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Experimental Investigations of Superconductivity in Quasi-Two-Dimensional Epitaxial Copper Oxide Superlattices and Trilayers

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Experimental Investigations of Superconductivity in Quasi-Two-Dimensional Epitaxial Copper Oxide Superlattices and Trilayers

Douglas H. Lowndes and David P. Norton

ABSTRACT

Epitaxial trilayer and superlattice structures grown by pulsed laser ablation have been used to study the superconducting-to-normal transition of ultrathin (one and two c-axis unit cells) $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ layers. The normalized flux-flow resistances for several epitaxial structures containing two-cell-thick $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ films collapse onto the "universal" curve of the Ginzburg-Landau Coulomb Gas (GLCG) model. Analysis of normalized resistance data for a series of superlattices containing one-cell-thick $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ layers also is consistent with the behavior expected for quasi-two-dimensional layers in a highly anisotropic, layered three-dimensional superconductor. Current-voltage measurements for one of the trilayer structures also are consistent with the normalized resistance data, and with the GLCG model. Scanning tunneling microscopy, transmission electron microscopy, and electrical transport studies show that growth-related steps in ultrathin $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ layers affect electrical continuity over macroscopic distances, acting as weak links. However, the perturbation of the superconducting order parameter can be minimized by utilizing hole-doped buffer and cap layers, on both sides of the $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ layer, in trilayers and superlattices. These results demonstrate the usefulness of epitaxial trilayer and superlattice structures as tools for systematic, fundamental studies of high-temperature superconductivity.

Key Words: Superconductivity, vortices, superlattices, trilayers, laser ablation film growth, flux-flow resistance, film-growth mechanisms, Ginzburg-Landau Coulomb Gas.

INTRODUCTION

In a two-dimensional (2D) superconductor, dissipation due to thermally generated 2D vortices is expected to determine the shape of the normal-to-superconducting (n-s) transition, broadening the transition and, in effect, depressing T_c .¹⁻⁸ Among the copper oxide-based high temperature superconductors (HTSc), $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ (YBCO) is especially interesting for investigations of the effects of reduced dimensionality because it is the *least* anisotropic; the CuO_2 bilayers are more strongly coupled along the c-axis direction in YBCO than in the Tl- or Bi-based phases, so that pure YBCO is significantly three-dimensional (3D).⁹⁻¹¹ However, YBCO's effective anisotropy can be systematically and quasi-continuously varied by artificially separating thin YBCO layers with nearly lattice-matched insulating materials in epitaxial superlattice structures. The properties of single, isolated YBCO layers also can be studied in epitaxial trilayer ("sandwich") structures.

Recent work in several laboratories has demonstrated that high quality HTSc superlattices and trilayers can be fabricated using several film-growth methods.¹²⁻²³ In particular, single-cell-thick YBCO layers in superlattices are superconducting with (zero-resistance) $T_c \sim 10\text{--}20$ K in a $\text{PrBa}_2\text{Cu}_3\text{O}_{7-x}$ (PBCO) matrix.¹²⁻¹⁴ T_c also increases when ultrathin (one or two c-axis unit cell) YBCO layers are embedded in less insulating PBCO alloys doped with Ca or Y.^{16,22,23} Rasolt et al. interpreted these experiments by suggesting that YBCO/PBCO superlattices provide a 3D system in which the interlayer (c-axis) coupling between YBCO layers can be weakened all the way to zero.⁷ Thus, they said, a crossover to 2D behavior must occur in the limit of very thin YBCO layers. This crossover should be accompanied by characteristic 2D dissipation,¹⁻⁸ and their analysis of data for YBCO/PBCO superlattices supported this conclusion.⁷ However, questions have remained concerning the applicability of a Kosterlitz-Thouless type of analysis over the extended temperature range of the data¹² (see below), and concerning the fact that even a single YBCO unit cell contains

two CuO_2 planes (a CuO_2 bilayer). These concerns have made it still unclear whether the superconductivity of isolated, ultrathin YBCO layers should be considered 2D or 3D.

In this paper we review recent experiments carried out in our laboratory in order to test an alternative description of the n-s transition in a 2D superconductor, using the Ginzburg Landau Coulomb Gas (GLCG) model due to Minnhagen^{6,24} and collaborators.^{8, 25–27} As outlined below, this description is expected to be valid over the extended temperature range of the n-s transition in YBCO-based epitaxial materials.^{6,8} Furthermore, the GLCG model provides predictions regarding both the resistive transition shape^{6,8,25–27} and current-voltage characteristics,²⁴ so it can be tested for self-consistency by making both types of measurements. Finally, we briefly discuss departures from ideal behavior due to growth mechanism-related microstructures in the thinnest YBCO films.

