Pinning Mechanisms in *a*-Axis-Oriented $EuBa_2Cu_3O_7/PrBa_2Cu_3O_7$ and $EuBa_2Cu_3O_7/SrTiO_3$ Multilayers

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a-axis-oriented (CuO_2 planes perpendicular to the substrates) $EuBa_2Cu_3O_7/PrBa_2Cu_3O_7$ and $EuBa_2Cu_3O_7/SrTiO_3$ multilayers have been grown by dc sputtering on (100) $SrTiO_3$ susbstrates and characterized by the refinement of the structure from x-ray spectra. The results show that interfacial structure (thickness fluctuations, interdiffusion, etc.) of the *a* axis are similar to the *c*-axis oriented superlattices.

The angular dependence of the resistivity in the mixed state allows us to study the interplay among different types of dissipation mechanisms, as, for example, intrinsic, surface, microscopic defects, and superlattice-induced pinning mechanisms. These mechanisms are relevant in different angular, magnetic field, and temperature regimes.

1. INTRODUCTION

One of the most recent [1] and active topics (see the whole issue in Ref. [2]) in high-T_c superconductors is the development of the charge stripes in the CuO_2 planes of some families of cuprates. The study of samples with the possibility of changing at will the length of the CuO_2 planes could be crucial in this stripes scenario. Very recently, several authors [3] and [4] have fabricated *a*-axis-oriented 123 films and superlattices. These *a*-axis-oriented systems allow us to study experimental situations that are impossible in single crystals and in the usual *c*-axis-oriented films.

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a-axis films grown on the usual cubic substrates have a microstructure with 90° microdomain (average size 20 nm) [5]. a-axis superlattices are very peculiar in comparison with the *c*-axis multilayers because in *a*-axis, the CuO_2 planes are perpendicular to the substrate and the effects due to the natural anisotropy (CuO_2 planes) and the artificial anisotropy (insulating layers) are uncoupled. An additional important aspect in *a*-axis superlattices of 123 superconductor/123 nonsuperconductor (for instance $EuBa_2Cu_3O_7/PrBa_2Cu_3O_7$) is that CuO_2 planes can be locally superconducting or insulating depending on whether the rare-earth neighbors of the plane are Eu or Pr.

In this paper, we present a carefully structural characterization of two types of superlattices, $EuBa_2Cu_3O_7/PrBa_2Cu_3O_7$ and $EuBa_2Cu_3O_7/SrTiO_3$, The former with the CuO_2 planes (superconducting/nonsuperconducting) running along the whole sample, and the latter with the CuO_2 planes interrupted by the $SrTiO_3$ layers. However, in these artificially structured systems, different dissipation mechanisms could compete. We show experimental results that could clarify the anisotropy, magnetic field, and temperature requirements needed to enhance different kinds of dissipation mechanisms.

2. EXPERIMENTAL

Superlattices of the so-called *a*-axis orientation (Cu-O planes perpendicular to the susbtrate) of $EuBa_2Cu_3O_7/PrBa_2Cu_3O_7$ (EBCO/PBCO) and $EuBa_2Cu_3O_7/SrTiO_3$ (EBCO/STO) were grown by dc magnetron sputtering from stoichiometric targets. The multilayers were grown by alternately depositing $EuBa_2Cu_3O_7$ and $PrBa_2Cu_3O_7$ or $SrTiO_3$ layers using two independent targets and stopping the substrates in front of the EBCO and PBCO or STO cathodes by a computer-controlled stepping motor. The samples were fabricated on (100) $SrTiO_3$ (STO) and (100) $LaAlO_3$ (LAO) substrates, and with a total thickness of 250 nm. A commercial cryostat with a 90 kOe superconducting magnet, a temperature controller, and a rotatable sample holder computer controlled by a stepping motor allows us to take angular dependence resistivity measurements with different values of the applied magnetic field. The structural and superconducting characterization of the multilayers have been reported elsewhere [6]. A powerful technique (SUPREX program) [7] of structural refinement of x-ray diffraction (XRD) profiles from superlattices has been used to characterize the quality of these *a*-axis EBCO/PBCO and EBCO/STO multilayers. In *a*-axis superlattices, it is not possible to subtract the diffraction maxima coming from the substrate as it is usually done in the *c*-axis-oriented superlattíces. These substrate maxima have to be included in the fitting data. The substrate peaks are at $2\theta = 46.5°$ (STO) and $2\theta = 48°$ (LAO), the (200) peak is at $2\theta = 47.3°$ (*a*-axis-oriented sample), and the (005) peak is at $2\theta = 38.5°$ (*c*-axis-oriented sample). Figure 1 shows the refinement result for both kind of superlattices. This method gives the actual thickness of the layers and parameters related with the interface. In these samples the refinement implies that the interface step disorder is around 1 unit cell and the interface diffusion 20%, values very similar to the values obtained in *c*-axis-oriented YBCO/PBCO multilayers [8].

