Zero-magnetic-field dynamic scaling in $Bi_2Sr_2CaCu_2O_8$ thin films

Z. Sefrioui, D. Arias, C. Leon, and J. Santamaria
GFMC, Departamento de Física Aplicada III, Facultad de Física, Universidad Complutense de Madrid, 28040-Madrid, Spain

E. M. Gonzalez and J. L. Vicent
Departamento de Física de Materiales, Facultad de Física, Universidad Complutense de Madrid, 28040-Madrid, Spain

P. Prieto
Departamento de Física, Universidad del Valle, Cali, Colombia
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We investigate the zero-magnetic-field dynamic scaling in $Bi_2Sr_2CaCu_2O_8$ thin films from nonlinear current-voltage (*I-V*) characteristics and by using the concavity criterion recently proposed by Strachan *et al.* [Phys. Rev. Lett. **87**, 067007 (2001)]. We find that fresh samples show a BKT-like transition with $z=0.8$, smaller than expected for a conventional Berezinskii-Kosterlitz-Thouless transition. The effect of sample size and finite Josephson coupling are discussed. We examine the effect of thermally-induced disorder in the oxygen sublattice finding that the BKT-like transition is suppressed by point disorder.

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I. INTRODUCTION

Phase transitions in vortex matter have attracted considerable interest in recent years in connection with high T_c superconductors (HTS). The layered structure and high anisotropy of HTS promote decoupling between copper oxygen planes, and breakdown of the superconducting coherence along the *c* direction. In 3D superconductors *c*-axis phase coherence is due to the finite interlayer (Josephson) coupling, but decoupling of vortex segments in adjacent layers may occur by increasing applied magnetic fields when intralayer interactions become dominant. In 2D superconductors, with negligible interlayer coupling, the dissociation of logarithmically interacting vortex-antivortex pairs in the individual layers gives rise to the Berezinskii-Kosterlitz-Thouless (BKT) transition[1] at a finite temperature, T_{BKT}, in zero applied magnetic field. While extensive work has been directed to examine the dynamics of the vortex phase transitions in presence of magnetic fields, comparatively less attention has been devoted to the BKT transition.

Close to the unbinding transition at T_{BKT}, the correlation length ξ_{BKT}, representing the scale at which vortices begin to unbind takes the form[2]

$$\xi_{\mathrm{BKT}}(T) \sim \exp[[b/(T/T_{\mathrm{BKT}}-1)]^{1/2}], \tag{1}$$

where *b* is a nonuniversal constant of order of unity. For temperatures above T_{BKT}, the system develops a finite density of free vortices ($n_v \sim \xi_{\mathrm{BKT}}^{-z}$) inducing Ohmic behavior at small current densities as

$$R_{\mathrm{lin}}(T)\alpha \exp[-z[b/(T/T_{\mathrm{BKT}}-1)]^{1/2}], \tag{2}$$

where *z* is the dynamic exponent of the transition. At low temperatures ($T<T_{\mathrm{BKT}}$), vortex-antivortex pairs dissociate in the presence of applied current densities *j*.[2,3] This results in powerlike dissipation of the form $V\alpha I^{\alpha(T)}$, with the temperature dependent exponent $\alpha(T)$ exhibiting a sudden decrease[4] from the universal value $\alpha(T_{\mathrm{BKT}})=z+1$ to $\alpha(T>T_{\mathrm{BKT}})=1$. Within this context, dynamic scaling has been proposed[5] for the BKT transition, resulting from the divergence of a time scale τ as ξ^z, provided its well established continuous nature. The scaling ansatz is basically similar to that proposed by Fisher, Fisher, and Huse (FFH),[6] but with a temperature dependent resistivity given by Eq. (2), and accordingly the *I-V* curves should scale as

