Transport properties of ultrathin $YBa_2Cu_3O_{7-\delta}$ layers: Evidence for two-dimensional vortex fluctuations

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We report on the transport properties of ultrathin $YBa_2Cu_3O_{7-\delta}$ (YBCO) layers, and compare the results with predictions of the Ginzburg-Landau Coulomb-gas (GLCG) model for two-dimensional (2D) vortex fluctuations. We find that the normalized flux-flow resistances for several ultrathin YBCO structures collapse onto a single universal curve, as predicted by the model. In addition, the values for the Kosterlitz-Thouless transition temperature T_{KT} and the Ginzburg-Landau temperature, T_{c0}, obtained by separate analyses of I-V and resistance data within the context of the GLCG model, are in general agreement. Finally, we find that the properties of a series of $YBCO/Pr_{0.5}Ca_{0.5}Ba_2Cu_3O_{7-\delta}$ superlattice structures are consistent with the GLCG treatment for anisotropic, 3D layered superconductors.

The high-temperature superconducting oxides are highly anisotropic due to their layered structure, with the superconducting CuO_2 planes being relatively weakly coupled. However, $YBa_2Cu_3O_{7-\delta}$ (YBCO) is one to two orders of magnitude less anisotropic than the Bi- and Tl-based superconducting cuprates, with significant c-axis coupling between CuO_2 bilayers in adjacent unit cells. Experiments on superlattice and sandwich structures containing YBCO layers as thin as a single c-axis unit cell show that YBCO's superconducting properties are significantly altered as the CuO_2 bilayers are isolated from each other by interposing layers of other nearly lattice-matched materials.[1–10] A decrease in T_c as well as a broadening of the resistive transition are observed as the YBCO layer thickness approaches a single unit cell (uc). Such observations suggest that YBCO may become quasi-two dimensional (2D) in the limit of very thin layers.[11]

In this paper, we report results of a study of the transport properties of ultrathin YBCO layers, addressing the question of whether their $R(T)$ and I-V characteristics are consistent with the Ginzburg-Landau Coulomb-gas (GLCG) model[12] for 2D vortex fluctuations. Structures with two unit-cell-thick YBCO layers were investigated, as well as several superlattice structures with single-unit-cell-thick YBCO layers. Consistency of the GLCG model is tested using both isolated, ultrathin (quasi-2D) YBCO layers, and coupled (3D), anisotropic layered superconducting systems. Implications of this analysis, in terms of the generality of the GLCG model for these systems, are discussed.

In a 2D superconductor, vortex fluctuations should dictate the shape of the transition from the normal state to the superconducting state.[12–14] At very low temperatures the vortices are bound as vortex-antivortex pairs, due to the logarithmic form of their interaction. As bound pairs, these vortices introduce no dissipation in the zero-current limit. However, as the temperature is increased above the Kosterlitz-Thouless temperature T_{KT}, the system undergoes a 2D phase transition, as unbinding of some of the vortex-antivortex pairs results in the creation of free vortices and the onset of dissipation. As the temperature is increased, more free vortices are generated and dissipation increases. Halperin and Nelson have developed analytical expressions for the form of the 2D flux-flow resistance very near the 2D transition temperature T_{KT}.[13] In principle, this offers a way to identify a Kosterlitz-Thouless (KT) transition. Fits to these expressions are often utilized as evidence for the existence of 2D vortex fluctuations in superconducting thin films.[11,15–19] Unfortunately, these expressions are expected to be valid only within the critical region, which lies very near T_{KT}, and their use appears inappropriate for the temperature range over which most experimental data has been analyzed.[12]

An alternative approach, which is valid outside the KT critical region, has been developed by Minnhagen to describe 2D vortex fluctuations. This approach is based on the Ginzburg-Landau Coulomb-gas (GLCG) model and the Coulomb-gas concept.[12] We briefly summarize this model as follows. The 2D vortices are treated as the particles of a 2D Coulomb gas. The superconductor, in the absence of vortices, is assumed to be well described by a Ginzburg-Landau theory. The shape and energy of an isolated vortex are obtained by minimizing the Ginzburg-Landau equations, and the energy of the vortex configuration is estimated by superposition of single Ginzburg-Landau vortices. Vortex fluctuations described by this model are controlled by two effective parameters, an effective dimensionless Coulomb-gas temperature variable $T^{CG}=k_BT/[2\pi\rho_0(T)(\hbar/m^*)^2]$, and the Ginzburg-Landau coherence length $\xi(T)$. The GLCG model leads to some rather simple scaling relations that should be valid well outside the critical region and should be universal for all 2D superconductors. In particular, the GLCG model states that any property arising from 2D vortex fluctuations, when expressed in dimensionless form, should be a universal function of the scaled temperature T^{CG}.