3. RESULTS AND DISCUSSION

The angular dependence of the resistivity with an applied magnetic field is a good tool to study the anisotropy of the dissipation mechanisms. The measurements have been done in the

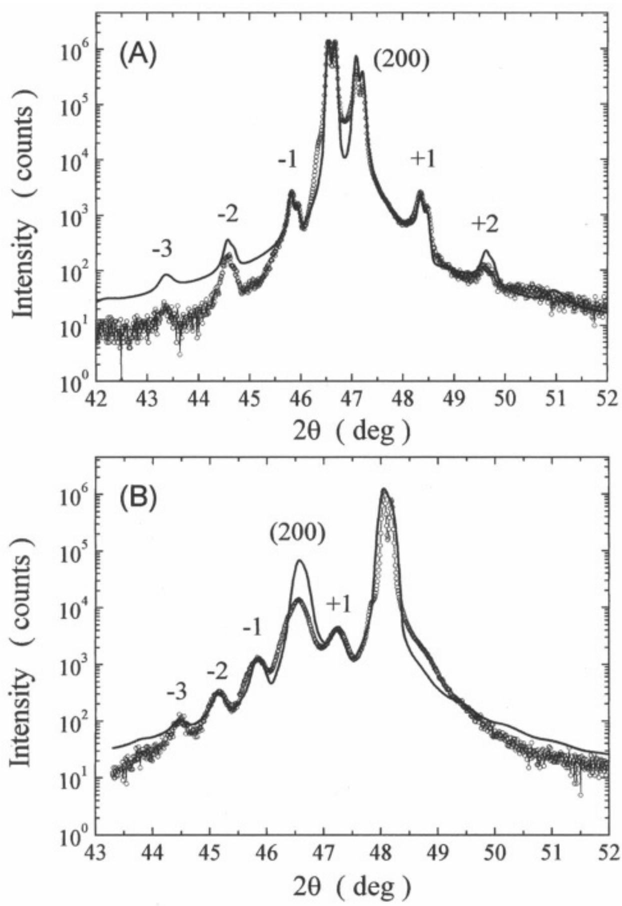

Fig. 1. Measured x-ray diffraction (XRD) profiles around the (200) peak of a-axis-oriented superlattices and calculated spectra (continuous line). (A) (16 u.c. $EuBa_2Cu_3O_7$/5 u.c. $PrBa_2Cu_3O_7$) × 31 bilayers on (100) $SrTiO_3$ substrate (B) (30 u.c. $EuBa_2Cu_3O_7$/5 u.c. $SrTiO_3$) × 8 bilayers on (100) $LaAlO_3$ substrate.

vortex liquid region close to T_c. Velez *et al.* [3] reported in a-axis-oriented 123 superlattices two minima in the angular dependence of the resistivity with constant temperature and applied magnetic field. These minima occur (a) when the magnetic field is applied parallel to the substrate or (b) with the applied field perpendicular to the substrate. These authors suggest that these two resistivity minima (critical current maxima) are due to two different pinning mechanisms. When the magnetic field is applied parallel to the CuO_2 planes, the intrinsic anisotropy leads to the pinnig due to the depression of the superconducting order parameter between the CuO_2 planes. Otherwise when the magnetic field is applied parallel to the substrate (perpendicular to the CuO_2planes) the magnetic field could be pinned by the artificial anisotropy due to the superlattice modulation. In this case, the PBCO insulating layers play a similar role to the areas between the superconducting CuO_2 planes in the intrinsic anisotropy case. In this artificially induced effect, Velez *et al.* [3] found that, when the modulation length of the multilayers and the vortex lattice parameter a_0 [given by the value of the applied magnetic field, $a_0 = (\Phi_0/B)^{1/2}$] have similar values an enhancement of the critical current occurs for a a range of applied magnetic field around this matching