$$I^{z+1}/[VT^z] = g(I^z/R_{\mathrm{lin}}(T)T^z). \tag{3}$$

Although the value of the dynamic exponent $z=2$ expected for the BKT transition has been theoretically confirmed in many numerical simulations, as for example the lattice Coulomb gas with Monte Carlo[7] or Langevin-type molecular dynamics,[8] or the 2D *XY* model with both resistively shunted junction and relaxation dynamics,[9,10] experimental work showing evidence of the $z=2$ universality class are scarce in HTS systems. A zero field BKT transition has been reported for the highly anisotropic BSCCO and TBCCO superconductors[11–14] assuming but *not* testing the value $z=2$. In fact quite high values of $z\sim 6$ have been reported[5] in various 2D systems and as low as 0.6–0.77 in Nb/Cu/Nb Josephson junctions arrays (JJA),[15] questioning the universality class of the transition. More recently it has been shown that finite size effects can be responsible for large changes in the scaling exponents as discussed by Medvedyeva *et al.*[16] and Holzer *et al.*,[17] which may explain the large *z* values of Ref. 5. A true BKT transition in ultrathin (one unit cell thick) YBCO films has also been questioned[18] on the basis of size effects. Reduced *z* values, on the other hand, have been discussed in terms of disorder affecting the dynamics of the transition.[15] In addition, limited instrumental resolution has also been shown to be critical in determining the correct exponents and transition temperature unambiguously:[19] a wide set of transition temperatures and exponents produce equally satisfactory scaling plots, questioning the validity of scaling arguments to provide the correct critical parameters. A criterion recently proposed by Strachan *et al.* [19,20] based on the change of curvature of the derivatives of *I*-*V* iosotherms at the transition has been used to arrive at the correct sets of exponents and critical temperature from scaling arguments in different vortex systems. Summarizing, it is not clear whether the observed departures from the $z=2$ value result from extrinsic effects like finite size or instrumental resolution, or whether intrinsic effects like disorder may change the dynamics of a BKT-like transition.

In this paper, we investigate this issue analyzing the zero field vortex system in epitaxial $Bi_2Sr_2CaCu_2O_8$ thin films 4000 Å thick. We report measurements of both nonlinear current-voltage (*I*-*V*) characteristics and linear resistance $R_{lin}(T)$. The criterion recently proposed by Strachan *et al.*[19,20] is used to arrive at the correct exponent and critical temperature from scaling arguments. Fresh $Bi_2Sr_2CaCu_2O_8$ films show a BKT-like transition with $z=0.8$, smaller than expected for the BKT transition but similar to that observed in frustrated Josephson junction arrays (JJA).[15] The possibility of the vortex dynamics being affected by disorder is explored introducing thermally induced point like disorder in the oxygen sublattice. We find that the BKT transition is suppressed by disorder and the transition displays the scaling behavior typically found under applied magnetic field.

II. EXPERIMENT

Samples were grown on (100) $SrTiO_3$ using a high pressure (4 mbar) pure oxygen sputtering apparatus at 900 °C. The correct oxygen stoichiometry was ensured by an *in situ* annealing at 700 °C in one pure oxygen atmosphere for 30 min followed by a slow cooling down ramp (1 K/min) to ensure an ordered structure in the oxygen sublattice. Samples were epitaxial as proven by x-ray diffraction (θ-2θ geometry and pole figures) and transmission electron microscopy. Further details about sample preparation and epitaxial properties can be found elsewhere.[21–23] Underdoped samples ($T_c=78$ K) with a disordered oxygen structure were obtained by vacuum annealing the samples at 500 °C as proposed in Ref. 24. These postdeposition anneals do not produce other structural defects as inducing point disorder (vacancies) in the oxygen sublattice as confirmed by x-ray diffraction and transmission electron microscopy. *I*-*V* curves were measured on photolithographically patterned bridges with dimensions $100\times400\ \mu m^2$. Contacts were done on evaporated silver pads to ensure small contact resistances. A temperature stability better than 10 mK was ensured prior to data acquisition. The effect of these postdeposition anneals on the scaling behavior described below was checked on three different samples to ensure reproducibility.

III. RESULTS AND DISCUSSION

Figure 1(a) shows the typical nonlinear *I*-*V* characteristics on a double logarithmic scale for a fresh $Bi_2Sr_2CaCu_2O_8$ thin film in zero magnetic field. The temperature range of these *I*-*V* isotherms is from 75 K at the lower right to 90 K at the upper left in increments of 1 K. While the *I*-*V* characteristics at high temperatures have positive curvatures, negative curvature is observed at low temperatures (note that the upturns