The flux-flow resistance ratio R/R_n, where R_n is the normal-state resistance, is such a quantity. All 2D superconductors that are well described by the GLCG model should produce a unique $R(T^{CG})/R_n$ curve. For convenience, the scaling variable is chosen to be $X=T^{CG}(T)/T^{CG}(T_{KT})$. Fitting the data to the universal curve requires the determination of two parameters, the critical temperature for the vortex 2D phase transition T_{KT}, and the Ginzburg-Landau temperature T_{c0}. The form of the universal resistance curve has been determined experimentally, using data from several type-II superconducting thin-film systems.[12] Comparison of data for other superconducting films to the universal R/R_n curve gives a good indication of their 2D nature.

Let us first consider the case of a quasi-2D superconducting system consisting of isolated, ultrathin YBCO layers. Three structures were fabricated, each with two unit-cell-thick YBCO layers. Sample 1 consists of a two unit-cell-thick YBCO layer sandwiched between a 24 unit-cell-thick $PrBa_2Cu_3O_{7-\delta}$ (PBCO) buffer layer and an eight unit-cell-thick cap layer. Structure 2 consists of a two-unit-cell-thick YBCO layer sandwiched between a 24 unit-cell-thick $Pr_{0.5}Ca_{0.5}Ba_2Cu_3O_{7-\delta}$ (PrCaBCO) buffer layer and an eight unit-cell-thick cap layer. These *c*-axis oriented PrCaBCO layers are nonsuperconducting, but more conductive than PBCO.[20] Sample 3 consists of a superlattice with two unit-cell-thick YBCO layers separated by 16 unit-cell-thick PBCO layers. All of these structures were grown by pulsed-laser deposition on (100) $SrTiO_3$ substrates as has been described elsewhere.[3,5] Film growth was performed at a substrate temperature of 700 °C in 200 mTorr O_2. After growth, the films were cooled at 10 °C/min in 1 atm O_2 with 30 min anneals at 625 and 550 °C.

Although each of these structures contains two unit-cell-thick YBCO layers, their transport properties differ significantly as seen in Fig. 1. The transition is broader and T_c is lower for the two unit-cell-thick YBCO layer in a PBCO trilayer structure than for the 2×16 YBCO/PBCO superlattice structure. In addition, the use of PrCaBCO as the cap and buffer layers significantly improves the properties of ultrathin YBCO layers, as has been reported elsewhere.[5,21] Thus, we have three structures, each having two unit-cell-thick YBCO layers, with significantly different transport properties. Nevertheless, we anticipate that the low-temperature transport properties of each may be strongly influenced by 2D vortex fluctuations, as each consists of ultrathin YBCO showing significant broadening of the superconducting transition (Fig. 1).

From the GLCG model, we know that the data for each of these structures should collapse onto the universal resistance curve when plotted against the scaled temperature variable, if, in fact, its transport properties are dictated by 2D vortex fluctuations.[12] Figure 2 shows the normalized resistance data for these three structures. R_n was simply chosen as the normal state resistance at 100 K. One can see that the resistance data do collapse onto the universal curve. Note that the scaling variable $X=T^{CG}(T)/T^{CG}(T_{KT})$ can be expressed as $X=T(T_{c0}-T_{KT})/(T_{c0}-T)T_{KT}$, assuming that the Ginzburg-Landau expression for $\rho_0(T)=\rho_0(1-T/T_{c0})$ is valid. Thus, the collapse of the data involves determining values for only two parameters, the Ginzburg-Landau transition temperature and the Kosterlitz-Thouless transition temperature. From the data, one obtains $T_{KT}=49.1$ K, $T_{c0}=74.4$ K for the 24 uc/2 uc/8 uc PrCaBCO/YBCO/PrCaBCO structure, $T_{KT}=19.8$ K, $T_{c0}=38.7$ K for the 24 uc/2 uc/8 uc PBCO/YBCO/PBCO structure, and $T_{KT}=43.4$ K, $T_{c0}=73.3$ K for the 2×16 YBCO/PBCO superlattice. Thus, the normalized resistance data for these three samples containing two unit-cell-thick YBCO layers are *consistent* with the predictions of the GLCG model for 2D vortex fluctuations.