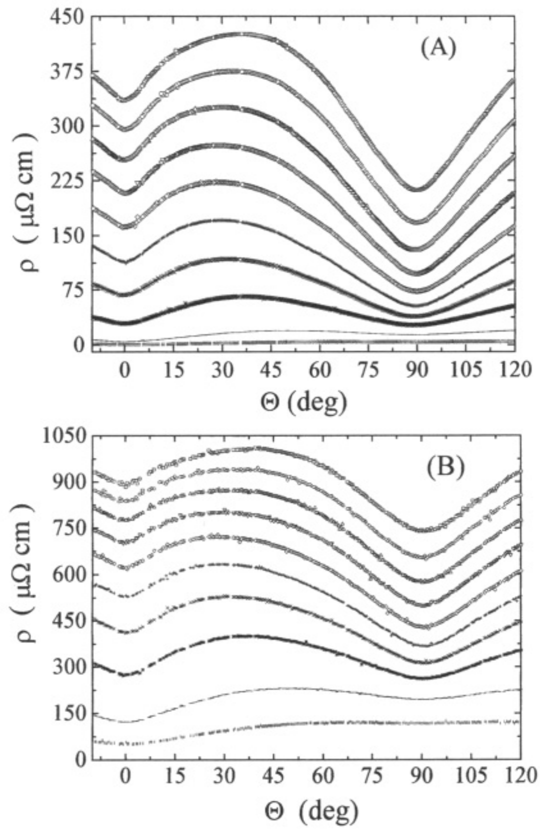

Fig. 2. Angular dependence of the resistivity at different constant fields for an a-axis oriented (50 u.c. $EuBa_2Cu_3O_7$/5 u.c. $PrBa_2Cu_3O_7$) superlattice. Fields: $9T$ (upper curve) to $0.5T$ (bottom curve) in steps of $1T$ up to the field $1T$. (A) $T/T_c = 0.80$. (B) $T/T_c = 0.98$.

field. Figure 2 shows these two minima in an a-axis-oriented EBCO (50 unit cells)/PBCO (5 unit cells) superlattice (matching field 5 *T*). This minimum still remains at temperature very close to T_c and in an interval of applied magnetic field around the matching field value (see Fig. 2B).

The role of the artificially induced structure (in this case, the PBCO layers) could be better understood studying another artificially layered system. a-axis-oriented EBCO (250 u. c.)/STO (5 u. c.). Figure 3, A and B, shows the data at the same reduced temperature (0.8 T_c and 0.98 T_c, respectively) than in the EBCO/PBCO sample. In this EBCO/STO multilayer, the matching field is 0.2 *T*. However, in addition to the minima due to the intrinsic pinning, a clear "second" minimun appears in the high magnetic field region. This "second" minimum vanishes when the temperature is increased (see Fig. 3B), whereas the actual minima due to the artificially induced anisotropy remains up to temperatures very close to T_c (see Fig. 2B). The experimental behavior of this pinning mechanism seems to indicate that it is due to the defects in the EBCO layers and that is not related to the artificially structure. Prouteau *et al.* [4] recently reported the same kind of minima in pure a-axis-oriented films. The very peculiar microstructure in a-axis-oriented films with 90° microdomains (see Ref. [5]) could pin the vortices when the magnetic field is parallel to