BACKGROUND: THE N-S TRANSITION IN YBCO/PBCO SUPERLATTICES

Figures 1 and 2 (taken from Ref. 14) summarize the superconducting behavior observed by several groups^{12–14} as YBCO layers are made very thin and their interaction is decreased by the increasing thickness of PBCO barrier layers. Figure 1 shows the normalized resistance $R_n(T) = R(T)/R(100 \text{ K})$ for $1 \times N$ and $2 \times N$ YBCO/PBCO superlattices. (These structures contain one or two c-axis unit-cell YBCO layers and $N = 1$ to 16 cell-thick PBCO layers.) T_c decreases substantially as the YBCO layer thickness is decreased from two to one unit cell, demonstrating the importance of having YBCO in adjacent unit cells to raise T_c . Figure 2 (derived from data similar to Fig. 1) shows that for a fixed YBCO layer thickness, increasing the PBCO thickness produces a rapid initial decrease of T_c , followed by saturation of T_c at a nonzero value for large PBCO thicknesses, for all of the $M \times N$ structures studied.¹⁴

The saturation values are $T_c \sim 19, 54, 71, 80$, or 87 K for structures with well-isolated 1-, 2-, 3-, 4-, or 8-cell-thick YBCO layers, respectively. Thus, although (an unspecified) intercell interaction increases YBCO's T_c , this work suggests that interlayer coupling is not required for superconductivity to occur, and that single-cell-thick YBCO layers are superconducting in a PBCO matrix. It should be noted that the 1×1 , 1×2 , and 1×4 superlattices have the same average composition as the 2×2 , 2×4 , and 2×8 structures, respectively, but very different T_c values and transition shapes. This establishes that the superconducting behavior in Figs. 1 and 2 is that of periodically layered structures, and not of random alloys of the same average composition.¹²⁻¹⁴

CHARACTERISTIC 2D BEHAVIOR: DISSIPATION BY 2D VORTICES

A second striking feature of Fig. 1 is the prominent transition broadening that occurs for the thinnest, well isolated YBCO layers. Observation of this broadening, and the accompanying depression of T_c , was the basis for the recent suggestion by Rasolt et al that ultrathin YBCO layers may be effectively two-dimensional (2D).⁷ In a completely 2D superconductor, the shape of the normal-to-superconducting resistive transition is expected to be determined by characteristic 2D vortex fluctuations.¹⁻⁸ In 3D, spontaneous thermal generation of free vortices (magnetic flux lines) is energetically highly improbable, so that $B = 0$ in a sample if the applied $H = 0$. However, in a 2D superconductor, vortex-antivortex (v-av) pairs (vortex currents with opposite circulation) can exist, bound together at low temperatures by a logarithmic interaction. Such bound pairs should produce no dissipation in the zero-current limit. However, when the temperature is increased above the Kosterlitz-Thouless temperature, T_{KT} , the v-av pairs undergo a 2D phase transition in which they thermally unbind to produce free vortices, accompanied by the onset

of dissipation.³⁻⁵ A further increase in temperature produces more free vortices and increased dissipation. Halperin and Nelson¹ showed that very near T_{KT} the normalized flux flow resistance due to free vortices should have the form

$$\ln [R_n(T)] \sim 1 / [(T - T_{KT}) / T_{KT}]^{1/2} , \quad (1)$$

where $R_n(T) = R_{\square}(T) / R_{norm}$ is the normalized resistance, $R_{\square}(T)$ the measured sheet resistance, and R_{norm} the normal-state resistance. Fits of resistance data to Eq. (1) have often been cited as evidence for the existence of 2D vortices in thin superconducting films.^{7,28-31} However, since this expression is logarithmic, many decades of data are required for a convincing fit. Moreover, Minnhagen has pointed out that Eq. (1) is expected to be truly valid only in the critical region very close to T_{KT} , and its use is unjustified for the temperature ranges over which most data have been analyzed.⁶