In order to further test the GLCG model, its predictions regarding universal behavior in other physical properties must be examined. For example, the nonlinear *I*-*V* characteristics of a 2D superconductor provide an additional means to determine T_{c0} and T_{KT}, and to compare with the values just determined from the resistance data.[22] The GLCG model predicts that, in the presence of vortex-antivortex pairs, the *I*-*V* relationship below T_{KT} should follow a power-law dependence, $V \sim I^{a(T)}$, so that $a(T)$ can be determined from the slope of experimen-

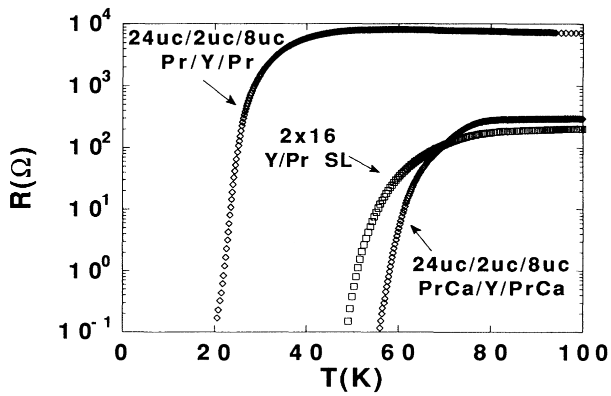

FIG. 1. Resistance plotted against temperature for three structures containing two unit-cell-thick YBCO layers.

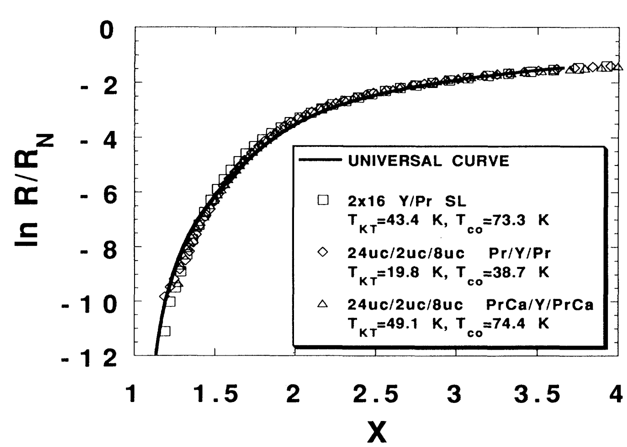

FIG. 2. Normalized resistance vs the scaling variable X for the three structures considered in Fig. 1.

tal I-V data. As the temperature is increased the coefficient $a(T)$ should decrease. The GLCG model predicts that $a(T)$ should equal 3 at the critical temperature T_{KT}. In addition, the temperature dependence of $a(T)$ below T_{KT} should follow the relation $[a(T)-1]T \sim (T_{c0}-T)$, thus providing a means to determine T_{c0}. Consequently, I-V measurements provide an independent method to determine the two parameters T_{KT} and T_{c0} utilized in fitting the universal resistance behavior, and give a good indication of the self-consistency of the GLCG model for the description of superconducting film behavior that is dominated by 2D vortex fluctuations.

I-V characteristics, shown in Fig. 3, were measured for the 24 uc/2 uc/8 uc PrCaBCO/YBCO/PrCaBCO structure for various temperatures in the range 35–60 K. As seen in the figure, each I-V curve contains a large region in which a well-defined power-law dependence $V \sim I^a$ is observed. Deviations from this behavior at the high- or low-current ends of these curves will be discussed later. From the curves, a value for the power-law coefficient $a(T)$ can be determined. Figure 4(a) shows the coefficient $a(T)$ plotted against temperature. As seen in the figure, $a=3$ corresponds to $T_{KT}=47$ K, which is close to the value $T_{KT}=49.1$ K determined by the universal resistance behavior seen in Fig. 2. From the Coulomb-gas model, it also follows that, for $T<T_{KT}$, $[a(T)-1]T \sim (T_{c0}-T)$. If $[a(T)-1]T$ is plotted against T, one should obtain a straight line for $T<T_{KT}$, extrapolating through zero at $T=T_{c0}$. As seen in the figure, this extrapolation gives $T_{c0}=79$ K, which is slightly larger than the value $T_{c0}=74.4$ K obtained from the universal resistance behavoir. From the two data sets, $R(T)$ and I-V, we obtain values for T_{KT} and T_{c0} which are in reasonable agreement, suggesting that the transport properties of these ultrathin YBCO structures are determined largely by 2D vortex fluctuations and are consistent with the GLCG model.