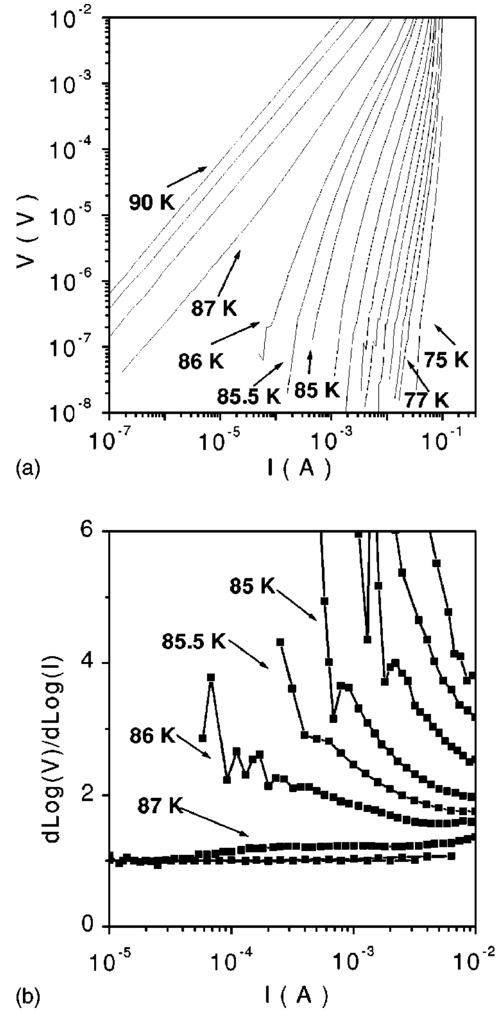

FIG. 1. (a) *I*-*V* characteristics in double logarithmic scale for the homogeneous BSCCO thin film in zero magnetic field. The temperature ranges from 75 K (lower right) to 90 K (upper left). Temperature increments for not labeled isotherms in the figure is 1 K. (b) Derivative plot $d\log(V)/d\log(I)$ vs I for the same sample as in (a).

of the low temperature isotherms at the highest current and voltage levels are due to sample heating). A pronounced jump in the low current dissipation is observed around 86 K, suggesting a transition at this temperature. In the following we use scaling arguments to show that this is actually a BKT-like transition and to obtain the critical exponent *z* and the transition temperature. The transition temperature is obtained from the derivative plot as suggested by Strachan *et al.*[19,20] The proposed criterion for *I*-*V* data is that $\log V$ vs $\log I$ isotherms above and below T_{BKT} must have opposite concavities at the same applied currents. Figure 1(b) shows the current dependence of the derivative of the $\log V$ vs $\log I$ isotherms of Fig. 1(a). Note that the isotherms below and above 86 K have opposite concavities at the same current level indicating a transition temperature in the range $85.5\ K < T_{BKT} < 87$ K. Now, in order to investigate the scaling properties of this transition, scaling plots were constructed using Eq. (3). Using the transition temperature, T_{BKT}, of 86 K all isotherms collapse into a single master

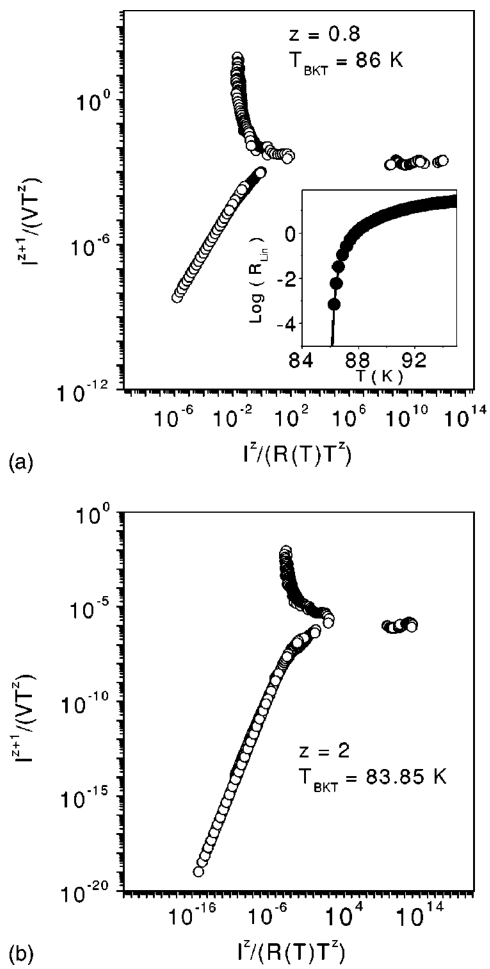

FIG. 2. (a) Scaling plot according to BKT theory, for the homogeneous BSCCO sample [same data as in Fig. 1(a)], with parameters $T_{BKT}=86$ K and $z=0.8$. Inset: Temperature dependence of linear resistance for homogeneous BSCCO thin film in zero magnetic field. The solid line represents the theoretical fit to Eq. (2) with parameters of $z=0.8$, $T_{BKT}=86$ K and $b=0.9$. (b) Scaling plot according to Ref. 14 with parameters $T_{BKT}=86$ K and $z=2$ for the same sample as in Fig. 1.