To deal with this difficulty, Minnhagen and co-workers^{6,8,24-27} have developed an alternative approach that is valid outside the critical region, in order to describe the experimentally observable effects of 2D vortex fluctuations. Their approach is based on the 2D Ginzburg–Landau Coulomb Gas model. The model’s name originates from the fact that charged particles in 2D interact by a logarithmic potential, so that v–av pairs are analogous to the positive and negative charges in a 2D Coulomb gas. The superconductor also is assumed to be well described by the Ginzburg–Landau theory. Consequently, the properties of individual vortices, such as the vortex energy, can be obtained by minimization (Ginzburg–Landau equations), and for vortex configurations by superposition. Within this model, the vortex fluctuations are completely described by two parameters, the dimensionless Coulomb gas temperature,

$$T^{CG} = k_B T / [2\pi\rho_o(T) (\hbar/m^*)^2], \quad (2)$$

and by $\xi(T)$, the Ginzburg–Landau coherence length. The most important result of the model is that it leads to scaling relations for measurable properties that are expected to be valid outside of the critical region, and to be “universal” for all 2D superconductors. Thus, any measurable property that is due to 2D vortex fluctuations, when expressed in the proper dimensionless form, should be a universal function of the scaled Coulomb gas temperature, T^{CG} .⁶

One such property is the normalized flux flow resistance, $R_n(T)$. All 2D superconductors whose flux flow resistance is due to 2D vortices, and that are well described by the GLCG model, are expected to fall on a universal curve of $R(T^{CG}) / R_{norm}$. For the scaled temperature it is convenient to take $X = T^{CG}(T) / T^{CG}(T_{KT})$, since by using the Ginzburg–Landau expression for $\rho_o(T) = \rho_o (1 - T/T_{co})$ together with Eq. (2), then $X = T (T_{co} - T_{KT}) / T_{KT} (T_{co} - T)$. The form of the universal curve for $R_n(X)$ has been determined from experimental data for several type-II superconducting film systems.⁶ Consequently, simply comparing data for other superconducting films to the universal $R_n(X)$ curve gives an indication of whether they are 2D.

Norton recently applied the GLCG model to analyze the resistive transitions of several well isolated YBCO films only two unit cells thick.³² Three different epitaxial structures were grown on (001) SrTiO₃ by pulsed laser ablation: (1) a trilayer structure consisting of a 2 uc YBCO film sandwiched between a 24 uc PBCO buffer layer and an 8 uc PBCO cap layer; (2) a similar trilayer with the PBCO replaced by less insulating hole-doped Pr_{0.5}Ca_{0.5}Ba₂Cu₃O_{7-x} (PrCaBCO); and, (3) a 2 × 16 YBCO/PBCO superlattice. Figure 3 shows that although these structures each contain well isolated 2 uc YBCO layers they have very different zero-resistance T_c values. (Possible reasons why hole-doped PrCaBCO raises T_c have been discussed

elsewhere.³³⁾ Nevertheless, each structure has a broad resistive transition, which suggests that 2D vortex fluctuations may be present. Figure 4 shows the result of applying the GLCG model analysis (outlined above) to the transitions of Fig. 3, with R_{norm} taken to be the normal state resistance at $T = 100$ K. It is apparent that the resistance data for all three structures collapse onto the universal curve when they are plotted versus the scaled temperature variable, X . For each specimen, this collapse of the data involves determining only two parameters, T_{c0} and T_{KT} . From this analysis it appears that the data for well-isolated 2 uc YBCO films are at least consistent with the GLCG model, and with the idea that the measured transition broadening is due to 2D vortex fluctuations. The values obtained for T_{c0} and T_{KT} are given in Table 1.

The GLCG model also makes definite predictions about the behavior of 2D vortices in a highly anisotropic, layered 3D superconductor.^{8,25-27} Cataudella and Minnhagen have shown²⁵ that if there is a weak interlayer coupling between 2D superconducting layers, then the 2D v-av interaction and the low temperature behavior of the vortex fluctuations both are modified. For large v-av separations, coupling between 2D layers introduces a v-av interaction term that varies linearly (rather than logarithmically) with separation. This linear term eliminates the low-temperature Kosterlitz-Thouless transition at T_{KT} . However, they also have shown that for such a highly anisotropic, layered 3D superconductor, the vortex fluctuations become effectively 2D above a temperature T^* . Thus, even though the individual layers are only quasi-2D because of interlayer coupling along the third dimension, the vortices behave like 2D vortices above T^* . The implication is that the GLCG model and the universal resistance curve should be applicable for $T > T^*$. With decreasing temperature, though, interlayer coupling will produce a 2D to 3D transition that will appear as a departure from the universal curve, with the interlayer coupling strength indicated by the extent of deviation.

