2D Vortex-Glass Transition with $T_g = 0$ K in $Tl_2Ba_2CaCu_2O_8$ Thin Films due to High Magnetic Fields

Hai-hu Wen,[1,2] H. A. Radovan,[1] F.-M. Kamm,[1] and P. Ziemann[1]
[1]*Abteilung Festkörperphysik, Universität Ulm, D-89069 Ulm, Germany*
[2]*National Laboratory for Superconductivity, Institute of Physics and Center for Condensed Matter Physics, P.O. Box 603, Beijing 100080, People's Republic of China*

S. L. Yan, L. Fang, and M. S. Si
Department of Electronics, Nankai University, Tianjing 300071, People's Republic of China
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By dc transport measurements, current-voltage characteristics of $Tl_2Ba_2CaCu_2O_8$ thin films were determined in magnetic fields up to 5 T. For high magnetic fields (3, 5 T), it is found that all data can be interpreted in terms of the 2D vortex-glass theory: (1) All E-j isotherms can be scaled onto one common branch applying the scaling suggested for a 2D vortex system; (2) the linear resistivity $\rho_{\rm lin}(T)$ as well as the nonlinear current density $j_{\rm nl}$ are found to follow the predicted relations $\rho_{\rm lin}(T) \propto \exp[-(T_0/T)^p]$ and $j_{\rm nl}(T) \propto T^{1+\nu_{\rm 2D}}$, respectively. Both scaling of E-j curves and fitting $j_{\rm nl}(T)$ consistently lead to value $\nu_{\rm 2D} = 2$ as predicted by the 2D vortex-glass theory. Also, the values found for T_0 (200 ± 30 K) and p (≈ 1.58) are either experimentally reasonable or within the limit expected by theory ($p \geq 1$). [S0031-9007(98)05840-2]

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For highly anisotropic superconductors, such as $Tl_2Ba_2CaCu_2O_8$, $Bi_2Sr_2CaCu_2O_8$, or $YBa_2Cu_3O_7$/$PrBa_2Cu_3O_7$ superlattices, it is expected that flux dynamics can be changed from 3D to 2D by increasing magnetic fields [1–3]. In the presence of a high density of weak pinning centers, for a 3D vortex system a second-order phase transition is predicted to occur at a finite temperature T_g [4], with a new phase, the vortex glass (VG), existing below T_g. The VG theory has triggered enormous experimental efforts [5–8], and most results show a reasonable agreement between theory and the experimental data. For 2D vortex systems, however, theory predicts that the VG transition will occur only at zero K. Experimentally, Dekker *et al.* [9] measured E-j curves on one-unit-cell thick $YBa_2Cu_2O_7$ thin films and found that the data can be fitted to the 2D VG theory. In a previous paper, Wen *et al.* [10] have shown that the μ values for parametrizing the activation energy $U(j,T) = \frac{U_c(T)}{\mu}[(\frac{j_c(T)}{j})^\mu - 1]$ are always negative for $Tl_2Ba_2CaCu_2O_8$, when the magnetic field is higher than about 0.7 T. Thus, for these higher fields the curvature of $\log(E)$ vs $\log(j)$ is always positive, leading to a finite linear resistivity $\rho_{\rm lin} = E/j|_{j\to 0} \neq 0$. The negative μ values were attributed to a field induced vanishing of T_g. In [10] emphasis is put on the resulting vortex phase diagram rather than on the 2D vortex dynamics. To the best of our knowledge, a direct experimental evidence for a genuine 2D VG is still lacking for highly anisotropic high-T_c superconductors. In this Letter, we unambiguously show that all the data measured for $Tl_2Ba_2CaCu_2O_8$ thin films at relatively high magnetic fields (3, 5 T) can be well described by 2D VG theory.

