Field Induced Vanishing of the Vortex Glass Temperature in $Tl_2Ba_2CaCu_2O_8$ Thin Films

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The current density j_s and relaxation rate Q have been measured on a ring shaped $Tl_2Ba_2CaCu_2O_8$ film between 4.2 K and the irreversibility temperature in magnetic fields up to 7 T. The temperature and field dependent exponent $\mu(T, B_e)$ used to parametrize the activation energy U in the form $U(j_s, T, B_e) = (U_c/\mu)[(j_c/j_s)^\mu - 1]$ is determined for many different fields. In the B_e-T phase diagram we associate the $\mu = 0$ line with the glass temperature T_g and find that T_g essentially drops to 0 K at $B_e \approx 0.7$ T, which indicates a dimensional crossover at this field. The $\mu > 0$ region ($B_e < 0.7$ T, $T \leq 55$ K) corresponds to 3D elastic vortex motin while the $\mu < 0$ region corresponds to 2D dislocation mediated flux creep. [S0031-9007(97)03832-5]

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The small coherence length, the presence of weak and dense point pinning centers, and the layered structure of high-T_c superconductors are at the origin of the intricate nature of the mixed state phase diagram of these superconductors [1–4]. A lot of effort has been put into investigations of various phases and phase transitions [5–8]. It is generally believed that below the irreversibility line $B_{\rm irr}(T)$ there exists a vortex solid state which is usually described in terms of collective flux pinning (CFP) [3,4] or vortex glass (VG) [2,9] models. Both the CFP and VG models are based on elastic vortex motion. Dissipation due to the thermally activated motion of vortices is associated with an electric field $E = v_0 B_e \exp[-U(j_s, T, B_e)/k_B T]$, where $U(j_s, T, B_e) = (U_c/\mu)[(j_c/j_s)^\mu - 1]$ is the activation energy at the external magnetic field B_e and temperature T, v_0 an attempt hopping velocity, and U_c the characteristic pinning energy. The superconducting current density j_s is always smaller than the critical current j_c for which U vanishes. Many different values have been predicted theoretically for the parameter μ on the basis of the CFP and VG models. For all regimes and dimensionalities [1–4,9], however, it is found that $\mu \geq 0$. A direct conclusion then is that the activation energy diverges when the current j_s approaches 0. This is reasonable for a 3D elastic vortex system, but for a 2D vortex system, it may not be true [9]. For example, for a 2D system, the vortex glass state does not exist at finite temperatures [1,10]. As mentioned by Vinokur *et al.* [4], in strongly layered systems such as $Bi_2Sr_2CaCu_2O_8$ and $Tl_2Ba_2CaCu_2O_8$ pinning is too strong at high magnetic fields to allow vortices to creep collectively. Instead, dislocation-mediated (plastic) creep is expected to be predominant. However, as far as we know, no direct evidence has been found for plastic creep except in a small part of the phase diagram ($T > 81$ K and $B_e < 6$ T) of a $YBa_2Cu_3O_7$ single crystal with a fishtail effect [11]. In this Letter, we conclude from a detailed investigation of the vortex dynamics in high quality $Tl_2Ba_2CaCu_2O_8$ thin films that the B_e-T plane below the irreversibility line is separated into two regions by a $\mu = 0$ line with a remarkable shape. At low fields where $\mu > 0$ vortex motion occurs via elastic creep while plastic creep [12] is made possible at higher fields by a 3D to 2D transition around 0.7 T.

The sample considered here is a$Tl_2Ba_2CaCu_2O_8$ thin film deposited on a (100) $LaAlO_3$ substrate by means of dc magnetron sputtering. Postannealing is done between 720 and 760 °C. Details of the fabrication of the films are published elsewhere [13]. ac susceptibility measurements show that $T_c(\text{zero}) = 106$ K and $\Delta T_c \approx 3$ K. The film is lithographically patterned into a ring of radius $r = 1.5$ mm and width $w = 25$ μm. Its thickness is $d = 200$ nm.

A very sensitive torque magnetometer (sensitivity 10^{-10}–10^{-11} Nm [14,15]) is used to measure the torque due to the magnetic moment of the sample. The field B_e, provided by a 7 T Oxford Instruments cryomagnetic system, is applied at an angle of 45° with respect to the c axis of the film. The temperature is stabilized to better than ± 0.1 K during field sweeps. For each temperature and field, the sweeping rate is varied between 1.25 and 40 mT/s, corresponding to induced electric fields $E = (r/2)(dB_e/dt)$ between 9.375×10^{-7} and 3×10^{-5} V/m, respectively.