curve for a value of the dynamic exponent $z=0.8$, showing the BKT-like character of the transition [see Fig. 2(a)]. Further support for a BKT transition in our homogeneous $Bi_2Sr_2CaCu_2O_8$ thin film is based on the analysis of the linear resistance $R_{lin}(T)$ data obtained from the low current resistance vs temperature measurements at zero magnetic field [see inset of Fig. 2(a)]. An analysis of those data in terms of Eq. (2) produced a very good fit with exactly the same values of the parameters $z=0.8$, and a T_{BKT} value of 85.98 K and a value for the nonuniversal constant $b=0.9$. The fit is also illustrated in the inset of Fig. 2(a). It is worth noting that the resistance data drops abruptly below 87 K suggesting a true superconducting state in our pure 2D system below 86 K. It is interesting to remark that the same set of parameters z,b, and T_{BKT} consistently accounted for the resistance measurements and for the scaling, which is not necessarily the case if the opposite concavity criterion by Strachan *et al.* is not observed.[19,20] Due to the large scaling flexibility equally satisfactory scaling plots can be constructed for different sets of b,z, and T_{BKT}. In fact, if we tentatively fix the value of $z=2$ for conserving the concept of universality of the BKT, it is actually possible to scale the data of Fig. 1 but, with a much smaller T_{BKT}. Figure 2(b) shows a fairly good scaling plot with $z=2$, but with a $T_{BKT}=83.85$ K. Obviously, this scaling is not consistent with the sharp resistance drop below 87 K, nor with the Strachan concavity criterion. Moreover, if we fix the *higher* value of $z=5.6$ reported by Pierson *et al.*,[5] it is also possible to scale the data of Fig. 1 eventually, but with a much smaller T_{BKT} of 76 K. It is worth stressing that the scaling argument by its own is not sufficient to provide the actual values of transition temperature and critical exponents, but the concavity criterion produces a value of the transition temperature which is consistent with the resistance drop in resistance curves. This flexibility of the scaling has been also discussed very recently by other authors.[20] It is important to notice here that the applicability of this scaling to the BKT transition has been recently questioned on the basis of size effects (discussed later)[25] and on an inconsistency with power law dependent isotherms below the transition temperature in the very small current limit.[20] Attempts to reanalyze the data of Fig. 1 using 3D or quasi-2D (Ref. 26) VG transition scaling relations proposed by Fisher, Fisher, and Huse[5] produced deteriorated scaling plots supporting the picture of a BKT-like transition. To check reproducibility we have measured two different samples all showing the same behavior. Figures 3(a) and 3(b) show *I-V* and derivative plots, respectively. Figure 4 shows the corresponding scaling plot with very similar scaling parameter as found for the sample of Fig. 2 ($z=0.8, T_{KT}=86, b=1.2$) supporting the picture of a BKT-like transition in these samples.

We now discuss the occurrence of a BKT-like transition in connection with sample details. In the BKT theory the critical separation between a bound pair, r_c, is defined (below T_{BKT}) such that vortex pairs separated a distance greater than r_c repel each other under the action of an applied current density j_{2D}, thus giving rise to linear dissipation. The critical distance r_c can be expressed as[20]

$$r_c = \frac{\phi_0}{\left(\frac{\varepsilon_\infty}{\varepsilon_0}\right) 2\pi\mu_o j_{2D}\lambda_\perp},$$

