Electric Field Effects on Vortex Dynamics in Ultrathin $YBa_2Cu_3O_{7-\delta}$ Films

A. Walkenhorst, C. Doughty, X. X. Xi, Qi Li, C. J. Lobb, S. N. Mao, and T. Venkatesan[(a)]
Center for Superconductivity Research, Department of Physics, University of Maryland, College Park, Maryland 20742
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The effects of charge-carrier density modulation on critical currents and vortex dynamics in ultrathin $YBa_2Cu_3O_{7-\delta}$ films were investigated through transport measurements in field-effect devices. Two distinct dissipation regions in resistive transitions in applied magnetic fields are identified by the electric field effect. A Kosterlitz-Thouless-like transition is observed in zero magnetic field, which can be tuned by the electric field. The importance of thermal fluctuations for the dissipation in high-T_c superconductors is stressed.

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Recent work has shown that the properties of ultrathin films of $YBa_2Cu_3O_{7-\delta}$ (YBCO) can be significantly modulated by the application of electric fields [1-5]. The electric field changes the charge-carrier density in a film without changing the chemical structure or composition, thus providing a powerful tool for understanding high-temperature superconductors. Mannhart *et al.* [4] studied the electric field effect on the critical current density and explained it by field-induced depinning. However, the consistency of this model with details of the effects remains to be proven. In this Letter we report the measurement of resistive transitions and the current-voltage characteristics of ultrathin YBCO films which are subjected to external electric and magnetic fields. It turns out that the electric field effect reveals details of the dissipation processes which are hard to access by other techniques. A transition from a high-temperature, high-dissipation state to a low-temperature, low-dissipation state is observed and identified by a different dependence on the charge-carrier density. The results provide evidence for a Kosterlitz-Thouless-type transition in zero magnetic field, and a transition from a low-temperature (solid or hexatic) to a high-temperature (liquid) vortex phase in magnetic fields.

The sample in this work consisted of a *c*-axis-oriented YBCO film prepared by pulsed laser deposition with a nominal thickness of 5 nm, i.e., four unit cells. The thickness fluctuation of such films is generally of the order of one unit cell [6]. On top of the YBCO layer, a 400-nm-thick $SrTiO_3$ dielectric layer was deposited *in situ* with the same technique, and then a gold gate electrode was evaporated. Details of the sample preparation and $SrTiO_3$ properties have been published earlier [5,7]. The charge-carrier density in the YBCO layer was modulated by applying a gate voltage between the gate electrode and the YBCO film. The total applied charge was measured by an electrometer. The maximum applied gate voltage is limited by the breakdown behavior of the dielectric. To avoid interference of leakage currents with the test currents, the gate voltage was kept low enough for the leakage current to not exceed 10 nA, while the measurement currents ranged from μA to mA. Current-voltage (I-V) characteristics were taken with a standard four-probe technique, and I_c, the experimental critical current, was determined by a 1-μV/mm criterion. The sample has a zero resistance temperature T_{c0}=43 K, and a critical current density, J_c(5 K), of around 10^5 A/cm^2. These values are higher than the data we reported in Ref. [5], due to the improvement of the film quality by optimizing the substrate treatment and parameters during the film deposition, and they can be obtained reproducibly in samples of this thickness range.

In the superconducting state, the I-V characteristics are significantly affected by the gate voltage V_g (see inset of Fig. 1): A positive V_g reduces the number of holes in the film and J_c decreases, while adding holes (negative V_g) enhances J_c. Figure 1 shows the temperature dependence of the relative change of the critical current density, $\Delta J_c/J_c$ for a gate voltage of 8 V. Since the critical temperature is affected by the gate voltage [5], $\Delta J_c/J_c$ diverges at T_{c0}, and it saturates at low temperatures at a

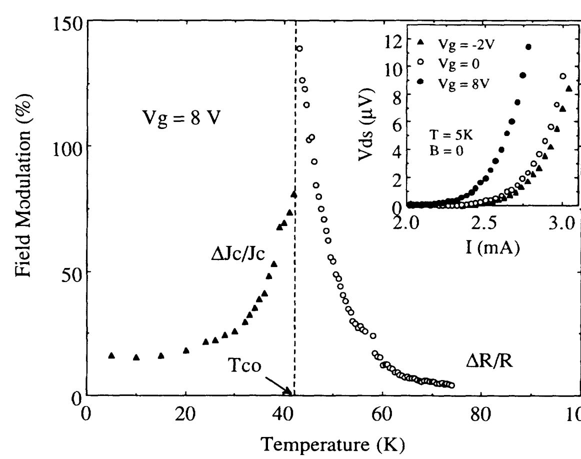

FIG. 1. Electric field modulation of the critical current density, $\Delta J_c/J_c$, as a function of temperature for a gate voltage of 8 V. Also shown is that of the normal state resistance, $\Delta R/R$ vs T. Inset: I-V characteristics for gate voltages of −2, 0, and 8 V measured at 5 K. The values of $\Delta J_c/J_c$ at 5 K and $\Delta R/R$ at 95 K are 14% and 4.5%, respectively.