Before presenting the experimental data, we briefly recall the major predictions for a 2D VG [2,11]. According to 2D VG theory, when approaching $T_g = 0$ K, a finite VG correlation length $\xi_{\rm 2D}$ develops and diverges at $T = 0$ K as

$$\xi_{\rm 2D} = a_0(\varepsilon_0 d/k_B T)^{\nu_{\rm 2D}}, \tag{1}$$

with $\nu_{\rm 2D}$ the 2D VG exponent and a_0 the spacing of the vortex lattice; $\varepsilon_0 d = \hbar^2 \rho_s d/m$, the core energy of a vortex segment of length d, where ρ_s and m are the density and mass of Cooper pairs, respectively. Dissipation in the vortex system is caused by vortex excitations. Assuming an excitation of size L, the energy barrier V_L which has to be surmounted is usually assumed to be proportional to L^α with $\alpha \geq 0$. For a 2D vortex system, since the upper limit for L is the correlation length $\xi_{\rm 2D}$, the linear resistivity $\rho_{\rm lin}$ due to thermal activation is given by

$$\rho_{\rm lin} \propto \exp(-V_{L=\xi_{\rm 2D}}/k_B T) \propto \exp[-(T_0/T)^p], \tag{2}$$

where T_0 is a characteristic temperature of the same order of magnitude as $\varepsilon_0 d$, and $p = 1 + \alpha\nu_{\rm 2D} \geq 1$. In the presence of a current density j, an energy $\phi_0 j \xi_{\rm 2D}$ is available to create vortex excitations. At a current density $j_{\rm nl} = k_B T/\phi_0 \xi_{\rm 2D}$, this energy becomes comparable to the thermal energy $k_B T$, resulting in nonlinear E-j curves. Combining with Eq. (1) one obtains

$$j_{\rm nl} = k_B T/\phi_0 \xi_{\rm 2D} = (k_B T)^{1+\nu_{\rm 2D}}/\phi_0 a_0 (\varepsilon_0 d)^{\nu_{\rm 2D}}. \tag{3}$$

In view of Eqs. (2) and (3), Dekker *et al.* [9] first suggested a 2D scaling method for the E-j characteristics as

$$\frac{E}{j}\exp\left[\left(\frac{T_0}{T}\right)^p\right] = g\left(\frac{j}{T^{1+\nu_{\rm 2D}}}\right), \tag{4}$$

where $g(x)$ is a general function for all temperatures at a given magnetic field. Equations (1)–(4) are the fundamental predictions for the dynamics of a 2D vortex system. In the special case of thermally activated flux creep, it is anticipated that $\nu_{2D} = 2$. A major difference between the predictions for quantum tunneling and thermal activation are the different values for p. For example, p is predicted to be 0.7 for quantum tunneling in contrast to $p \geq 1$ as quoted above. In the following, we will show that all of our experimental data can be consistently described by the 2D VG theory for the regime of thermally activated flux creep.

The samples are $Tl_2Ba_2CaCu_2O_8$ thin films which were prepared by a two-step procedure on (001) $LaAlO_3$ substrates. Details on the fabrication of the films were published previously [12]. dc resistive measurements show that T_c $(R = 0) = 104$ K with a transition width $\Delta T_c \approx 4$ K. X-ray diffraction patterns taken from the samples show that only $(00l)$ peaks are observable, indicating highly textured growth.

The four-probe technique was used to measure the E-j curves. The magnetic field is applied perpendicular to the film surface as well as to the current direction. The films are patterned lithographically into a bridge with lateral dimensions of 33×500 μm^2. After chemical etching, gold pads were deposited onto four contact areas of the $Tl_2Ba_2CaCu_2O_8$ films providing the current and voltage connects. After this process, typical contact resistances are below 0.1 Ω allowing the measurement of E-j curves with almost negligible heating effects. During the measurement for each E-j curve, the temperature of the sample holder was stabilized to better than 0.1 K. Results will be presented for two films (denoted as Sample-1 and Sample-2) prepared independently. It is found that the results obtained for these two films are essentially the same though their thickness differed (110 nm for Sample-1 and 230 nm for Sample-2). Thus, in this paper, the data from Sample-1 are presented exclusively, except for a comparison given in the inset of Fig. 2(a) for Sample-2.