By sweeping the magnetic field up and down at a given rate around a certain field, we measure the width ΔM of the irreversible magnetic moment curve. For the ring geometry of our sample, the current density j_s can be determined directly from ΔM by means of $j_s = \Delta M/(2\pi r^2 wd)$. Since $j_s \propto \Delta M$ and $E \propto dB_e/dt$ the measured ΔM vs dB_e/dt curves can be converted into E vs j_s curves (or I-V curves). In Fig. 1 we present a selection of the extensive data accumulated during this study. Figure 1(a) shows the temperature dependence of the current density $j_s(T, B_e)$ measured at given fields B_e with $dB_e/dt = 40$ mT/s. The slopes of the $\ln j_s$ vs $\ln E$ curves are plotted as a function of T in Fig. 1(b). As has been extensively discussed in Refs. [16,17], $Q \equiv d \ln j_s / d \ln(dB_e/dt) = d \ln j_s / d \ln E$ determined in a magnetic dynamic relaxation experiment is closely related to the normalized relaxation rate $R \equiv -d \ln M / d \ln t$ measured in a conventional magnetization relaxation experiment. From Fig. 1(b) one can easily see that a plateau in the Q vs T curves exists only when the field is below approximately $B_{cr} \approx 1$ T. A similar behavior was found in $YBa_2Cu_3O_7$ films for fields at least up to 7 T and was ascribed to the occurrence of a 3D vortex glass or collective creep [18,19]. When the field exceeds B_{cr}, the plateau disappears completely and the Q value increases monotonously. This indicates that the magnetic field drives the vortex system from the 3D collective creep (or vortex glass) regime to another one to be specified in this Letter.

To proceed with the analysis and discussion of the measured data in Fig. 1 we parametrize the activation energy $U(j_s, T, B_e)$ for thermally activated vortex motion in the form [19]

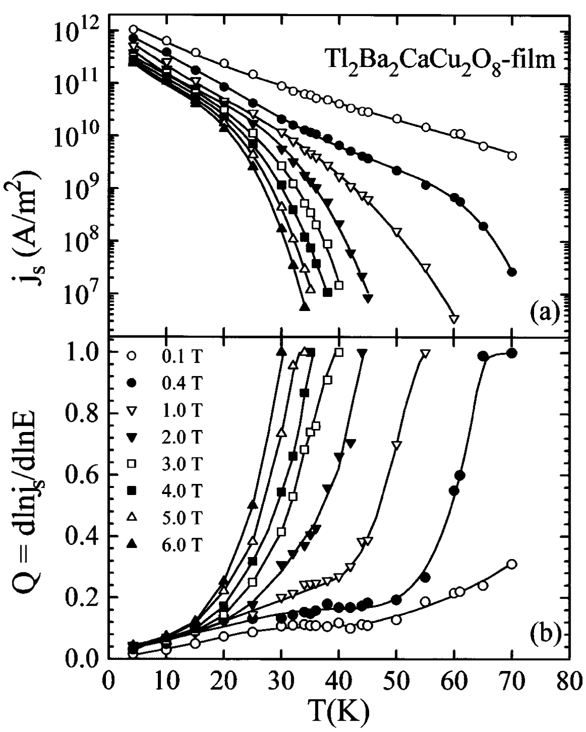

FIG. 1. Temperature dependence of (a) the superconducting current density j_s and (b) the dynamic relaxation rate $Q \equiv d \ln j_s / d \ln(dB_e/dt) = d \ln j_s / d \ln E$ for fields ranging from 0.1 to 6 T. A plateau of Q can be observed in the intermediate temperature region when the field is lower than about 1 T. The plateau disappears completely at higher fields. The lines are guides to the eye.