Although much of the I-V curve follows a well-defined power-law dependence, significant deviations from this behavior are observed at the high- or low-current ends of the curves. At the low-current end, the I-V characteristics change from a power-law to a linear dependence as I is decreased below 10^{-4} A. At the high-current end, the dependence changes from a well-defined power law to one in which the power-law coefficient decreases with increasing current. Let us first consider the linear dependence at low currents. Recall that the predicted power-law dependence below T_{KT} results directly from the free vortices produced by current-induced depairing of 2D vortex pairs. In the absence of an applied current below T_{KT}, it is assumed that no free vortices are present. The model predicts a change from power law to linear as the temperature is increased above T_{KT} due to the formation of thermally generated free vortices. For the I-V curves shown in Fig. 3, we see that, at the low currents, the I-V dependence is always linear with a crossover to a power-law dependence only as the current is increased above $\sim 10^{-4}$ A. This behavior would be expected if a small, but finite density of free vortices were present below T_{KT} in the absence of any current. The free vortices present below T_{KT} may be induced by ambient magnetic fields. For example, the earth's magnetic field (~ 0.7 G) is greater than H_{C1} for the thin structures considered here.

At the high-current end of the I-V curves, one also observes a deviation from a well-defined power-law dependence. The coefficient $a(T)$ decreases as the current is increased. Such a behavior may indicate saturation of the density of free vortices produced by current-induced vortex depairing. Since the density of vortex pairs is finite, the number of free vortices that can be produced by a vortex pair-breaking mechanism is limited at very high currents.

In addition to these quasi-2D systems, it is also interesting to consider the case of an anisotropic, 3D layered superconductor in the context of the GLCG mod-

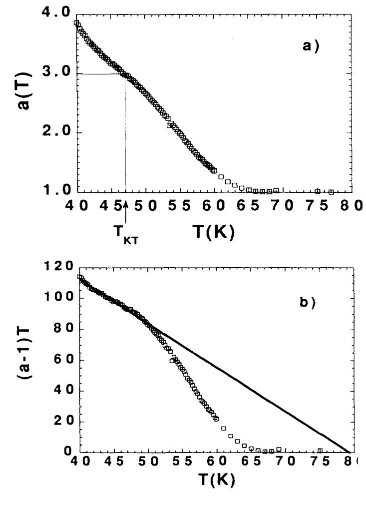

FIG. 4. From the I-V data in Fig. 3, (a) the power-law coefficient $a(T)$ and (b) the expression $[a(T)-1]T$ are plotted vs T, showing how T_{KT} and T_{c0} are determined.

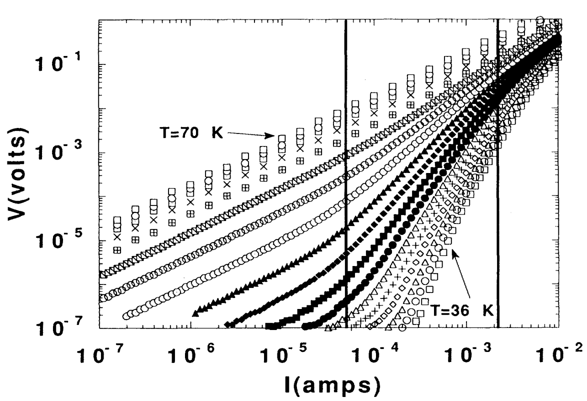

FIG. 3. I-V characteristics measured at temperatures ranging from 36 to 70 K for the 24uc/2uc/8uc $Pr_{0.5}Ca_{0.5}Ba_2Cu_3O_{7-\delta}/YBa_2Cu_3O_{7-\delta}/Pr_{0.5}Ba_2Cu_3O_{7-\delta}$ structure. The vertical lines show the approximate boundaries of the low- and high-current behavior discussed in the text.

