field dependence of the Bose-glass transition temperature at very low fields is in agreement with the theory of boson localization in the presence of correlated disorder. The applicability of this theory in the case of highly anisotropic superconductors, such as Bi-2:2:1:2, was explained through an increase of the tilt modulus in the presence of the columnar defect structure. For fields significantly larger than the dose-equivalent field, the vortex delocalization in our samples seems to proceed via melting.

The kind assistance of the Alexander von Humboldt Foundation is gratefully acknowledged.

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