$$U(j_s, T, B_e) = \frac{U_c(T, B_e)}{\mu(T, B_e)} \left[\left(\frac{j_c(T, B_e)}{j_s(T, B_e)} \right)^{\mu(T, B_e)} - 1 \right], \quad (1)$$

where μ, U_c, and j_c are explicitly allowed to vary with temperature and magnetic field. Only the parameter μ influences the current dependence of U, which for all values of μ is a decreasing function of j_s. This form is chosen because it contains the weak collective pinning models ($\mu = \frac{1}{7}, \frac{3}{2}, \frac{7}{9}$ etc. [1]), the Kim-Anderson model ($\mu = -1$), and the Zeldov logarithmic model ($\mu = 0$) as special cases. For $\mu < 0$ it also includes expressions developed for plastic motion of dislocations as discussed below. Equation (1) is thus physically meaningful for any value of μ, both positive and negative, as well as 0, in contrast to other forms such as $U(j) = U_c(j_c/j)^{\mu}$ [11] or $U(j) = U_c \,\mathrm{sgn}(\mu) [(j_c/j)^{\mu} - 1]$ [20] which lead to unphysical results when $j \to j_c$ or $\mu \to 0$. Equation (1) is most suitable for a consistent analysis when a transition occurs in the type of pinning as reported in this Letter. From the general creep relation

$$U(j_s, T, B_e) = k_B T \ln\left(\frac{2\nu_0 B_e}{r \, dB_e/dt} \right) \quad (2)$$

for a thin film ring of radius r, Eq. (1) and the definition of the dynamic relaxation Q, one finds that

$$\frac{T}{Q(T, B_e)} = \frac{U_c(T, B_e)}{k_B} + \mu(T, B_e) C T \,, \quad (3)$$

where $C = \ln[(2\nu_0 B_e)/(r \, dB_e/dt)]$. As shown in Refs. [17,21] the parameter C at a given field B_e can be determined from the low temperature slope of the $\ln j_s$ vs T curves in Fig. 1(a) by means of $C = (T/Q)(-d \ln j_s / dT)$ after correction for quantum creep. Here we find $C = 22$.

In Fig. 2 we show the temperature dependence of T/Q for various fields. At low fields, T/Q first exhibits a positive slope, which is followed by a sharp drop at higher temperatures. With increasing field the initial slope gradually changes from positive to negative. At $B_e = 0.7$ T the slope is 0 over essentially the whole temperature range (from 4.2 to 50 K). The temperature dependence of T/Q gives directly information about the variation of μ with T since $U_c(T)$ is essentially constant below the irreversibility line in highly anisotropic superconductors. For such superconductors $T_{irr}(B_e)$ in the field range considered here is so low that the temperature dependence of the characteristic superconducting parameters can be neglected [1]. Even for the moderately anisotropic $YBa_2Cu_3O_7$ [17] and $(Y, Pr)YBa_2Cu_3O_7$ [22] one finds experimentally that $U_c(T_{irr}) \approx U_c(T = 0)$. This is confirmed by theoretical models, independent of the type of pinning centers [23].

The values of $\mu(T, B_e)$ in Fig. 3 derived from the T/Q vs T data in Fig. 2 show clearly that at a given temperature μ changes from positive to negative with increasing

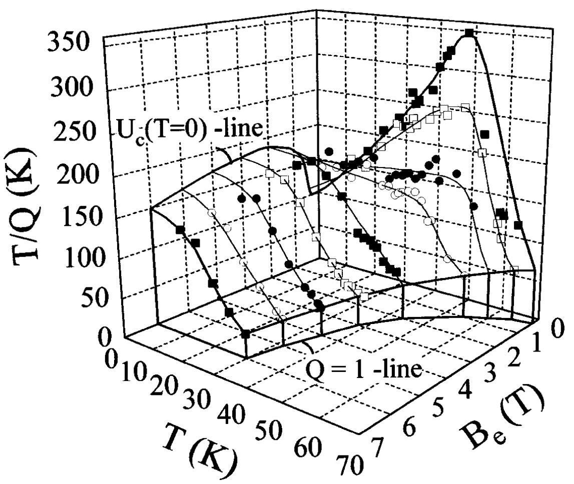

FIG. 2. Temperature dependence of T/Q for fields of 0.3, 0.4, 0.7, 1, 2, 3, 4, 5, and 6 T. At low fields, the slope of T/Q vs T in the intermediate temperature region is positive. With increasing magnetic field the slope gradually changes from positive to negative. Near the crossover field $B_e = 0.7$ T, the slope remains zero up to 50 K. The $U_c(T = 0)$ line in the $(T/Q, B_e)$ plane, obtained by taking the extrapolation of T/Q to 0 K, indicates the field dependence of the characteristic pinning energy. In the (T, B_e) plane the $Q = 1$ line indicates the lowest temperature at which $Q = 1$ is reached at a given field B_e. For higher temperatures the current-voltage curves exhibit Ohmic behavior.

