Scaling behavior of activation energy of $HgBa_2CaCu_2O_{6+\delta}$ thin films

B. W. Kang,* W. N. Kang,† S. H. Yun, and J. Z. Wu
Department of Physics and Astronomy, University of Kansas, Lawrence, Kansas 66045
(Received 4 April 1997)

The scaling behavior of the effective activation energy of high-quality epitaxial *c*-oriented $HgBa_2CaCu_2O_{6+\delta}$ thin films has been studied as functions of temperature and magnetic field. It has been found that the effective activation energy scales as $U_e(T,H)=U_0(1-T/T_c)^m H^\alpha$ with exponent $m=1.10\pm0.04$ which is similar to that of the $Bi_2Sr_2CaCu_2O_8/Tl_2Ba_2CaCu_2O_8$ systems, while the field scaling $1/H$ ($\alpha=-1$) is the same as that of the $YBa_2Cu_3O_{7-\delta}$ system. Our results suggest the following: (1) The temperature dependence of U_e is not necessarily correlated with the field dependence, but it might be governed by the dimensionality of the material, and (2) the field dependence might not be directly associated with the dimensionality of the material. [S0163-1829(97)03837-X]

The mixed-state flux dynamics in high-T_c superconductors (HTS's) is an interesting and complicated subject. Much attention has been focused on the relationship between the dissipative flux motion and the flux pinning mechanism,[1–12] but many issues are still unresolved. Since the thermal energy kT near the superconducting transition of HTS's is considerably higher than that of the conventional superconductors, thermally activated flux motion plays an important role during the onset of finite resistance, expressed as $\rho \sim \exp(-U_e/kT)$ in the superconducting mixed state. Therefore, the effective activation energy U_e, which measures the depth of the activation energy well, is a critical parameter for interpretation of the thermally activated flux motion in the mixed state.

It is generally accepted that U_e scales as $U_e(T,H)\sim(1-T/T_c)^m g(H)$ for HTS's, where $g(H)$ describes the field dependence. Different scaling laws, however, have been discovered for different HTS systems such as $YBa_2Cu_3O_{7-\delta}$ (YBCO),[1–5,8] $Bi_2Sr_2CaCu_2O_8$ (Bi-2212),[6–9] and $Tl_2Ba_2CaCu_2O_8$ (Tl-2212) (Bi/Tl-2212 systems in the following).[10–12] The YBCO system has been found to have $m=1.5-1.8$ and $g(H)=1/H$.[2–5,8] The same measurements on the Bi/Tl-2212 systems, however, revealed a different scaling behavior such as $m\sim1.0$ and $g(H)=1/\sqrt{H}$.[6–12] One of the major discrepancies between YBCO and Bi/Tl-2212 is the dimensionality of the system which is inferred from the anisotropy of the electronic band structure. Since the dimensionality constrains the flux motion, it has been used as a key parameter to understand the observed different scaling behaviors in different HTS's. YBCO has been regarded as a three-dimensional-like (3D-like) system due to its small effective mass anisotropy [$\gamma=\sqrt{m_c/m_{ab}}=5.5$ (Ref. 13)]. On the other hand, Bi-2212 and Tl-2212 have been considered to be two-dimensional-like (2D-like) systems due to their much larger mass anisotropies such as $\gamma\sim55-200$ (Refs. 14 and 15) and $\gamma\sim100-300$,[16] respectively.