In Fig. 1, typical I-V curves are presented on a double-logarithmic scale. Each curve is an isotherm, ranging from 24 K at the lower right to 80 K at the upper left in increments of 1 K as determined in an external magnetic field of 3 T. From about 32 to 80 K, each I-V curve shows a positive curvature, and a linear behavior is anticipated for small currents. Below 32 K, the I-V curves closely approach each other and become very steep. A slightly negative curvature appears for the I-V curves in the high current regime at low temperatures (e.g., from 24 to 26 K). This can be attributed to the gradual crossover from flux creep to flux flow [7]. Assuming that this slightly negative curvature is due to a vortex-glass transition at a temperature close to 30 K, one would have $E \propto j^{(z+1)/(D-1)}$ [2,4,5] at T_g with a value of $(z + 1)/(D - 1) \approx 8.8$, where z is an exponent expected to be in the range 4–6, and D is the dimensionality. For a 3D VG transition the experimental value

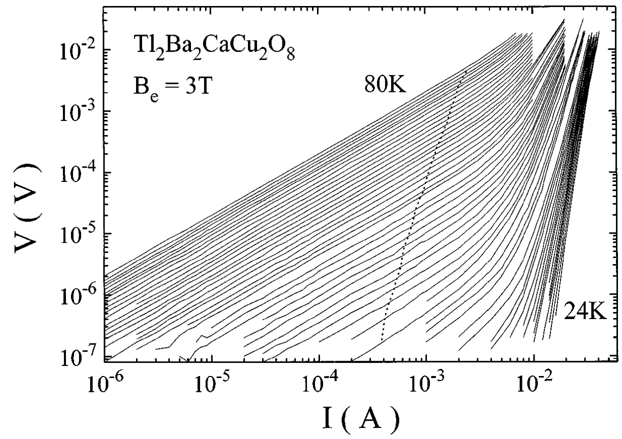

FIG. 1. Double logarithmically plotted I-V curves as determined on Sample-1 with $B_e = 3$ T. The isotherms range from 24 K at the lower right to 80 K at the upper left in increments of 1 K. The dotted line marks the boundary between the linear and nonlinear regimes of the I-V curves.

of 8.8 leads to an unreasonably high value of $z = 16.6$. Similarly, even the assumption of a quasi-2D VG transition [13] results in the rather large value of $z = 7.8$. It is found that the E-j curves shown in Fig. 1 cannot be scaled according to the 3D VG or the quasi-2D VG scaling method [5–8,13] by choosing any finite temperature as T_g. In contrast, an excellent description is given by the 2D VG theory as is demonstrated by the following 2D scaling analysis of E-j curves. In Figs. 2(a) and 2(b) the corresponding scaling results are presented for 3 and 5 T, respectively. To obtain such a good scaling, the parameters $\nu_{2D} = 2 \pm 0.3$, $p = 1.58 \pm 0.05$, and $T_0 = 230 \pm 5$ K had to be chosen for 3 T; and $\nu_{2D} = 2 \pm 0.3$, $p = 1.58 \pm 0.05$, $T_0 = 190 \pm 5$ K for 5 T, respectively. Shown in the inset of Fig. 2(a) is the scaling for Sample-2 at 3 T. It is important to note that for Sample-2 practically almost the same parameters ($\nu_{2D} = 2 \pm 0.3, p = 1.6 \pm 0.05, T_0 = 230 \pm 5$ K) had to be used to obtain a scaling of the same quality as for Sample-1 providing strong evidence that the parameters derived here reflect an intrinsic property of the extremely anisotropic $Tl_2Ba_2CaCu_2O_8$ system. Another important observation is that the quality of the above scaling sensitively depends on the numerical values of p and T_0. For example, even a small change from $p = 1.58$ to $p = 1.7$ causes the drastic deterioration of the scaling quality as shown in the inset of Fig. 2(b). The tolerance for changing the value of ν_{2D} is a bit larger but has to be restricted to ± 0.3. On the other hand, the almost perfect scaling obtained with the optimized parameters for 3 and 5 T indicate that a 2D VG scaling is valid for $Tl_2Ba_2CaCu_2O_8$ thin films at high magnetic fields. Since for high current densities flux flow is expected to be the dominating dissipation process, the corresponding data have been removed from the E-j curves at low temperatures for the scaling analysis.