value around 14%. Also included in Fig. 1 is the change in the normal state resistance $\Delta R/R$. Note that $\Delta R/R$ at high temperatures amounts to only 4.5%. Previous work [5] has shown that $\Delta R/R$ is equal to $\Delta N/N$, the field-induced change in the areal carrier density, $N=nd$, where n is the volume carrier density and d is the film thickness. The $\Delta R/R$ value for the sample is in agreement with the measured $\Delta N/N$ of 4%, assuming $n \cong 5 \times 10^{21}$ cm^{-3}. This clearly shows that $\Delta J_c/J_c$ is not equal to $\Delta N/N$.

In a recent work, Mannhart *et al.* [4] ruled out weak-link effects as the explanation for the field effect on J_c and suggested that the electric field reduces the pinning potential thereby suppressing J_c. The rather slow drop of J_c as a function of magnetic field in our samples confirms that the processes are not weak-link dominated. However, as was pointed out by Feenstra *et al.* [8], in strongly pinning dominated systems the critical current density is proportional to the superconducting carrier density n_s. Analogous to the analysis of the field effect on the kinetic inductance, this translates into a requirement that $\Delta J_c/J_c = \Delta N/N$. The experimental result is in clear contradiction with this requirement.

In order to elucidate the field effects on the pinning potential, we measured resistive transitions in various magnetic fields for different gate voltages. Figure 2 shows Arrhenius plots of the sample for two gate voltages, 0 and 8 V, in a magnetic field of 2 T. Two distinct linear regions (marked as "low R" and "high R") occur, and the slope in the region corresponding to the low dissipation limit (i.e., the activation energy U_L) is smaller than that at higher temperatures U_H. This is in contrast to the usually observed [9] temperature dependence of $U(T) = U_0(1-T/T_c)^q$ (q ranging from 1 to 2), which yields larger activation energies at lower temperatures. A crossover temperature T_{cr} can be identified from the data as indicated in Fig. 2. A similar crossover behavior was found for various magnetic fields. T_{cr} depends on the external magnetic field. The field dependence of T_{cr} up to 4 T is plotted in the inset to Fig. 2.

The electric field affects the activation energy in both linear regions. However, the magnitude of the effect is larger in the low R region as compared to that in the high R region. The field modulations of the activation energy for $V_g = 8$ V in the two regions are plotted in Fig. 3 for different magnetic fields, and compared with the field-induced changes in J_c and N, which are indicated by the dashed lines. No evident magnetic field dependence is found for any of these quantities. In the low dissipation limit (low R, $10^{-6}\rho_n < \rho < 10^{-4}\rho_n$), U_L is changed by an amount of around 15%, i.e., $\Delta U_L/U_L \cong \Delta J_c/J_c$. In the higher dissipation region (high R, $10^{-3}\rho_n < \rho < 10^{-1}\rho_n$) the relative change in U_H amounts to about 6%, which is comparable to $\Delta N/N$. Mannhart *et al.* [4] attributed the difference between $\Delta J_c/J_c$ and $\Delta N/N$ to defect-induced surface-bound pinning potentials at the interface between YBCO channel and dielectric, which are more sensitive to changes in N. This picture assumes one single activation energy and cannot account for the existence of the two regions with activation energies depending differently on N.

Therefore, we propose that a transition between phases with different dissipation mechanisms is occurring. At higher temperatures, the vortices are in a "vortex liquid" phase, and move approximately independently of each

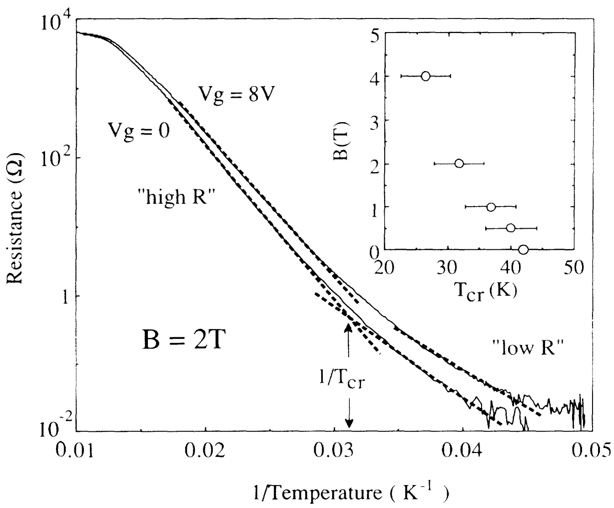

FIG. 2. Arrhenius plots for gate voltages of 0 and 8 V in $B=2$ T. Two distinct regions are found, illustrated by the dashed lines. Different activation energies U can be determined from each region. A crossover temperature T_{cr} is obtained by the intersection of the two dashed lines. Inset: Dependence of T_{cr} on the magnetic field.