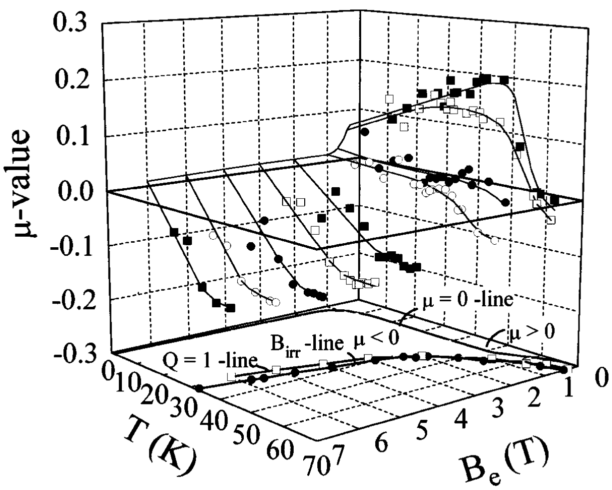

FIG. 3. Temperature and magnetic field dependence of the exponent μ appearing in Eq. (1) for the activation energy $U(j_s, T, B_e)$. The corresponding fields are 0.3, 0.4, 0.7, 1.0, 2.0, 3.0, 4.0, 5.0, and 6.0 T, respectively. μ is determined from the data shown in Fig. 2 by using Eq. (1) with the assumption $U_c(T) \approx U_c(0)$. On the (T, B_e) plane are shown (i) the irreversibility line determined with the criterion $j_s = 10^7$ A/m^2 from current measurements with field sweeping rate 10 mT/s (open squares), (ii) the $Q = 1$ line defined in Fig. 2 (filled circles), and (iii) the $\mu = 0$ line. For fields above 0.7 T there is a large region where μ is negative.

magnetic field. At low temperatures the extrapolated values of μ are essentially zero for fields above 0.7 T. The $\mu = 0$ line exhibits a remarkable plateau at $B_e = 0.7$ T for $T < 55$ K and an asymptote at low temperatures. It cuts the B_e-T plane into two regions: one where $\mu < 0$ for all $T < T_{\mathrm{irr}}(B_e)$ and one with $\mu > 0$ for all $T < T^*(B_e)$, where $T^*(B_e)$ is a temperature very close to the irreversibility line $B_{\mathrm{irr}}(T)$ corresponding to a current density of 10^7A/m^2 at $dB_e/dt = 10$ mT/sec. This irreversibility line in turn is close to the $Q = 1$ line which defines the lowest temperature at which $Q = 1$ is reached for a given field B_e. The fact that the $\mu = 0$ line merges with the field axis at $T = 0$ K indicates that the glass temperature for $B_e > 0.7$ T is essentially zero.

The occurrence of a $\mu = 0$ line and of a large region of the B_e-T diagram with $\mu < 0$ can be understood as the combined action of a 3D to 2D transition opening the way to plastic vortex creep. We discuss these two effects below.

(i) *Dimensional crossover.*—Within a vortex glass model the line in the B_e-T plane on which $\mu = 0$ separates the vortex glass phase from the vortex liquid phase and is associated with the vortex glass temperature T_g. This is evident since $\mu = 0$ implies that $U(j_s) = U_c \ln(j_c/j_s)$ and consequently, from Eq. (2), that the j_s vs dB_e/dt or j_s vs E curves exhibit power-law behavior, which typically occurs at T_g. For fields $B > 0.7$ T we find $\mu \approx 0$ at $T \approx 0$ K and thus $T_g \approx 0$ K. According to vortex glass theories a zero glass temperature is characteristic for 2D systems and we conclude that around 0.7 T a transition takes place from a 3D vortex glass to a 2D vortex glass with a vanishing glass temperature. From 0 to 50 K the 3D to 2D transition occurs at $B_e = 0.7$ T. We note that this crossover field is much higher than $B_{\text{3D-2D}} = \phi_0/\gamma^2 s^2 \cong 0.05$ T [24] obtained from the anisotropy parameter $\gamma = 135$ [25] and $s = 1.5$ nm appropriate for our sample. At $B_e = 0.4$ T, $\mu = 0$ is reached around 58 K. At that temperature $Q \approx 0.38$ which implies that $E \propto j_s^{2.63}$. As theoretically $E \propto j_s^{(z+1)/(D-1)}$, where D is the dimensionality of the vortex system [1], we find $z = 4.26$. Interestingly this value of z is similar to that determined by Wöltgens *et al.* [10] for the 3D superconductor $YBa_2Cu_3O_7$. We note, furthermore, that at low fields $B_e \sim 0.1$ T, μ assumes a value close to $\frac{1}{7}$ as expected for the 3D-single vortex regime.