YBCO-based superlattices provide a model system in which these predictions can be tested, if it is the c-axis coupling between YBCO layers that is being systematically varied by making the barrier layers progressively thicker. Norton has carried out a GLCG analysis of the resistive transitions of a series of $1 \times N$ YBCO/PrCaBCO epitaxial superlattices.³² These structures contain single-cell-thick YBCO layers, with $N = 1, 4$, or 8 uc of PrCaBCO. Figure 5 shows that the normalized resistance data for these 1 uc YBCO films follow the universal curve over a progressively larger temperature range as the separation of the YBCO layers is increased, in agreement with the GLCG model. According to the GLCG model, the 2D to 3D transitions occur at the temperatures of these successive pronounced deviations from the universal curve, as interlayer coupling modifies the vortex behavior.⁸

Although these resistive data are consistent with the GLCG model predictions, other measurable properties of ultrathin superconducting films also are expected to be modified by the presence of 2D vortices, and other tests of the model are possible. Current-voltage (I-V) measurements provide an independent way to determine the parameters T_{KT} and T_{c0} , and a test of the self-consistency of the GLCG description.²⁴ In the presence of v-av pairs, the GLCG model predicts that for $T < T_{KT}$ the voltage, V , due to a current, I , should follow a power-law dependence,²⁴

$$V \sim I^a(T), \quad (3)$$

so that $a(T)$ can be determined from the logarithmic derivative of V-I data. This power-law behavior below T_{KT} is due to free vortices that are produced by current-induced depairing of what would otherwise be bound v-av pairs, since in the absence of a current no free vortices or dissipation are expected for $T < T_{KT}$. For $T < T_{KT}$, $a(T)$ is expected to behave as $[a(T) - 1] T \sim [T_{c0} - T]$, so that T_{c0} can be determined.²⁴ Also, $a(T) = 3$ for $T = T_{KT}$, from which T_{KT} can be determined.

Figure 6 (from Ref. 32) shows the V-I characteristics for the trilayer structure consisting of a 2 uc YBCO film with 24 uc and 8 uc PrCaBCO buffer and cap layers, respectively. The V-I characteristic is linear at low currents; at intermediate current values there is an extended region of $V \sim I^{a(T)}$ power-law behavior; finally, at high currents, the power-law coefficient decreases. The linear V-I behavior at low currents would result if a low density of vortices was present below T_{KT} even in the absence of a current. These vortices might be due to weak ambient magnetic fields, since the earth's magnetic field of ~ 0.7 gauss is greater than H_{c1} for ultrathin YBCO. Norton has suggested³² that the decrease of $a(T)$ at high currents may simply reflect saturation of the free vortex density: Since the v-av pair density is finite, so then is the density of free vortices that can be produced by current-induced pair-breaking. Figure 7[a] shows the coefficient $a(T)$ plotted versus temperature, using data from the central (power-law) region of Fig. 6. Table 1 shows that the values of T_{KT} and T_{co} , determined from $a(T_{KT}) = 3$ and from the extrapolated intercept, T_{co} , of $[a(T) - 1]T$ [as shown in Fig. 7(b)], are close to the values determined from the $R_n(X)$ analysis for this trilayer. This again suggests that the transport properties of ultrathin YBCO superconducting films are governed largely by 2D vortex fluctuations, and are described consistently by the GLCG model.

GROWTH-RELATED MICROSTRUCTURE AND WEAK-LINK BEHAVIOR

In parallel with our studies of characteristic 2D behavior in ultrathin YBCO films, we also have used scanning tunneling microscopy³⁴ (STM) and Z-contrast scanning transmission electron microscopy³⁶ (STEM) to study near-surface and sub-surface microstructures in YBCO films and YBCO/PBCO superlattices. These studies revealed that these epitaxial structures contain single-cell-high growth-related steps; from the existence of these steps we were able to infer their growth mechanism.³⁴⁻³⁶

These steps apparently influence the electrical continuity and transport properties of the thinnest ($\sim$ one-cell thick) YBCO layers, in addition to the effects of reduced dimensionality discussed above.