where ϕ_0 is the flux quantum, μ_o is the permeability of vacuum, and the ratio $\varepsilon_\infty/\varepsilon_0$ is approximately 1, with ε_∞ the permittivity taking into account screening of pairs and ϵ_0 the vacuum permittivity. $\lambda_\perp$ is the effective penetration depth for a thin film which in the case of decoupled layers can be written as λ^2/s, where λ is the penetration depth (≈ 2000 Å for BSCCO) and s the interlayer distance. $\lambda_\perp$ can be estimated to be in the 100 μm range for our BSCCO film. The competition between r_c and the sample characteristic length scales can drastically modify or even suppress the BKT transition.[5] A first issue which deserves discussion is size effects.[17] Free vortices can be induced below T_{BKT} resulting from size effects when the critical distance r_c is larger than $\min[W,\lambda_\perp]$, where W is sample width. Since no free vortices are expected for $r_c \ll \min[W,\lambda_\perp]$ size effects may yield an apparent transition, termed "ghost" transition by

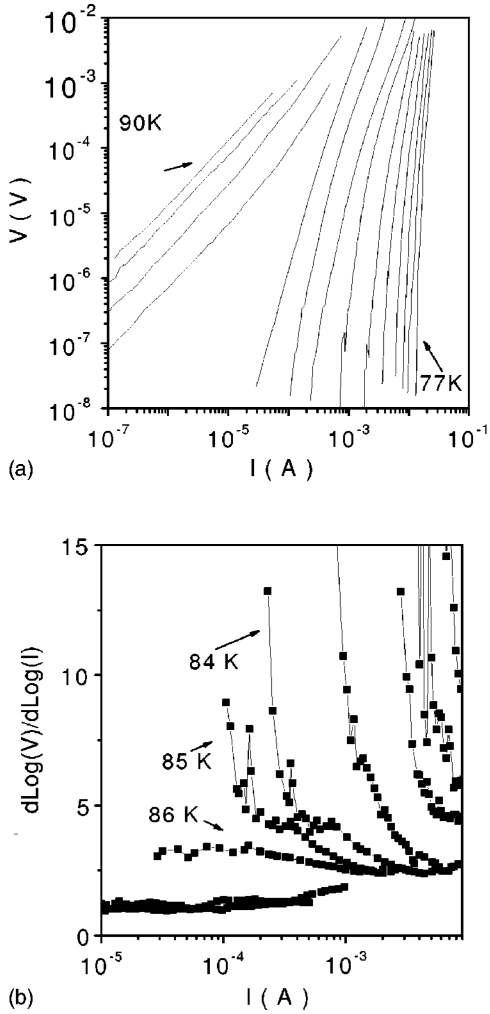

FIG. 3. (a) *I-V* characteristics in double logarithmic scale for an additional homogeneous BSCCO thin film in zero magnetic field. The temperature ranges from 77 K (lower right) to 90 K (upper left). Temperature increment for the isotherms in the figure is 1 K. (b) Derivative plot $d\log(V)/d\log(I)$ vs I for the same sample as in (a).

Medvedyeva *et al.*[16] obeying a specific scaling behavior. Using the expression for r_c given above, and since $\lambda_\perp$ and W are both in the 100 μm range, size effects are expected for current levels such that

$$\lambda_\perp \leqslant \frac{\phi_0}{\left(\frac{\epsilon_\infty}{\varepsilon_0}\right) 2\pi\mu_o j_{2D}\lambda_\perp},$$

i.e., $I_{2D} \leqslant 2\times 10^{-6}$ A, a current range practically out of our experimental window (see isotherms of Fig. 1). We therefore do not expect the observed scaling behavior being affected by size effects. Another issue to consider is the influence of 3D correlation in our BSCCO sample. Although there is consensus that at low magnetic field and low temperatures a finite interlayer (Josephson) coupling may exist in this highly anisotropic superconductor, it is well known that increasing an applied magnetic field perpendicular to the layers triggers

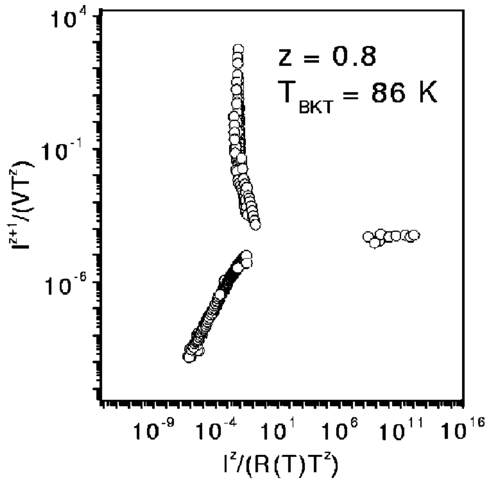

FIG. 4. (a) Scaling plot according to BKT theory, for the data of Fig. 3(a), with parameters $T_{\mathrm{BKT}}=86$ K and $z=0.8$ and $b=1.2$.