An alternative but more sensitive way to show the validity of a 2D VG description is to fit the linear

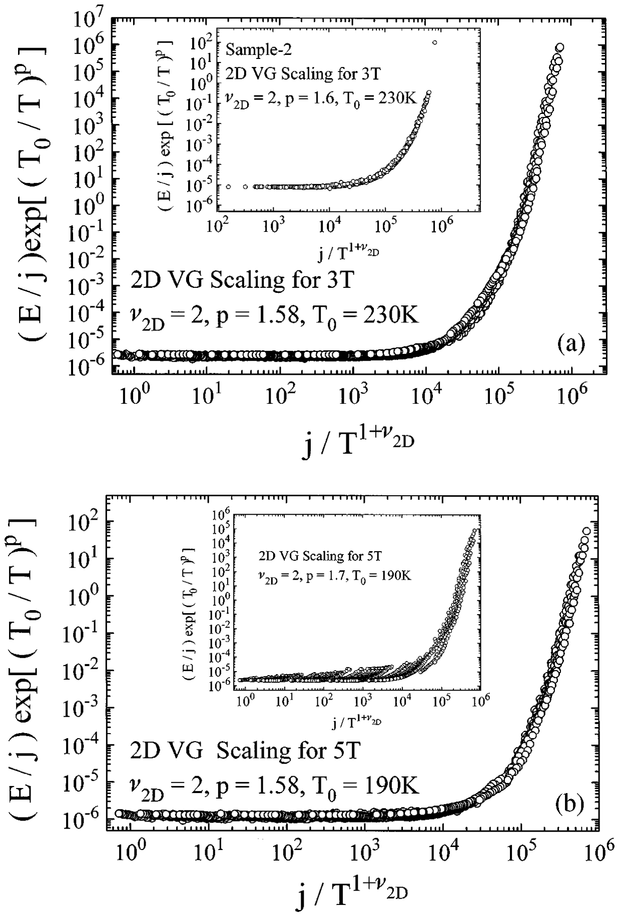

FIG. 2. (a) Scaling of E-j curves (from 24 to 80 K, 57 E-j curves, 1640 data points) measured with $B_e = 3$ T on Sample-1 according to 2D VG theory with $\nu_{2D} = 2$, $p = 1.58$, and $T_0 = 230$ K. The inset shows the same scaling of E-j curves (from 29 to 69 K, 39 E-j curves, 1500 data points) measured with $B_e = 3$ T on Sample-2 with $\nu_{2D} = 2$, $p = 1.6$, and $T_0 = 230$ K. (b) Scaling of E-j curves (from 24 to 75 K, 52 E-j curves, 1470 data points) measured with $B_e = 5$ T on Sample-1 according to 2D VG theory with $\nu_{2D} = 2$, $p = 1.58$, and $T_0 = 190$ K. The inset shows the same scaling of E-j curves with the slightly changed values $\nu_{2D} = 2$, $p = 1.7$, and $T_0 = 190$ K.

resistivity $\rho_{\mathrm{lin}}(T)$ to Eq. (2) keeping the same values for p and T_0 as obtained from scaling. The results of this procedure are shown in Fig. 3, where the experimental data obtained for magnetic fields of 3 and 5 T (symbols) are presented together with the corresponding fits to Eq. (2) (solid and dashed lines). The theoretical curves calculated from Eq. (2) with fixed parameters p and T_0 as extracted from the above scaling analysis give remarkably good fits to the experimental data, except for a physically irrelevant prefactor determining their vertical offset. This provides strong additional support for an interpretation of the experimental results in terms of a 2D VG.

Still another piece of evidence in favor of a 2D VG is offered by an analysis of the temperature dependence of the nonlinear current density. As defined above, j_{nl} is the current density at which the E-j curves start to become nonlinear. The values of j_{nl} are obtained by choosing the