(ii) *Plastic creep.*—$U_c(T = 0) \cong 150$ K (see Fig. 2) and of the critical currents $j_c(T = 0) \cong 10^{12}$ A/m^2 in the present system are an indication of strong pinning. It is therefore reasonable to assume that dislocation mediated plastic vortex creep occurs with increasing field [26]. This idea is strongly supported by the following analogy. Above 0.7 T the negative values of μ imply that the activation energy in Eq. (1) can be written in the form $U(j_s) = U_0[1 - (j_s/j_c)^a]$ with $a \equiv -\mu > 0$. This dependence is of the same form as that predicted by the theory of thermally activated motion of dislocations in crystalline solids for which the activation energy $U_{\rm dis}$ changes with the applied strain f as $[1 - (f/f_c)^a]^b$ and the exponents a and b satisfy $0 < a \leq 1$ and $1 \leq b \leq 2$, respectively. The driving force for dislocation motion is the applied strain while it is the Lorentz force (proportional to the current j_s) for vortices in a superconductor. The μ value found in our experiment (-0.2) at high fields near the irreversibility line implies $a = \frac{1}{5}$ and $b = 1$. For dislocations in a crystalline solid this would correspond to the case of pinning sites with a homogeneous core and long-range interaction [27].

The characteristic activation energy U_c for the motion of a dislocation in the vortex lattice is of the order of $(\phi_0^2 a_0)/(4\pi\mu_0\lambda^2\gamma)$ with ϕ_0 the flux quantum, $a_0 \cong \sqrt{(\phi_0/B_e)}$, λ London's penetration depth, and γ the anisotropy factor. One thus expects a $B_e^{-1/2}$ dependence of the activation energy for fields B_e above a matching field B^* at which all the strong pinning centers present in the sample are occupied by a vortex. When $B_e > B^*$ the Lorentz force acting on the weakly pinned additional vortices is transmitted via shear interactions to the strongly pinned vortices. Consequently, the pinning energy per vortex decreases when B_e increases. Although $U_c(T = 0)$ is found to decrease slightly for fields above 2 T it does not exhibit a $B_e^{-1/2}$ behavior between 2 and 6 T yet. The magnitude of U_c is, however, consistent with the prediction $U_c \sim (\phi_0^2 a_0)/(4\pi\mu_0\lambda^2\gamma)$ with $\lambda = 200$ nm and $\gamma = 135$ [25] which lead to $U_c \sim 150$ K.

In conclusion from the vanishing of T_g and the negative values of μ we conclude that around $B_e = 0.7$ T a 3D to 2D transition occurs, at a much higher field than expected from $B_{\rm 3D\text{-}2D} = \phi_0/\gamma^2 s^2$. At $B_e < 0.7$ T there are 3D vortex bundles in $Tl_2Ba_2CaCu_2O_8$ which move from one pinned configuration to another. With increasing field vortex motion at $B_e > 0.7$ T is dominated more and more by dislocation mediated plastic creep in a 2D pancake vortex system. Our 3D to 2D transition is thus of a completely different nature than that reported by Kopylov *et al.* [28] which corresponds to a 2D to 3D crossover in weak magnetic fields when the coherence length ξ_c along the c axis becomes larger than the interlayer spacing when T approaches T_c.

In $Tl_2Ba_2CaCu_2O_8$ films plastic creep appears to be operative in a very large region of the B_e-T plane. This is a rather general property of strongly layered systems with large critical currents, since we obtained recently similar results for single crystals of $Bi_2Sr_2CaCu_2O_8$ and electron doped $Pr_{1.85}Ce_{0.15}CuO_{4+\delta}$ [29].

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