Figure 8 shows an STM image of the surface of a c -axis perpendicular ($c_{\perp}$) YBCO film grown at a heater temperature of 730°C on (001) SrTiO_3 . STM studies of $c_{\perp}$ YBCO films deposited on accurately aligned (001) substrates show that the films are formed by coalescence of well-defined islands, each island being epitaxially aligned with the (001) substrate.³⁴ Each island, in turn, consists of a stack of terraces (Fig. 8), with most terrace heights being a single $c_{\perp}$ unit cell. This terraced structure reveals that the YBCO grows unit cell-by-unit cell.^{36,37} Although individual terraces on a particular island/grain are flat on nearly the atomic scale, the terraced-island growth mechanism produces a slowly varying surface height and film thickness between the center of an island/grain and its edge, which appears macroscopically as a gradual “roughening” of the film surface. The surface height variation is a function both of film thickness and substrate temperature. For example, for ~ 200 nm-thick films, the surface “roughness” is ~ 10 nm for films grown at a heater temperature of 730°C , and ~ 30 nm at 780°C .³⁴ STM images also indicate that individual YBCO layers in superlattices are not flat but can undulate up and down by ~ 10 – 30 nm (depending on growth temperature) over lateral distances corresponding to a grain/island diameter (~ 100 – 500 nm, also depending on growth temperature). The undulation amplitude is largest for the YBCO layers closest to the film surface. These undulations can be seen clearly in cross-section Z-contrast STEM images (e.g., Fig. 1 of Ref. 36).

These growth-related microstructures have important implications for the transport properties of ultrathin YBCO layers in superlattice or trilayer structures, since both the terraced steps and the granular film structure can affect the electrical continuity of the YBCO layers. For example, if a PBCO layer has terraced steps on it

at the time when the laser ablation targets are exchanged in order to grow the YBCO layer, then the YBCO layer will not be flat but will have a step in it wherever it crosses the end of a PBCO terrace. Although the crystalline continuity of the heteroepitaxial structure is unaffected, the electrical continuity of the YBCO layer is interrupted.

We have observed these steps in the YBCO layers of superlattices directly, using cross-section Z-contrast STEM.^{31,35,36} The average lateral distance, L_s , between the terrace steps in cross-section Z-contrast STEM images was $L_s \sim 20$ nm, consistent with the average separation of 15 ± 5 nm between successive terrace steps in STM images of films grown at a substrate heater temperature of 730°C. Consequently, the supercurrent must tunnel at least one cell along the c -direction for every distance L_s that it travels laterally. For single-cell-high kinks in a thick YBCO layer, there should be no serious effect on the critical current density, J_c , or transition temperature, T_c , so long as the average “overlap” of the two adjacent pieces of the YBCO layer is a large fraction of its thickness. However, for a 1-cell-thick YBCO layer, there will be no overlap at a 1-cell step. The layer’s electrical continuity then depends entirely on there being enough chance areas of overlap in different in-plane directions to produce a continuous percolative path, or else on tunneling along the c -axis. A high density of steps could result in no superconducting phase coherence across a macroscopic specimen, and no zero-resistance state, even though the individual epitaxially aligned grains (islands) of the film are superconducting. Consequently, one should expect weak-link behavior for single-cell-thick $c_\perp$ YBCO films. Indeed, we observed a significant reduction of J_c in single-cell YBCO layers, apparently due to disruption of the phase of the superconducting order parameter at these weak-linked “kinks” in electrical continuity.³⁶

EFFECT OF THE MATRIX SURROUNDING A THIN YBCO LAYER

Norton has pointed out ³³ that a complete superconducting transition has been observed for a single-cell-thick YBCO layer in a PBCO trilayer structure only when there was careful in situ monitoring of the growing film's thickness (e.g., by RHEED). More often, nominally one-cell-thick YBCO layers in trilayer structures with PBCO show a superconducting onset but no zero-resistance state above ~5 K. (In contrast, one-cell YBCO layers in superlattices show zero resistance at ~10–20 K, as illustrated in Fig. 1.) However, the superconductivity of one-cell-thick YBCO layers in trilayers can be greatly enhanced by hole-doping the buffer and cap layers. For example, PBCO can be hole-doped by substituting divalent Ca on some of the Pr sites, to produce a metallic or even superconducting material,³⁸ and similar effects are seen by substituting Y for Pr.²² Replacing the PBCO cap and buffer layers of a PBCO/YBCO/PBCO trilayer by PrCaBCO produces the large improvement of superconducting properties illustrated in Fig. 3. The onset T_c increases from ~45 K to ~75 K and the zero-resistance T_c from ~20 K to ~55 K. Similar increases are seen for a one-cell-thick YBCO layer in a PrCaBCO matrix, with $T_c(R = 0) \sim 45$ K. The explanation for this behavior appears to be that the terrace steps in the YBCO layer act as weak links in YBCO's electrical continuity, since at each step there is a "kink" in the conduction path that requires transport along the c-axis, and the one unit-cell length of the kink is longer than the c-axis coherence length ($\xi_c \sim 2\text{--}3 \text{ \AA}$). If one thinks of the kink as an S-N-S junction, then conduction through the "N" region depends on the properties of the buffer and cap layers. The coherence length in the N-region should increase with increasing carrier density, so replacing PBCO by PrCaBCO should decrease the perturbation of the superconducting order parameter at the kink. This is consistent with the change in superconducting behavior that we observe as carriers are added to the buffer and cap layers (Fig. 3).