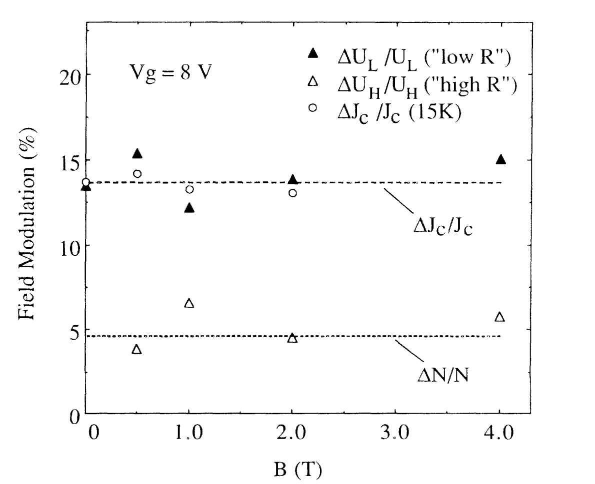

FIG. 3. Electric field modulations of the activation energy U in the two regimes as a function of B. The dashed lines represent $\Delta J_c/J_c$ and $\Delta N/N$, respectively. For low dissipation ("low R"), $\Delta U/U$ is nearly equal to the observed $\Delta J_c/J_c$. At higher dissipation ("high R"), $\Delta U/U$ is smaller and nearly equal to $\Delta N/N$.

other. If the samples were three dimensional, the vortex glass model of Fisher and co-workers [10,11] would predict that the low-temperature phase would have zero resistance. In a two-dimensional system, a vortex glass phase only truly exists at $T=0$ [11,12]. In our sample, the normal state sheet resistance R is ~ 3 kΩ, so that a true vortex glass state can only be expected [13] very close to $T=0$. Therefore in the low-temperature region shown in Fig. 2, our sample is expected to be in either a hexatic or a defected two-dimensional vortex-solid phase [14]. In this picture, the inset to Fig. 2 is a phase diagram for the system.

In the vortex liquid phase, dissipation is dominated by independent motion of the vortices, characterized by an activation energy U_H, in a manner similar to simple flux-creep theory. This is in agreement with the result $\Delta U_H/U_H=\Delta N/N$, i.e., the linear dependence of U on N in that region [8]. In the low-temperature vortex phase, on the other hand, fluctuation-induced dislocation pairs in the vortex lattice may dominate the dissipation. The observed activation energy in this regime may describe the energy required to move these dislocation pairs which could be smaller than the pinning energy U_H. Another possibility is that rigid vortex bundles move collectively in the low-temperature phase [15]. The increased rigidity of the bundles could give rise to an effectively lower U [16]. Since the voltage criterion for the critical current density falls into this region, the equality $\Delta U_L/U_L=\Delta J_c/J_c$ can be expected. However, the dependence on the charge carrier density for the activation energy at low temperatures U_L remains to be clarified.

To further investigate the effects of thermal fluctuations, zero magnetic field I-V characteristics were measured. As shown in Fig. 4(a), they obey a power law, $V\propto I^{\alpha}$, in agreement with the Kosterlitz-Thouless (KT) theory [17]. The exponent α, given by the slope of these curves, is a function of temperature for a given gate voltage. The temperature dependence of α for three different gate voltages is shown in Fig. 4(b). There is a significant change in $\alpha(T)$ at temperatures around 37 K. Similar behavior has been observed in high-T_c superconductors by many groups [18–20]. According to the KT theory, α drops from 3 to 1 at a transition temperature T_{KT}, and the linear extrapolation of the low-temperature data to the value of 1 gives the mean-field critical temperature T_c. For the data shown we obtain $T_c\cong 50$ K. We compare this result with a theoretical fit of R vs T between the mean-field and KT transitions (Ref. [17]) and they are in good agreement.

