

Angular dependence of the artificially induced anisotropy in a -axis-oriented $\text{EuBa}_2\text{Cu}_3\text{O}_7/\text{PrBa}_2\text{Cu}_3\text{O}_7$ superconducting superlattices

M. Vélez

Departamento de Física de Materiales, Facultad de Físicas, Universidad Complutense, 28040 Madrid, Spain

E. M. González

Departamento Propiedades Ópticas, Magnéticas, y de Transporte, Instituto de Ciencia de Materiales de Madrid, Consejo Superior de Investigaciones Científicas, Cantoblanco, 28049 Madrid, Spain

J. I. Martín and J. L. Vicent

Departamento de Física de Materiales, Facultad de Físicas, Universidad Complutense, 28040 Madrid, Spain

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a -axis-oriented $\text{EuBa}_2\text{Cu}_3\text{O}_7/\text{PrBa}_2\text{Cu}_3\text{O}_7$ (EBCO/PBCO) superlattices allow us to separate contributions to the anisotropy coming from the natural layered structure of EBCO from that introduced by the artificial layering with PBCO. The angular dependence of the critical current and resistivity in a magnetic field has been studied with different superlattice modulation lengths (strong coupling regime). The increase in the insulating PBCO layer thickness produces a crossover from an a -axis-oriented three-dimensional (3D) superconductor with a distribution of planar pinning centers to a 3D superconductor with an angular anisotropy behavior similar to single-phase c -axis-oriented films. [S0163-1829(96)03126-8]

The high- T_c superconducting oxides have a layered structure that is at the origin of their highly anisotropic behavior, both in the superconducting¹ and normal state.² The relationship between this intrinsically layered structure and the actual angular dependence of the transport and magnetic properties has been studied from different points of view, such as the intrinsic pinning model proposed by Tachiki and Takahashi³ or the anisotropy in the upper critical field and the crossover from anisotropic three-dimensional (3D) to quasi-2D behavior derived from the Lawrence-Doniach model.⁴

Superconducting-insulating superlattices, both of high-⁵ and low- T_c superconductors,⁶ are a very useful artificial system which permits a study of this anisotropic behavior in a controlled way. For example, c -axis-oriented $\text{YBa}_2\text{Cu}_3\text{O}_7/\text{PrBa}_2\text{Cu}_3\text{O}_7$ superconducting multilayers, in which the insulating $\text{PrBa}_2\text{Cu}_3\text{O}_7$ layers are parallel to the CuO_2 planes, have made possible to study the effect of the reduced coupling on vortex dynamics.⁵ On the other hand, if this artificial layered structure is oriented perpendicular to the intrinsic one [see the sketch in Fig. 1(a)], as it is the case in a -axis-oriented $\text{EuBa}_2\text{Cu}_3\text{O}_7/\text{PrBa}_2\text{Cu}_3\text{O}_7$ superlattices (EBCO/PBCO in the following) it will be possible to compare, on the same sample, the intrinsic material anisotropy with the effect of the superlattice layered structure, for different values of the superconducting and insulating layer thicknesses. For example, in these a -axis multilayers an enhancement of the pinning force and a reduction in the resistivity have been found⁷ when the field is applied parallel to the superlattice structure. This can even lead to a crossover reversing the resistivity anisotropy compared to the single a -axis films behavior, in which the dissipation is always lower for a magnetic field perpendicular to the substrate [$\theta=0^\circ$ in Fig. 1(b), where the angle is measured respect to

the film normal] than for a parallel one [$\theta=90^\circ$ in Fig. 1(b)]. [That is, $\rho(90^\circ) > \rho(0^\circ)$ in the single a -axis films, but $\rho(90^\circ) < \rho(0^\circ)$ is found in these a -axis superlattices.⁷] These changes in the behavior of the superlattices could be related to pinning in the insulating PBCO layers,⁹ which could have a similar effect to the weakly superconducting areas between the CuO_2 planes in the intrinsic pinning model. On the other hand, it has also been proposed¹⁰ that the reduction in resistivity for $\theta=90^\circ$ could be related to the angular dependence of the critical field due to this artificial structure.

Therefore, in order to have a clearer picture of the anisotropic properties of these a -axis EBCO/PBCO superlattices, in this paper we will report on the whole angular dependence of the critical current and the resistivity in the mixed state for different magnetic fields and temperatures, and we will study the role played by the artificial layered structure as the insulating PBCO layer thickness is increased.