SUMMARY

The broadening of the superconducting-to-normal transition for ultrathin YBCO films is consistent with dissipation by 2D vortices, in that the normalized resistance data for two-unit-cell-thick YBCO films, in three different epitaxial structures, all collapse onto the “universal” curve for normalized resistance vs scaled temperature of the Ginzburg-Landau Coulomb Gas model. Similarly, normalized resistance data for a series of $1 \times N$ superlattices show the behavior expected for a highly anisotropic layered, 3D superconductor, i.e. they follow the universal curve for high temperatures but deviate from it at lower temperatures. The temperature at which deviation occurs decreases as the interlayer coupling is weakened, also as expected from the GLCG model. Current-voltage measurements on a single structure containing a 2-unit-cell YBCO layer also gave T_{KT} and T_{c0} values close to those derived from resistance measurements for this structure. Thus, it appears that 2D vortices strongly influence the low-temperature properties of ultrathin YBCO films.

However, YBCO’s terraced-island (unit cell-by-unit cell) growth mechanism also can affect the macroscopic electrical properties of ultrathin YBCO layers. YBCO layers grown on a PBCO buffer layer contain one-cell-thick growth steps; these steps act as weak links where the supercurrent must tunnel along the c-axis direction, interrupting the macroscopic electrical continuity of the layer. These “kinks” in electrical continuity cause a significant drop in J_c for one-cell-thick YBCO layers. However, the macroscopic superconductivity of one-cell-thick YBCO layers can be greatly enhanced by hole-doping the buffer and cap layers in trilayer structures.

These results illustrate the usefulness of epitaxial YBCO superlattices and trilayers for studies of the behavior of quasi-2D vortices in both 2D and 3D, as well as in studies of the connection between growth mechanisms and macroscopic superconducting transport properties.

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Table 1. Values of T_{co} and T_{KT} obtained from GLCG model analysis of two-unit-cell-thick YBCO films in epitaxial trilayer and superlattice structures (see text).

	T_{KT} (K)	T_{co} (K)
<u>$R_n(X)$ Analysis</u>		
2×16 superlattice	43.4	73.3
PBCO trilayer	19.8	38.7
PrCaBCO trilayer	49.1	74.4
<u>V-I Analysis</u>		
PrCaBCO trilayer	47	79

Figure Captions

- Figure 1. Normalized resistance vs temperature for $1 \times N$ and $2 \times N$ YBCO/PBCO superlattices.
- Figure 2. T_c vs PBCO layer thickness for YBCO/PBCO superlattices with 1- through 8-cell-thick YBCO layers.
- Figure 3. Resistance vs temperature for structures containing 2 unit-cell-thick YBCO layers.
- Figure 4. Normalized resistance vs scaled temperature, X , for the three structures of Fig. 3.
- Figure 5. Normalized resistance vs scaled temperature, X , for a series of $1 \times N$ superlattices (see text).
- Figure 6. I-V characteristics measured at temperatures of 36 K to 70 K for a 2 unit cell YBCO layer with PrCaBCO buffer and cap layers.
- Figure 7. (Top) the power-law coefficient $a(T)$, and (Bottom) the expression $[a(T)-1]T$, plotted vs T , using the I-V data of Fig. 6, to show how T_{KT} and T_{co} are determined.
- Figure 8. STM image of a ~ 200 nm thick, c-axis-perpendicular epitaxial YBCO film grown on (001) SrTiO₃ at a substrate heater $T \sim 730^\circ\text{C}$. The dimensions of the region shown are 670×670 nm².

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

Figure 8

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