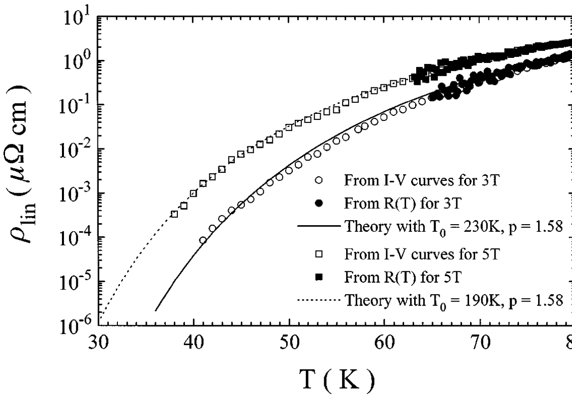

FIG. 3. Temperature dependent of linear resistivity $\rho_{\mathrm{lin}}(T)$ as measured on Sample-1 with $B_e = 3$ and 5 T. The open symbols are determined from the E-j curves by an extrapolation to $I = 10^{-6}$ A, where the I-V curves can be approximated by a linear behavior (cf. Fig. 1). The full symbols are obtained directly from resistance measurements using a current of $I = 10^{-6}$ A. The solid and dashed lines represent theoretical curves calculated from Eq. (2) with fixed parameters p and T_0 as extracted from scaling.

currents at which the resistivity deviates about 5% from the corresponding linear resistivity (as shown in Fig. 1 by the dotted line). The data found in this way for magnetic fields of 3 and 5 T are presented in Fig. 4 (symbols), together with theoretical curves (solid lines) calculated by assuming the validity of Eq. (3) and again keeping the value $\nu_{2D} = 2$ fixed as above. Since the parameter ν_{2D} determines the shape of the $j_{\mathrm{nl}}(T)$ curve, the good agreement between experiment and theory found in Fig. 4 further corroborates the 2D VG picture. To demonstrate how well the onset of nonlinearity in the different E-j curves can be scaled, in the inset of Fig. 4 a log-linear plot of the scaling data is presented [as shown in Fig. 2(a)] enlarging the crossover regime. It is found that these scaling curves collapse onto one narrow band. As an example, the experimental data of the 60 K isotherm are added as filled points.

In view of these remarkable results, some remarks are in order concerning the numerical values of ν_{2D}, p, and T_0 which were derived from the experimental data. As already mentioned, $\nu_{2D} = 2$ is fully consistent with 2D VG theory predicting this value for thermally activated creep, a regime which is realized in our experiments. Another prediction of 2D VG theory, which is valid for thermally activated flux creep only, is the relation $p = 1 + \alpha\nu_{2D}$ with $\alpha \geq 0$. Taking our experimental values of $p = 1.58 \pm 0.05$ and $\nu_{2D} = 2$, one arrives at $\alpha = 0.29$. To the best of our knowledge, for the case of thermally activated flux creep these are the first experimentally derived values for the above parameters. Unfortunately, there are no specific theoretical predictions for p and α making a direct comparison impossible. For a 2D vortex system, however, the energy needed to move a vortex is expected to be much smaller than in the corresponding 3D case. Thus, a correspondingly smaller value of $\alpha = 0.29$ as found experimentally is anticipated

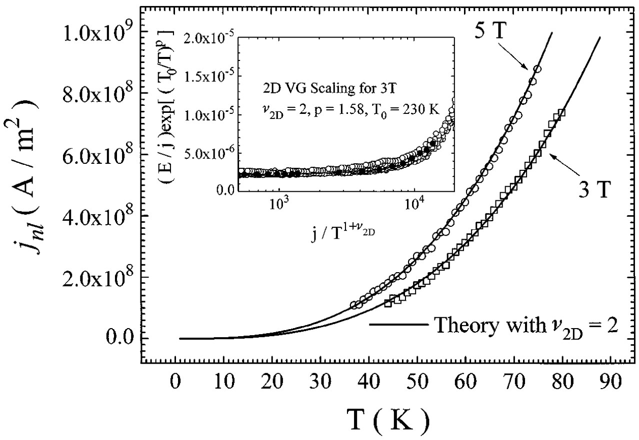

FIG. 4. Temperature dependence of the nonlinear current density $j_{\mathrm{nl}}(T)$ as measured on Sample-1 with $B_e = 3$ and 5 T. The value of $j_{\mathrm{nl}}(T)$ represents the deviation of the E-j curves from linearity as given in Fig. 1 by the dotted line. The solid lines are fits to the 2D VG theory with $\nu_{2\mathrm{D}} = 2$. Inset: An enlarged view for the scaling shown in Fig. 2(a) in the crossover regime. The full points represent the 60 K isotherm.

as compared to $\alpha = 1.28$ and 0.84 for the creep of small or large vortex bundles in 3D, respectively [1].