Yeshurun and Malozemoff[1] and Tinkham[2] proposed a model for the less anisotropic YBCO system. They argued that for fields greater than $0.2H_{c2}$, the relevant correlation length which is perpendicular to the field becomes the flux-line spacing a_0 due to collective pinning effect. U_e is, thus, scaled as $U_e\propto H_c^2 a_0^2 \xi_c \sim (1-T/T_c)^{3/2}/H$ which is consistent with the experimental results of YBCO.[2–4,8] Nikolo *et al.*[10] used the same approach to explain the $(1-T/T_c)/\sqrt{H}$ dependence of the 2D-like Tl-2212 system. According to their argument, the vortex length along the *c* axis scales as a_0, the flux line spacing, at the low-field and high-temperature limit, and therefore the vortex occupies a characteristic volume of $\xi^2 a_0$, where ξ is the coherence length in the *ab* plane. On the other hand, the model proposed by Geshkenbein *et al.*[17] and later extended by Vinokur *et al.*[18] associated the scaling behavior of the 2D-like Bi/Tl-2212 systems with the plastic deformation of the flux-line lattice at flux-line-lattice dislocations. They regarded U_e as the energy required to create a double-link configuration, which scales as $U_e\sim\phi_0^2 a_0/\lambda^2 \propto(1-T/T_c)/\sqrt{H}$ near T_c.

Previous observations imply that the scaling laws are associated with the dimensionality of the system and the temperature scaling and the field scaling are correlated. However, recent studies[19,20] on ultrathin YBCO films with a thickness of 24–200 Å, which is a 2D-like system, reveal a different scaling behavior from the above, $m=1.0-1.2$, which is consistent with the Bi/Tl-2212 systems and $g(H)=-\ln H$ which is different from the expected $1/\sqrt{H}$ law. These results raise the following two questions: (1) Are the temperature scaling and field scaling always correlated? (2) What kind of scaling behavior would we expect for a system with dimensionality between YBCO and Bi/Tl-2212 systems? Recall that dimensionality here is defined based on the anisotropy of the material. The answers to these questions would probe the variation of the vortex dynamics as the dimension of the system changes from 2D-like to 3D-like.

Hg-based cuprates such as Hg-1212 provide ideal systems for understanding this issue because the dimensionality of the Hg-1212 system stays between that of YBCO and Bi/Tl-2212 systems. The effective mass anisotropy γ of Hg-1212 was reported to be in the range of 7.7–67 by different groups.[21,22] The power law index *n* of the irreversibility line

$H_{irr} \sim (1 - T_{irr}/T_c)^n$ of Hg1212 has been found to be 5/2,[23] ranging between that of YBCO ($n = 3/2$) and Bi/Tl-2212 ($n = 11/2$), which confirms that the anisotropy of the Hg-1212 system is between that of YBCO and Bi/Ti-2212. Moreover, Hg-1212 has $T_c \sim 124$ K,[24] which is much higher than that of YBCO (~92 K) and Bi/Tl-2212 systems (~90–110 K). The higher T_c in combination with the moderate pinning strength provides a wide temperature range for the mixed state making the observation of the thermally activated flux motion much easier. Thus the investigation of the scaling behavior of the effective activation energy of Hg-1212 will bridge the discrepancy between the YBCO and Bi/Tl-2212 systems.

High-quality epitaxial *c*-axis-oriented Hg-1212 films were prepared on $SrTiO_3$ (100) substrates by rf magnetron sputtering. The fabrication process of the films has been described in detail elsewhere.[25,26] These films have a midtransition temperature of 123 K with 2–3 K transition widths in zero magnetic field. The critical current density at 77 K and zero field is $\sim 10^6$ A/cm^2. The thicknesses of the films were ~800 nm. The samples were patterned by chemical etching to form a 100-μm-wide and 2-mm-long microbridge. The electrical contacts were made by sputtering four ~100-nm-thick Ag pads on the samples which were then annealed at 350 °C for 20 min in flowing O_2 to ensure low contact resistance. A superconducting quantum interference device (SQUID) magnetometer was used to apply an external magnetic field of up to 5.5 T in a temperature range of 5–300 K. In this experiment the magnetic field was always normal to the surface and parallel to the *c*-axis of the films. The electrical resistivity measurements were carried out by using the standard four-probe dc technique. The typical current density used for this experiment was ~100 A/cm^2. The current was small enough to remain within the linear portion of the *I*-*V* characteristic at all temperatures and fields.