As can be seen in Fig. 4(b), the KT transition can be significantly changed by the gate voltage. Defining the temperature T_{KT} by $\alpha(T_{KT})=3$, we find that the increase in the carrier density (adding holes) causes an increase in T_{KT} while filling holes suppresses T_{KT}. The result demonstrates the possibility of tuning T_{KT} by direct modification of the charge-carrier density using the electric field effect. The gate voltage dependence of T_{KT} is shown in the inset of Fig. 4(b). It should be noted that the relative change $\Delta T_{KT}/T_{KT}$ is about 12%. Although it is comparable to the changes in J_c and U_L, implying that the creation of dislocation pairs in a finite magnetic field and the breaking of vortex-antivortex pairs in zero field may have a common origin, it contradicts the prediction of the KT theory that $T_{KT}\propto n_s$ and thus $\Delta T_{KT}/T_{KT}=\Delta N/N$. Another peculiar behavior is that the jump of α in our sample is from 6 to 1 instead of from 3 to 1 as predicted by the KT theory. However, the perpendicular penetration depth in our sample is smaller than the slim size, and hence the KT theory should only be viewed as an approximate description for these films (we note that the thicker films reported by other groups [18–20] have even smaller penetration depths). More work will be done in this area.

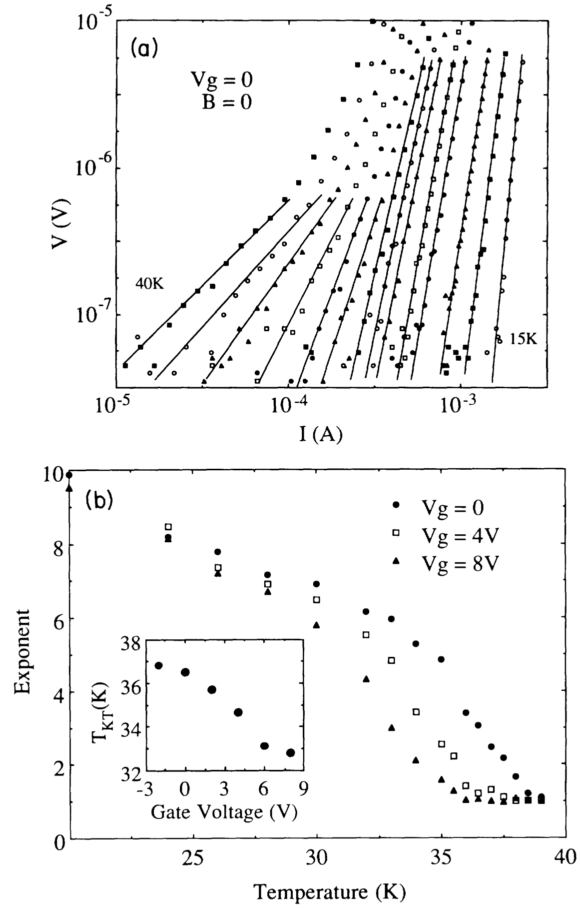

FIG. 4. (a) I-V characteristics for different temperatures and $V_g=0$ in log-log scale, showing a power-law behavior $V\propto I^{\alpha}$. (b) Temperature dependence of α. The abrupt drop in α is affected by the gate voltage. Inset: T_{KT} [defined by $\alpha(T_{KT})=3$] as a function of the gate voltage.

The I-V characteristics from the KT theory, $V\propto I^{(1+z)}$, where $z(N)\propto N$, for a two-dimensional system in zero magnetic field can also account for the difference between $\Delta J_c/J_c$ and $\Delta N/N$. It leads to a relation between

J_c and N through the definition of the experimental critical current by a constant voltage criterion. Least-squares fits to the data predict that $\Delta J_c/J_c = 4.2\Delta N/N$ for our sample at low temperatures, which leads to $\Delta J_c/J_c = 16.8\%$, in rough agreement with the observed $\Delta J_c/J_c = 14\%$.

In summary, resistive transitions of ultrathin YBCO films in SuFET devices in an external magnetic field show activated behavior in two different regions. These two regions of the Arrhenius plot respond differently to the electric field which allows one to identify them as distinct regions of different dissipative behavior. For low dissipation, the activation energy changes as a function of the charge-carrier density in the same proportion as the critical current density, but more than the change in the carrier density. However, in higher dissipation regions the activation energy is changed by an amount comparable to the change in the carrier density. The crossover between the two regions is likely the phase transition between a low-temperature two-dimensional ordered vortex phase and the vortex liquid. In the superconducting state, the I-V characteristics in zero magnetic field follow a power law with the exponent dependent on the charge-carrier density. A Kosterlitz-Thouless-type transition is observed in zero magnetic field, with T_{KT} dependent on the carrier density.

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[a]Also Department of Electrical Engineering, University of Maryland, College Park, MD 20740.

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