decoupling of the layers turning the vortex system into 2D.[26] Similarly, increasing temperature can also induce decoupling due to enhanced fluctuations, and a low current decoupling temperature $T^*=84$ K has been reported by Miu *et al.*[27] for BSCCO samples similar to ours which is below the transition temperature of our sample. It has been reported[5] that, at low temperatures, finite Josephson coupling may cut-off BKT behavior when $r_c(j_{2D})$ becomes smaller than the Josephson length λ_J which is related to effective mass anisotropy, γ, and interplane separation, s, as $\lambda_J=\gamma s$. At in plane distances shorter than λ_J vortices interact logarithmically (2D) while at distances larger than λ_J the interaction becomes linear (3D). BKT behavior will then be suppressed when $r_c \geqslant \lambda_J$ what, according to the expression given above for r_c, sets a lower current limit below which 3D effects are observed. On the other hand 3D vortex correlations are destroyed by thermal fluctuations and the layers decouple favoring 2D correlations. This introduces a new length scale, $l_{3D/2D}$,[28] which has been estimated to be $l_{3D/2D}=\gamma\xi_c$, where ξ_c is the vortex correlation length in the c-direction. Vortex decouples for in-plane distances longer than $l_{3D/2D}$. The competition between both length scales λ_J and $l_{3D/2D}$ is responsible for 3D effects to be present in a current interval below T_{BKT} such that $\lambda_J < r_c < l_{3D/2D}$, as reported recently by Pierson *et al.* for BSCCO single crystals.[5] Note that when temperature is increased towards the transition temperature this interval will narrow since ξ_c will approach s, and thus $l_{3D/2D}$ will approach λ_J.

Our results reveal that the dynamic critical exponent z is 0.8, smaller than that expected for BKT transition but similar to that observed in frustrated Josephson junction arrays (JJA).[15] A possible explanation for the reduced value of the exponent z is the effect of disorder on the dynamics of the vortex system as proposed in the case of JJA.[15] The effect of point disorder through modified pinning has shown to deeply influence the vortex phase diagram. To further explore the influence of point disorder on the dynamics of the vortex system we have analyzed samples with point disorder introduced intentionally during the vacuum postgrowth anneal. The effect of quenched disorder was supported by the in-

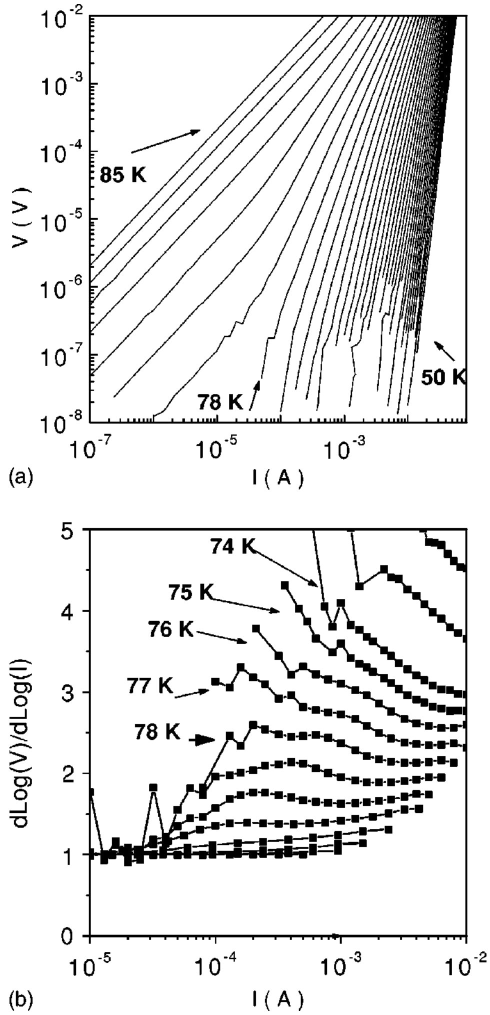

FIG. 5. (a) *I-V* curves in log-log scale for the disordered BSCCO sample in zero magnetic field. The temperature ranges from 50 K (lower right) to 85 K (upper left) in increments of 1 K. (b) Derivative plot $d\ \log(V)/d\ \log(I)$ vs I for the same sample as in (a).