The multilayers used in the present work have been grown by dc magnetron sputtering on (100) SrTiO_3 substrates and their structural and transport properties have been reported elsewhere.^{7,11} In particular, we have selected two different sets of samples; in the first one the PBCO layer thickness is kept constant at 5 unit cells and the superconducting layer thickness is varied, and in the second one we will compare superlattices with 40 unit cells EBCO layer thickness and insulating layers of 5 and 20 unit cells thick, respectively.

Figure 2 presents the angular dependence of the resistivity for two a -axis superlattices with the same PBCO layer thickness (75 unit cells EBCO/5 unit cells PBCO) [Fig. 2(a)] and (40 u.c. EBCO/5 u.c. PBCO) [Fig. 2(b)], measured at the same reduced temperature, $0.9T_c$, and different magnetic fields. In both cases there is a minimum in the resistivity for

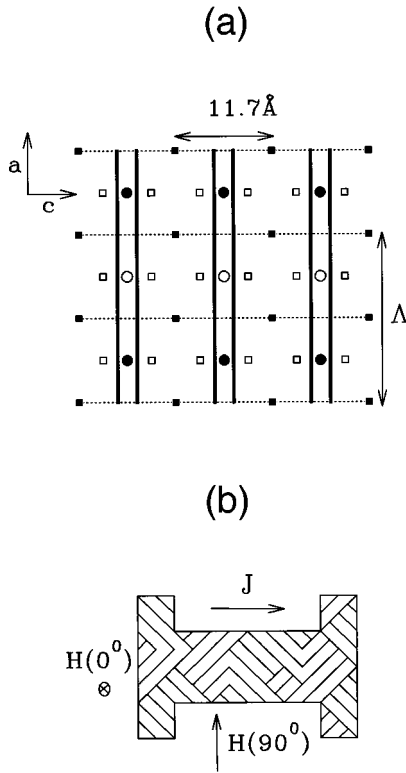


FIG. 1. (a) Sketch of the microscopic structure of an a -axis-oriented (1 unit cell EBCO/1 unit cell PBCO) superlattice (—, CuO_2 planes; O, Eu; ●, Pr; □, Ba; ■, CuO chains) in which the CuO_2 planes are perpendicular to the artificial Eu and Pr layers. (b) Current and field geometry with respect to the 90° domain microstructure typical of a -axis films (see Ref. 8) for two different field directions, $\theta=0^\circ$ and 90° . The angle θ is measured from the film normal and it is related to the angle (θ_i) between H and the CuO_2 planes by $\sin\theta_i = \sin 45^\circ \sin\theta$.

$\theta=0^\circ$ where the field is parallel to the CuO_2 planes, due to the material intrinsic anisotropy and similar to the behavior of single crystals¹² and thin films.¹³ The multilayer effect clearly shows up as another minimum in the dissipation for $\theta=90^\circ$, that is, when the applied field is oriented parallel to the multilayer structure. This shape of the $\rho(\theta)$ curve with two minima at 0° and 90° can be observed for multilayers with a wide range of superconducting layer thickness, from 20 to 100 unit cells, and in the whole temperature range. The minimum due to the artificial modulation of the superlattices persists for fields up to 90 kOe, even though it looks weaker in the lower field curves ($H=10$ kOe). The clear influence of the superlattice structure on the anisotropic behavior of the a -axis multilayers is remarkable since in this first set of samples the insulating layers are only 5 unit cells thick (19 Å), which is comparable to the superconducting coherence length¹ perpendicular to the superconducting layers $\xi_{ab}=16$ Å, and much smaller than the value of the coupling length through a -axis PBCO (which is estimated to be about 480 Å in a -axis YBCO/PBCO superlattices¹⁴). Therefore, in this series of samples the coupling between the EBCO layers must be strong.

The influence of the PBCO layers is also seen in the angular dependence of the J_c vs H curves. In Fig. 3 we have plotted the critical current of an a -axis (75 u.c. EBCO/5 u.c.