Figure 1 shows the Arrhenius plot of the resistivity at various magnetic fields plotted in a semilogarithmic scale. As shown in Fig. 1, resistivity in a magnetic field decreases exponentially and the straight lines for low resistivity indicate that the dissipation mechanism is thermally activated. At finite temperatures, thermally activated flux creep produces dissipation as follows:

$$\rho = \rho_0 \exp(-U_e/kT), \tag{1}$$

where ρ_0 is the preexponential factor and k is the Boltzman constant. U_e is the effective activation energy which generally depends on the temperature and the applied magnetic field at a fixed current density such that

$$U_e(T,H) = U_0 \beta(T) g(H), \tag{2}$$

where U_0 is the unperturbed activation energy and the functions β and g incorporate the temperature and magnetic field dependence. It is apparent that the slope of the plots, U_e, varies with different magnetic fields.

In order to determine the field dependence of U_e, the resistivity of the sample is plotted as a function of inversed

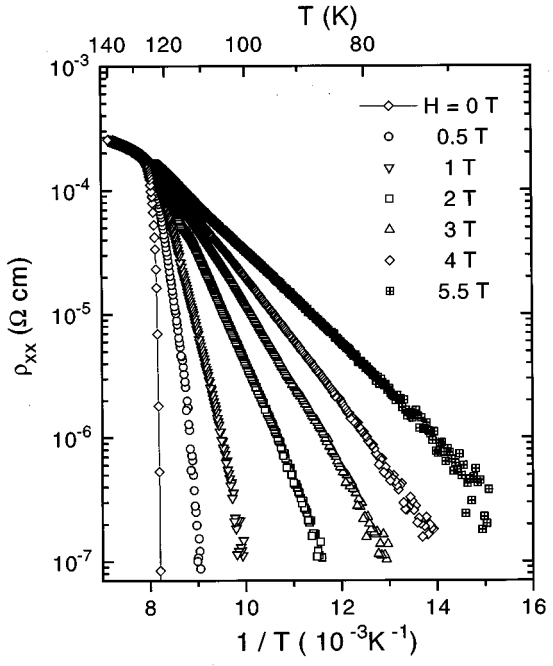

FIG. 1. Arrhenius plot of resistive transition at various magnetic fields applied parallel to the *c* axis of the film.

magnetic field at several temperatures in the range of 80–120 K in Fig. 2. The solid straight lines are the fits of data, which suggest that $U_e(H) \sim H^{-1}$ for one order of magnetic fields and a wide temperature range below T_c. The slope of the straight lines gives directly the quantity $U_e H/kT$ at a given temperature. The experimental data deviate from the linearity slightly as T approaches T_c, for example at $T \geqslant 110$ K, where other types of flux motion, other than thermally activated flux creep, may become important. We were not able to fit our data with $1/\sqrt{H}$ or $-\ln H$, which are the reported scalings for Bi/Tl-2212 and ultrathin YBCO films, respectively.

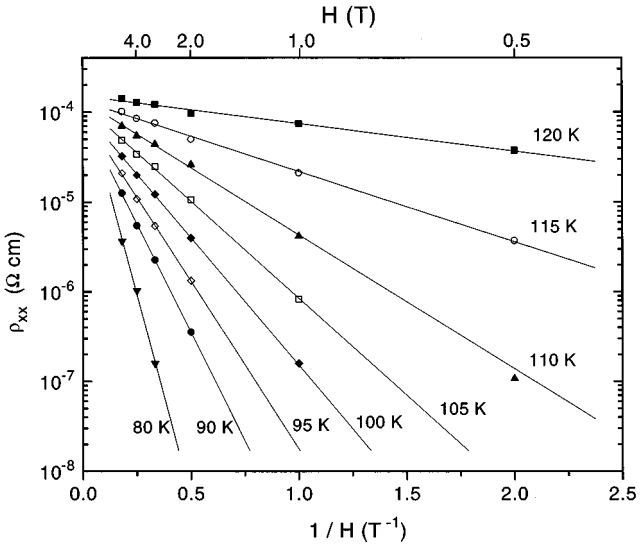

FIG. 2. Field dependence of U_e at several temperatures in the range 80–120 K. The solid lines are the fits of the data indicating $U_e(H) \sim 1/H$.