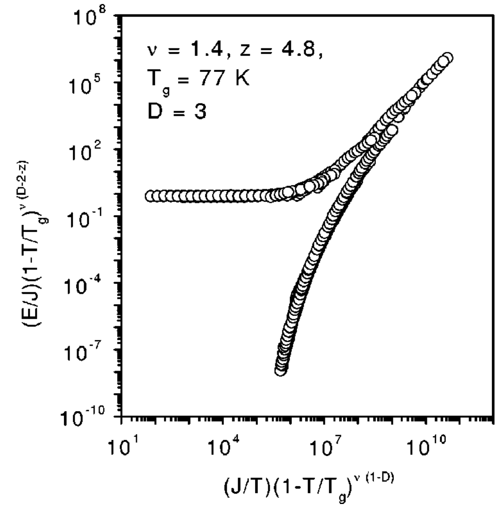

FIG. 6. FFH scaling plot for the disordered BSCCO thin film in zero magnetic field [same data as in Fig. 5(a)].

crease of the normal state resistivity relative to that of homogeneous sample and a slight reduction of the critical temperature. Shown in Fig. 5(a) are the *I-V* isotherms for a disordered $Bi_2Sr_2CaCu_2O_8$ film measured at zero magnetic field. From an analysis of those data in terms of the derivative plots shown in Fig. 5(b) one could say transition temperature to be around 78 K, but instrumental resolution does not allow us to exclude the possible existence of an ohmic tail at lower currents for the $T=78$ K isotherm, and thus the transition temperature cannot be determined unambigously from the concavity criterion. However it is clear that the 79 K isotherm has an ohmic tail (and downward curvature in the derivative plot) and the 76 K isotherm has a clear upward curvature in the derivative plot, this pointing to a transition in the vortex system in the temperature range 76–79 K. Nevertheless, no matter which transition temperature was used in this range (76–79 K), it was not possible to scale *I-V* curves according to a BKT transition scheme, what allows discarding this mechanism for the transition. On the other hand, a good scaling similar to that typically seen under an applied magnetic field is obtained using the FFH scaling relation[6]

$$E(J) \sim J\ \xi_g^{D-2-z} E_{\pm}[J \xi_g^{D-1} \phi_0 / k_B T], \tag{4}$$

where $\xi_g \sim |T\text{-}T_g|^{-\nu}$ is the vortex-glass coherence length, ν and z are the static and dynamic exponents, respectively, the parameter D is the dimension of the system, and $E_{\pm}$ is a universal scaling function above (E_+) and below (E_-) T_g. Critical exponents were $\nu=1.4$ and $z=4.85$ similar to those found for $YBa_2Cu_3O_{7-\delta}$ in presence of magnetic field,[20] $T_g=77$ K and $D=3$ (see Fig. 6). The same behavior was found in other two different samples after the same annealing process. An example of the reproducibility is shown for one of them in Figs. 7 and 8. This sample had a slightly higher $T_g=79.6$ K and critical exponents ($\nu=1.4$ and $z=4.7$) also very similar to those found for the sample of Fig. 6. Again, a reasonable collapse consistent with a 3D vortex system was obtained (see Fig. 8). While it is clear that this scaling reflects a change of the dynamics of the vortex system with point disorder, we stress that the concavity criterion is not satisfied unambiguously, and due to the large flexibility of the scaling parameters this does not permit us to conclusively determine whether a change in the dimensionality occurs. This result seems to be at variance with previous studies on the effect of percolative disorder in Nb-Au-Nb JJA's.[29] They found that although disorder suppresses T_c and broadens resistive transition, the scaling invariance of the transition is conserved as shown by not modified values of the dynamic exponent z. This result was discussed in connection with the theoretical analysis of Harris[30] of the disordered 2D Ising model. However it is important to remark that at the time Ref. 29 was published the concavity criterion was not known and we do not know how the scaling flexibilty might have affected the value of the critical exponent z. Our result, on the other hand, illustrates that quenched disorder has a drastic effect on the dynamics of the vortex system suppressing the BKT-like transition. Several examples exist in the literature where samples with the same composition and in the same magnetic fields show different dimensionality of the