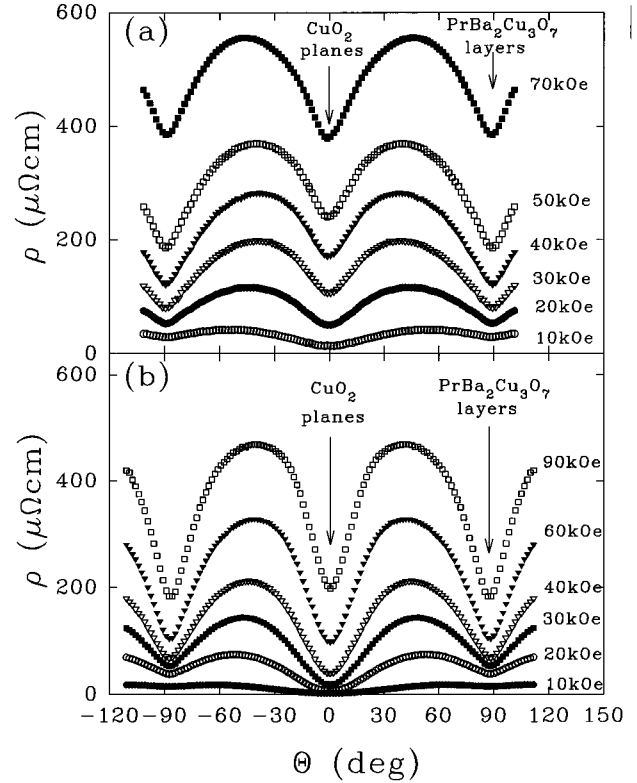


FIG. 2. Angular dependence of the resistivity for two a -axis-oriented superlattices: (a) (75 u.c. EBCO/5 u.c. PBCO) and (b) (40 u.c. EBCO/5 u.c. PBCO), at $0.9T_c$ and different magnetic fields. The arrows indicate the direction of the field parallel to the CuO_2 planes and the direction where the field is parallel to the insulating PBCO layers.

PBCO) superlattice as a function of the magnetic field and for several values of the angle between the field and the film normal. We observe two different angular ranges; in the first one ($\theta < 50^\circ$), the field direction is closer to the CuO_2 planes [Fig. 3(a)] than in the second one ($\theta \geq 50^\circ$); in the latter, it is closer to the artificial layered structure [Fig. 3(b)]. In the first case, we can observe the typical behavior of an anisotropic superconductor with an angular dependent $H_{c2}(\theta)$, so that there is a similar angular dependence in the whole field range and there exist scaling relations¹⁵ of the kind $J_c(H, \theta) = J_c[H\varepsilon(\theta)]$ [see the inset of Fig. 3(a)]. In this case, the anisotropy factor $\varepsilon(\theta) \propto 1/H_{c2}(\theta)$ is that of a 3D anisotropic superconductor $\varepsilon(\theta) = (\cos^2\theta_i + \gamma^2\sin^2\theta_i)^{1/2}$ with $\gamma=3$ and $\sin\theta_i = \sin 45^\circ \sin\theta$ (θ_i is the actual angle between H and the CuO_2 planes taking into account the typical a -axis film microstructure^{8,11}).

On the other hand, in Fig. 3(b) we find a completely different picture, that is, at low fields the critical current is almost independent of the angle, while at high fields there is a clear maximum in J_c for $\theta=90^\circ$, and therefore no scaling relations in terms of an angular-dependent critical field will hold in this case. The crossover between both field regions happens around the matching field between the vortex lattice and the multilayer structure H_Λ , defined by $a_0 = \Lambda$, where a_0 is the vortex spacing assuming an Abrikosov lattice and Λ is the superlattice modulation length. Thus, the influence of the superlattice structure, at least in these multilayers with