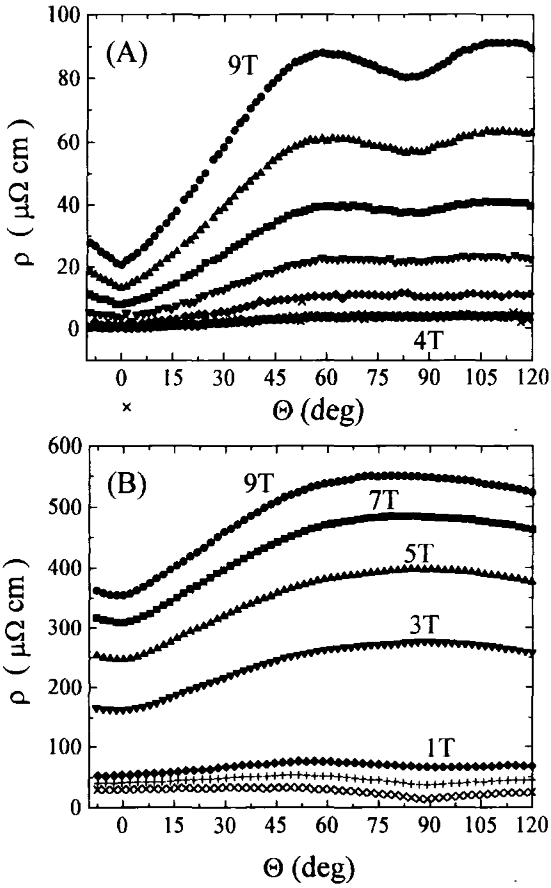

Fig. 3. Angular dependence of the resistivity for an *a*-axis-oriented (250 u.c. $EuBa_2Cu_3O_7$/5 u.c. $SrTiO_3$) superlattice. The labels close to every curve mean the magnetic field value. (A) $T/T_c = 0.80$. Fields: $9T$ (upper curve) to $4T$ (bottom curve) in steps of $1T$. (B) $T/T_c = 0.98$. Fields from upper curve to bottom curve: $9T$, $7T$, $5T$, $3T$, $1T$, $0.8T$, and $0.6T$.

the substrate. Another experimental fact that is interesting to point out is shown in detail in Fig. 4. A new minimun develops in the EBCO/STO multilayer at high temperature, close to T_c, and low values of the magnetic field when the field is applied parallel to the substrate. These are the footprints of the surface pinning effect (see, for instance, Ref. [9]).

4. CONCLUSIONS

In summary, *a*-axis-oriented 123 superlattices are the ideal system to study the competition among different dissipation processes.

The angular dependence of the resistivity shows two minima: (1) when the magnetic fieldis applied parallel to the CuO_2 planes (perpendicular to the substrate), and (2) when the applied magnetic field is parallel to the substrate (perpendicular to the CuO_2 planes) and parallel to the artificial structure. The former is due to the intrinsic pinning, and in the case of the latter, three different origins were experimentally detected: (a) microstructure defects

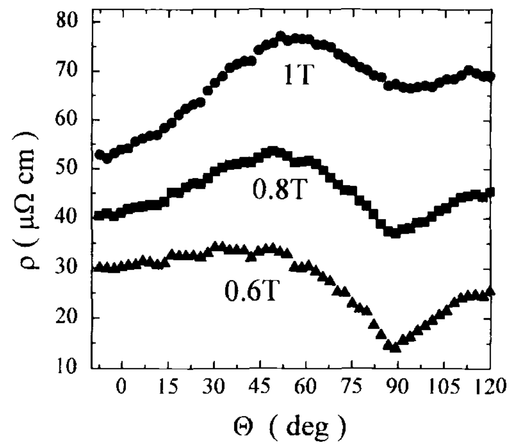

Fig. 4. Angular dependence of the resistivity at different constant fields for an a-axis-oriented (250 u.c. $EuBa_2Cu_3O_7$/5 u.c. $SrTiO_3$) superlattice. The labels close to every curve mean the magnetic field value. $T/T_c = 0.98$.

(90° microdomains) in the superconducting layers, which were observed at high magnetic fields and low temperatures; (b) surface and interface pinning, which was observed at low applied magnetic fields and temperatures close to T_c; and (c) pinning due to the artificially induced anisotropy (superlattice structure), a very effective mechanism that could be tuned with the value of the modulation length of the multilayer, and is relevant in a wide magnetic field interval, around a matching field, which is given by the modulation of the artificially layered structure. The insulating layers seem to be very effective pinning centers, and they could enhance the critical current when the applied magnetic field is around the matching field value and it is applied close to or parallel to the substrate.

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