Finally, we consider the value of T_0. As mentioned above, T_0 is of the same order of magnitude as the core energy $\varepsilon_0 d = \hbar^2 \rho_s d/m$ of a vortex segment with length d. Assuming $\rho_s = 10^{27}\ \mathrm{m}^{-3}$, $m = 1.82 \times 10^{-30}$ kg and $d \approx 0.4$ nm (note that we use the thickness of the bilayer Cu-O planes instead of the interlayer spacing 1.5 nm in $Tl_2Ba_2CaCu_2O_8$), a value of $\varepsilon_0 d = 176$ K is obtained in close agreement with the experimentally found $T_0 = 200 \pm 30$ K. The calculated value obviously hinges on the assumption on d. If instead of the thickness of the bilayer Cu-O planes as above, the film thickness of 110 nm is used, a physically unreasonable value of $T_0 = 5 \times 10^4$ K is deduced. On the other hand, by pointing to the thickness of the bilayer Cu-O planes as the relevant length, the above estimates strongly support the consistency of the 2D picture of moving pancake vortices. The different values for T_0 found for 3 T (230 K) and 5 T (190 K) may be attributed to the field dependence of correlation length $\xi_{2\mathrm{D}}$. By assuming $V_L \propto T_0 L^\alpha$, $\nu_{2\mathrm{D}} = 2$ and $a_0 \propto B^{-1/2}$, one derives from Eqs. (1) and (2) that $T_0 \propto B^{-1/4}$. This rough estimate gives a value $T_0(3\ \mathrm{T})/T_0(5\ \mathrm{T}) \approx 1.14$, which is indeed close to the experimentally found value of $T_0(3\ \mathrm{T})/T_0(5\ \mathrm{T}) = 230/190 - 1.21$.

In this Letter, only data for high fields (3, 5 T) have been presented, because in this case the chances to realize a 2D VG are much higher. For low fields a 3D VG is expected [10,14]. Indeed, recent experiments by Ta Phuoc *et al.* [15] show that the E-j curves determined on $Tl_2Ba_2CaCu_2O_8$ for 0.1 T can be scaled according to the 3D VG theory. In addition, for lower temperatures ($\leq$20 K), quantum tunneling may gradually set in. As a consequence, it will be impossible to scale the E-j curves measured in high and low temperature regimes by using a single set of parameters $\nu_{2\mathrm{D}}$, p, and T_0. A final remark may be in order in the context of a recent experiment by Fuchs *et al.* [16] who found that in the transport measurements on $Bi_2Sr_2CaCu_2O_8$ single crystals, most of the vortex liquid phase is affected by the surface barrier properties rather than the bulk pinning properties. This interesting finding will, however, not change our conclusion here because of the following: (1) Our samples are thin films for which only a weak surface barrier would be expected comparing to strong bulk pinning. For example, magnetization measurements on our films revealed symmetric hysteresis curves in contrast to what is expected if strong surface barrier effects are present. (2) Our experiments were performed under high magnetic fields which certainly fully penetrate the sample. Thus, the intrinsic vortex dynamics, rather than that due to a surface barrier, was detected.

In conclusion, it has been experimentally demonstrated that the vortex behavior in $Tl_2Ba_2CaCu_2O_8$ thin films at high magnetic fields (3 and 5 T) and at temperatures high enough to guarantee thermally activated flux creep, can consistently be described in terms of a true (i.e., $T_g = 0$ K) 2D VG. This conclusion is based on a corresponding scaling analysis of E-j curves as well as of the temperature dependencies of both the linear resistivity $\rho_{\mathrm{lin}}(T)$ and the nonlinear current density $j_{\mathrm{nl}}(T)$. In all three cases, a common set of parameters, i.e., $\nu_{2\mathrm{D}} = 2$, $p = 1.58$, and $T_0 = 200 \pm 30$ K, delivers an excellent agreement between the experimental data and 2D VG theory.

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