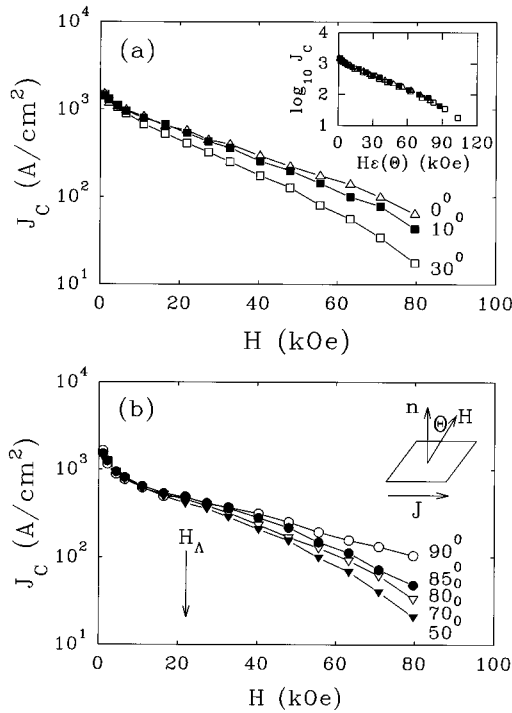


FIG. 3. $J_c(H)$ curves for an a -axis (75 u.c. EBCO/5 u.c. PBCO) superlattice at $0.4T_c$ and different angles between the field direction and the film normal, (a) H near the CuO_2 planes, $\theta \leq 50^\circ$ and (b) H near the artificial PBCO layers, $\theta \geq 50^\circ$. The inset shows the collapse of the $J_c(H, \theta \leq 50^\circ)$ curves vs a reduced magnetic field $H\varepsilon(\theta)$ with the anisotropy factor $\varepsilon(\theta) = (\cos^2\theta_i + \gamma^2\sin^2\theta_i)^{1/2}$ of a 3D superconductor with $\gamma = 3$ and where θ_i is the angle between the field direction and the CuO_2 planes ($\sin\theta_i = \sin 45^\circ \sin\theta$).

thin insulating layers (5 unit cells), is clearly different from the intrinsic material anisotropy. The role of the PBCO layers can be described as planar pinning centers, characterized by a matching field H_Λ and very effective when the field is parallel to the substrate. This pinning force arising from the multilayer structure causes the slower decrease of the critical current as a function of the magnetic field around H_Λ at $\theta = 90^\circ$, since this pinning force is acting on the very soft vortex lattice of high-temperature superconductors.⁹

The influence of the PBCO layers on the behavior of the anisotropy is modified as the PBCO layer thickness is increased; for instance, the changes in anisotropy of the a -axis multilayers in comparison with the a -axis single films can be seen in Fig. 4 for an a -axis (40 u.c. EBCO/20 u.c. PBCO) superlattice. The minimum in the angular dependence of the resistivity when the field is parallel to the CuO_2 planes associated with the intrinsic anisotropy has almost disappeared, and the most obvious feature in the $\rho(\theta)$ curve is the minimum due to the artificial superlattice structure. As a matter of fact, the anisotropy of this a -axis multilayer is completely reversed from the a -axis single-film behavior, and the overall curve shape looks quite similar to the angular dependence of the resistivity of a c -axis single film [shown in the inset of Fig. 4(a)]. It has to be noted that the superconducting layers are not decoupled in this superlattice, since the insulating layer thickness is only 77 \AA , still much smaller than the decoupling length estimated in Ref. 14; however, as the data in Fig. 4 show, the natural anisotropy

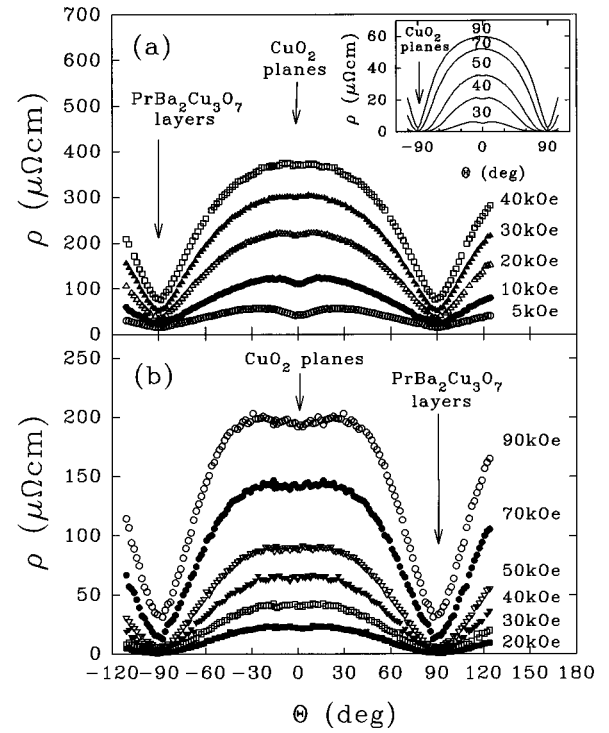


FIG. 4. Angular dependence of the resistivity for an a -axis-oriented (40 u.c. EBCO/20 u.c. PBCO) superlattice at (a) $0.9 T_c$ and (b) $0.7T_c$ and different magnetic fields. The arrows indicate the direction of the field parallel to the CuO_2 planes and to the insulating PBCO layers. The inset shows $\rho(\theta)$ curves of a c -axis EBCO thin film at $0.9T_c$.

due to the CuO_2 planes becomes weaker.