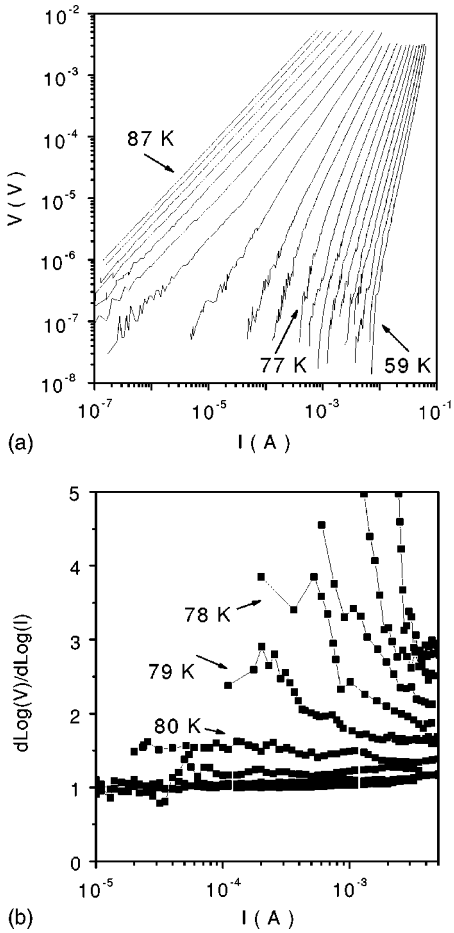

FIG. 7. (a) *I-V* curves in log-log scale for a different disordered BSCCO sample in zero magnetic field. The temperature ranges from 59 K (lower right) to 87 K (upper left). Temperature increments are 2 K below the isotherm marked with 77 K and 1 K above it. (b) Derivative plot $d\,\log(V)/d\,\log(I)$ vs I for the same sample as in (a).

glass transition. This is most likely due to different anisotropies resulting from different disorder. For example, a quasi-2D vortex glass transition has been observed for $Tl_2Ba_2CaCu_2O_8$ thin films at low fields ($H=0.1$ T);[14] however a 3D VG transition[31] was found for the same compound and in the same magnetic field, suggesting different anisotropies in both samples. Concerning deoxygenated YBCO samples, while a quasi-2D vortex glass transition has been

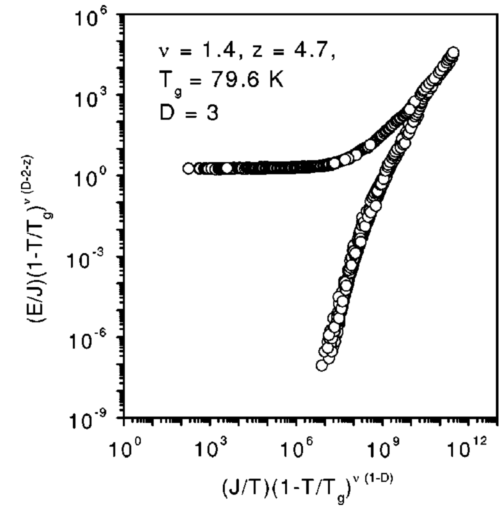

FIG. 8. FFH scaling plot in zero magnetic field for the same data as in Fig. 7(a).

reported in high magnetic fields,[32] other authors have found a 3D transition at the same doping level and magnetic fields.[33] These differences can be explained by different levels of disorder which are expected to result in different anisotropy values. However, previous studies[24] on the effect of disorder generated by vacuum annealing of BSCCO films (similar to those used here) show that carrier concentration is reduced and anisotropy is increased, suggesting that the suppression of the BKT transition is most likely related to the generated pointlike disorder. Further work will be necessary to clarify the influence of disorder on the vortex transition in zero magnetic field.

In summary, we have explored the zero field vortex matter in $Bi_2Sr_2CaCu_2O_8$ thin films. We have provided evidence for a BKT-like transition in fresh high quality epitaxial samples. Scaling arguments and the concavity criterion consistently yielded a reduced value of the dynamic exponent $z=0.8$, similar to that found recently in JJA. The introduction of point disorder suppresses the BKT-like transition and yields a behavior like that usually observed under applied magnetic field, i.e., the concavity criterion is not demonstrated unambiguously.

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