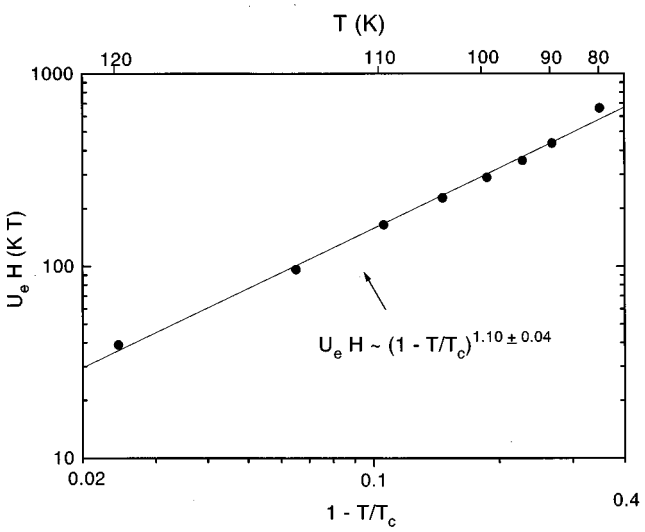

FIG. 3. Power law temperature dependence of U_e plotted as the product U_eH. A linear regression (solid line) gives $U_e(T) \sim (1-T/T_c)^{1.10\pm0.04}$ in this regime.

The temperature dependence of U_e at a fixed field is not universal in the whole temperature range below T_c. At temperatures much lower than T_c, the temperature dependence of U_e is approximately $(1-T/T_c)$, which is the linear part of the slope of the Arrhenius plot of Fig. 1. A different scaling law is implied by the curvature of the slope at high temperature near T_c. If we assume a general power law for the temperature dependence of $U_e(T) \sim (1-T/T_c)^m$, the temperature dependence of U_e can be extracted by plotting the product U_eH vs $(1-T/T_c)$ and $m=1.10\pm0.04$ has been obtained for a temperature range of $0.98T_c-0.6T_c$ as shown in Fig. 3. This number is very close to the reported value for the 2D-like Bi-2212/Tl-2212 and the ultrathin YBCO systems.

Contrary to what was previously believed,[1,2,10,17,18] our experiments show that the temperature scaling and the field scaling are not necessarily correlated, since $m=1.1$, an expected 2D-like behavior, and $g(H)=1/H$, an expected 3D-like behavior, occur simultaneously in Hg-1212. Since Hg-1212 has an anisotropy between that of YBCO and that of Bi/Tl-2212 systems, our observation of $m=1.1$, which sits between $m=1.5-1.8$ of YBCO and $m=1.0$ of Bi/Tl-2212, suggests that the temperature scaling law is governed by the dimensionality of the material. This argument is consistent with our recent experimental results that the exponent m increases from 1.10 to 1.75 as the inter-CuO_2 plane coupling is improved by c-axis-aligned columnar defects.[27] Since $m=1.1$ is close to $m=1$ of the highly anisotropic system, Hg-1212 is possibly regarded as a 2D-like system. If the temperature scaling and the field scaling were necessarily correlated as discussed in the theories,[1,2,10,17,18] the $1/H$ law of Hg-1212 films could not be expected for a 2D-like system. Therefore, combined with the $1/\sqrt{H}$ dependence of the Bi/Tl-2212 systems and the $-\ln H$ dependence of the ultrathin YBCO films, our experiments suggest that the field scaling behavior might not be directly associated with the dimensionality of the material. This poses a serious question to the existing theories because most of them predict a correlated temperature and field scaling law in the effective activation energy.