There is also a qualitative change in the behavior of the superlattice structure as compared to the superlattices with thin insulating layers. In this case, the main role of the artificial layers is not just as pinning centers but we can find scaling relations of the kind $\rho(H, \theta) = \rho[H\varepsilon(\theta)]$ close to 90° . This means that the artificial layered structure is introducing modifications in the angular dependence of $H_{c2}(\theta)$

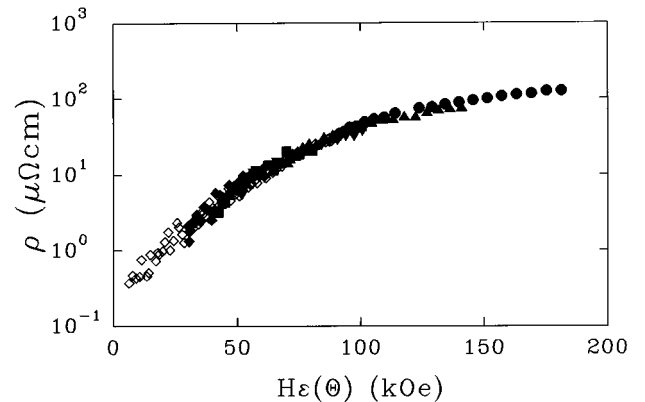


FIG. 5. Resistivity vs reduced magnetic field $H\varepsilon(\theta)$ in the angular range $|\theta - 90^\circ| < 25^\circ$ for an a -axis-oriented (40 u.c. EBCO/20 u.c. PBCO) superlattice at $0.7T_c$ and with the anisotropy factor $\varepsilon(\theta)$ of a 3D superconductor with $\gamma = 4.5$ [\bullet , $\rho(\theta, 90 \text{ kOe})$; \blacktriangle , $\rho(\theta, 70 \text{ kOe})$; \blacktriangledown , $\rho(\theta, 50 \text{ kOe})$; \blacksquare , $\rho(\theta, 40 \text{ kOe})$; \blacklozenge , $\rho(\theta, 30 \text{ kOe})$; \diamond , $\rho(\theta = 90^\circ, H)$].

$\propto 1/\varepsilon(\theta)$. This is shown in Fig. 5, where the field dependence of the resistivity measured at $\theta=90^\circ$ has been plotted together with the curves $\rho(\theta)$ from Fig. 4(b) vs this reduced magnetic field $H\varepsilon(\theta)$. We have used the anisotropy factor of a 3D superconductor [$\varepsilon(\theta)=(\sin^2\theta+\gamma^2\cos^2\theta)^{1/2}$ and $\gamma=4.5$], which is in agreement with the fact that the insulating layers are much thinner than the coupling length.⁴ However, the collapse of the curves only holds in a limited angular range near the insulating PBCO layers $|\theta-90^\circ|<25^\circ$, indicating that the effect of the intrinsic anisotropy has still to be taken into account even though the minimum at $\theta=0^\circ$ is not observed any more.

In summary, we have studied the anisotropy in the critical current and resistivity of *a*-axis-oriented EBCO/PBCO su-

perlattices, where the CuO_2 planes are perpendicular to the artificial multilayer structure. We have found strong modifications from the single *a*-axis film behavior even in strongly coupled superlattices with thin PBCO layers (5 unit cells). In this case the role of the artificial insulating layers can be described as anisotropic pinning centers characterized by a matching field between the vortex lattice and the superlattice structure. On the other hand, as the PBCO layer thickness is increased up to 20 unit cells the anisotropy of the multilayers is completely reversed in comparison with *a*-axis single-phase films, and the artificial layered structure can be described in terms of an angular-dependent $H_{c2}(\theta)$.

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