el.[23–26] If one considers a 3D layered superconductor as a set of coupled 2D superconducting layers (coupled, for example, by Josephson tunneling), then the 2D vortex fluctuations associated with the quasi-2D layers are modified due to interlayer coupling. Cataudella and Minnhagen[23] have shown that, for large separations and in the presence of coupling to adjacent planes, the vortex interaction involves a term that varies linearly with distance (as opposed to the logarithmic dependence in the coupled, 2D case). At low temperatures, this linear term eliminates any 2D KT transition. However, it has been shown that the vortex fluctuations in the 3D anisotropic *XY* model become effectively 2D-like above a certain critical temperature. Even though the system is 3D, if there is sufficient anisotropy, the vortices behave almost as 2D vortices would above this critical temperature. Consequently, for the upper temperature range the vortices should obey the GLCG model; in particular, the universal resistance curve should be applicable. As the temperature is decreased, however, the coupling of vortices in adjacent planes results in a 2D to 3D transition that should manifest itself by a significant deviation from the universal resistance curve, with the degree of deviation providing a measure of the strength of the interlayer coupling.

The interlayer coupling between quasi-2D layers can be systematically varied by utilizing YBCO-based superlattices with ultrathin YBCO layers. By making the barrier layers progressively thicker, one can decouple the YBCO layers and observe the transition from an anisotropic, 3D layered structure to a quasi-2D structure with no significant interlayer coupling. We have studied this transition utilizing a series of $1\times N$ YBCO/PrCaBCO superlattice structures. Figure 5 shows the normalized resistance behavior as a function of the scaling variable X for 1×1, 1×4, and 1×8 YBCO/PrCaBCO superlattices. The strength of the interlayer coupling is varied by changing the thickness of the nonsuperconducting PrCaBCO barrier layers. As seen in the figure, the departure of the normalized resistance data from the universal 2D resistance curve diminishes as the separation of the YBCO layers increases. The 1×1 YBCO/PrCaBCO superlattice shows a significant departure from the 2D universal resistance, indicative of a system in which strong interlayer coupling exists. For the 1×4 and 1×8 superlattices, the $R(T)$ data collapse onto the universal resistance curve over a progressively larger range of temperatures. The temperature at which departure from the universal resistance curve occurs signifies the 2D to 3D transition as the interlayer coupling (linear interaction) term becomes dominant.

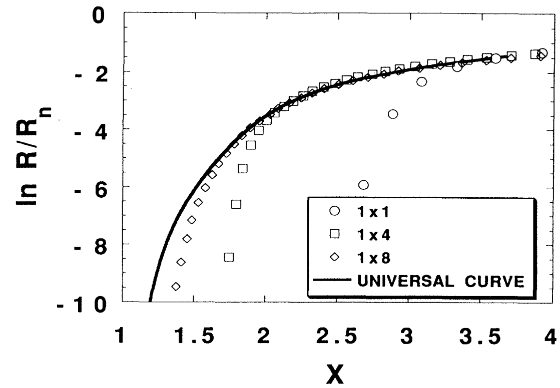

FIG. 5. Normalized resistance vs the scaling variable (X) for a series of $1\times N$ $YBa_2Cu_3O_{7-\delta}/Pr_{0.5}Ca_{0.5}Ba_2Cu_3O_{7-\delta}$ superlattice structures. The anisotropic, 3D layered superconductor shows progressively larger departures from the universal resistance curve for a quasi-2D superconductor, as interlayer coupling is increased.

In conclusion, it appears that the GLCG model for 2D vortex fluctuations gives a consistent description of the broadening of the superconducting transitions that is observed in epitaxial trilayer and superlattice structures that contain ultrathin YBCO layers. The collapse of the $R(T)$ data to a single universal curve, as well as the consistency of the values for T_{KT} and T_{c0} determined from $R(T)$ and I-V data, suggest that 2D vortex fluctuations strongly influence the low-temperature transport properties of these ultrathin superconducting systems. In addition, the general agreement between the systematic progression of $R(T)$ data for a series of $1\times N$ YBCO/PrCaBCO superlattices, and the predicted behavior for an anisotropic, 3D layered superconductor, suggests that the GLCG model effectively describes the transition from a coupled, 3D layered system to a quasi-2D system. It appears that YBCO-based ultrathin layered structures are attractive systems for the study of vortex fluctuations in two and three dimensions.

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