In conclusion, the activation energy of high-quality epitaxial c-axis-oriented Hg-1212 thin films has been studied in terms of the thermally activated flux creep model. We have found that the effective activation energy can be described by the scaling law

$$U_e(T,H)=U_0(1-T/T_c)^m H^\alpha. \tag{3}$$

The exponent of the temperature scaling is found to be $m=1.10\pm0.04$ from near T_c to $0.6T_c$, indicating that the temperature scaling is very similar to that of the Bi-2212/Tl-2212 systems, while the field scaling law $1/H$ ($\alpha=-1$) for an order of magnetic fields is the same with that of the 3D-like YBCO system. Our results suggest the following: (1) The temperature dependence of U_e is not necessarily correlated with the field dependence, but it might be governed by the dimensionality of the material, and (2) the field dependence might not be directly correlated with the dimensionality of the material.

ACKNOWLEDGMENTS

This work was supported in part by USAFOSR Grant No. F49620-96-1-0358, NSF Grant No. DMR-9632279, the NSF EPSCoR fund, the University of Kansas GRF fund, and a new faculty start-up fund. The authors are very grateful to Midwest Superconductivity Inc. for providing access to their experimental facilities.

*Electronic address: kang@kuphsx.phsx.ukans.edu
†Present address: Texas Center for Superconductivity at University of Houston, Houston, Texas 77204-5932.

[1] Y. Yeshurun and A. P. Malozemoff, Phys. Rev. Lett. **60**, 2202 (1988).
[2] M. Tinkham, Phys. Rev. Lett. **61**, 1658 (1988).
[3] E. Zeldov *et al.*, Appl. Phys. Lett. **56**, 680 (1990).
[4] S. Zhu *et al.*, Phys. Rev. B **46**, 5576 (1992).
[5] T. Matsuura and H. Itozaki, Appl. Phys. Lett. **59**, 1236 (1991).
[6] W. Gerhauser *et al.*, Phys. Rev. Lett. **68**, 879 (1992).
[7] T. T. M. Palstra *et al.*, Phys. Rev. Lett. **61**, 1662 (1988).
[8] T. T. M. Palstra *et al.*, Phys. Rev. B **41**, 10 (1992).
[9] Hirofumi Yamasaki *et al.*, in *Advances in Superconductivity VI*, Proceedings of the 6th International Symposium on Superconductivity (ISS'93), 1993, Hirosima, edited by T. Fujita and Y. Shiohara (Springer, Tokyo, 1994), p. 487.
[10] M. Nikolo *et al.*, Phys. Rev. B **45**, 5641 (1992).
[11] D. G. Steel *et al.*, Physica C **265**, 159 (1996).
[12] K. C. Woo *et al.*, Phys. Rev. Lett. **63**, 17 (1989).
[13] D. R. Harshman *et al.*, Phys. Rev. B **39**, 851 (1989).
[14] D. E. Farrell *et al.*, Phys. Rev. Lett. **63**, 782 (1989).
[15] K. Okuda *et al.*, J. Phys. Soc. Jpn. **60**, 3226 (1991).
[16] D. E. Farrell *et al.*, Phys. Rev. B **42**, 6758 (1990).
[17] V. Geshkenbein *et al.*, Physica C **162-164**, 239 (1989).
[18] V. M. Vinokur, M. V. Feigel'man, V. B. Geshkenbein, and A. I. Larkin, Phys. Rev. Lett. **65**, 259 (1990).

[19] O. Brunner *et al.*, Phys. Rev. Lett. **67**, 1354 (1991).
[20] J. J. Sun *et al.*, Physica C **270**, 343 (1996).
[21] L. Krusin-Elbaum, C. C. Tsuei, and A. Gupta, Nature (London) **373**, 679 (1995).
[22] M. S. Kim *et al.*, Phys. Rev. B **53**, 9460 (1996).
[23] Z. J. Huang *et al.*, Phys. Rev. B **49**, 4218 (1994).
[24] C. C. Tsuei, A. Gupta, G. Trafas, and D. Mitzi, Science **263**, 1259 (1994).
[25] S. H. Yun and J. Z. Wu, Appl. Phys. Lett. **68**, 862 (1996).
[26] S. H. Yun *et al.*, Appl. Phys. Lett. **68**, 2656 (1996).
[27] B. W. Kang *et al.* (unpublished).