# Magnetic Field Dependence of the Critical Currents in $Bi_2Sr_2CaCu_2O_8/Bi_2Sr_2CuO_6$ Multilayers: An Approach to an Ideal Two Dimensional Superconductor

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Angular magnetic field dependence of the critical currents of $(Bi_2Sr_2CaCu_2O_8)_m/(Bi_2Sr_2CuO_6)_n$ multilayers has been investigated, $m$ and $n$ being the numbers of $c$-axis half unit cells of each phase in one layer. In the limiting case of 15 Å thick 2212 layers and 24 Å thick 2201 layers per multilayer unit ($m = 1, n = 2$), we have achieved a superconducting system where $J_c(H)$ is independent of a magnetic field ($H \leq 20$ T) parallel to the layers. We demonstrate that this system behaves like an ideal 2D superconductor. [S0031-9007(97)03895-7]

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Since the discovery of high $T_c$ superconductivity in cuprate compounds, a large amount of work has been done to understand the vortex dynamics and the mechanisms of flux pinning. For these highly anisotropic superconductors in a transverse magnetic field, the vortices may be represented by a stack of 2D pancakes localized in the $CuO_2$ planes [1,2]. Besides the anisotropy of the material, the strength and the nature of the coupling between stacked adjacent pancakes depend strongly on both temperature and magnetic field conditions. A model based on Josephson mediated coupling between the 2D vortices has been proposed [3] when the distance $d$ (along the $c$ axis) between these vortices is not too large with respect to the penetration depth of the screening current in the $ab$ plane, $\lambda_{ab}$. In the opposite limit ($d > \lambda_{ab}$) the pancakes are just magnetically coupled [4].

A study of multilayers represents a good approach for understanding the physical properties of the high-$T_c$ superconductors by artificially engineering their crystalline structure. It is possible in such artificial layered structures to control the distance $d$ between the superconducting ($CuO_2$) planes, and the nature of the separating layers (insulating, metallic, or superconducting). Through this approach it is possible to achieve the modulation of the magnitude of the superconducting layer coupling. This idea was first developed for the YBaCuO system. Several groups have studied the physical properties of YBaCuO/PrBaCuO multilayers [5,6], where the PrBaCuO compound is insulating, and of YBaCuO/$Y_xPr_{1-x}$BaCuO samples [7,8] where the separating $Y_xPr_{1-x}$BaCuO layers can be insulating or superconducting, depending on the value of $x$. In all cases the critical temperatures ($H = 0$) of the multilayers are smaller than that of YBaCuO bulk. In these previous studies, the effect of the multilayering on the transport properties under magnetic fields was considered. The dependence of the critical currents with a magnetic field applied parallel to the layers is found to be smaller than in the case of YBaCuO single phase films [8].

The study of artificial multilayers based on the BiSrCaCuO compound is more recent. Multilayers $(Bi_2Sr_2CaCu_2O_8)_m/(Bi_2Sr_2CuO_6)_n$ were obtained by growing sequentially 2212 phase (high $T_c$) layers and 2201 phase (low $T_c$, semiconducting or metallic) layers. The numbers $m$ and $n$ are the numbers of $c$-axis half unit cells of 2212 and 2201 phases, respectively, per superlattice period $\Lambda$. The effect of the multilayering on the broadening of the resistive transition was studied [9–12]. In all cases, $T_c$ ($R = 0$) is lower than (or equal to [12]) the value for the 2212 single phase. We have shown that, for a given multilayer, the broadening of the resistive transition, and the consequent $T_c$ ($R = 0$) decrease, are observed when the 2201 phase is semiconducting [13]. But when the 2201 phase is grown under conditions which produce metallic 2201 single layers, $T_c(R = 0)$ of the multilayer can be enhanced with respect to that of the 2212 phase [13].

We have investigated the critical currents $J_c$ under an applied magnetic field of these multilayers with a high $T_c$ value. We concentrate in this Letter on the results obtained for a multilayer with $m = 1, n = 2$, called SL1. The thickness of the 2212 phase layer of the superlattice is the smallest possible superconducting unit, i.e., half a unit cell: 15.4 Å. The distance between the $CuO_2$ double planes is 40 Å, which is more than 2 times larger than its value in the pure 2212 phase (15 Å). We compare the results to the data obtained on a single phase 2212 film, called SF, and on a multilayer with $m = 2, n = 2$, called SL2. For this second multilayer, the superlattice period is composed of one unit cell (30.8 Å) of 2212 phase separated by one unit cell of 2201 phase (24.6 Å). The stacking of the different component units for SL1, SL2, and the 2212 film, SF, is schematically drawn in Fig. 1. It

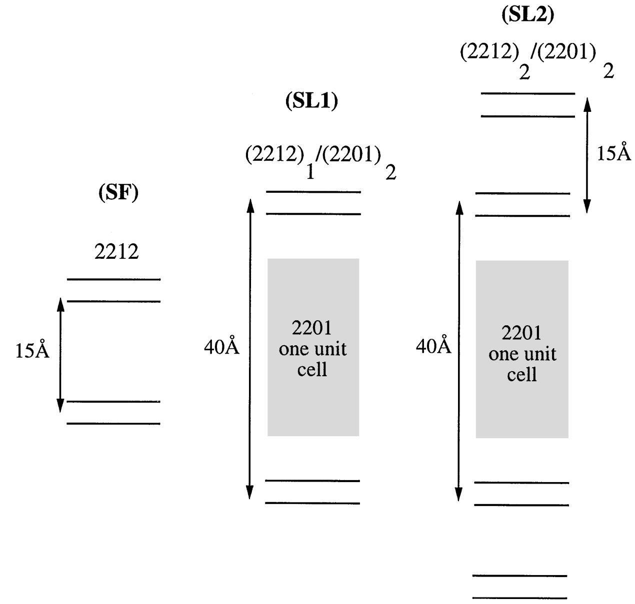

FIG. 1. Scheme giving the distances separating $CuO_2$ bilayers (solid lines) in a 2212 film SF, in multilayer SL1, and in multilayer SL2 (see text).

shows that for multilayer SL2 the $CuO_2$ double planes are separated either by a distance of 40 Å (as for SL1) or by a distance of 15 Å (as in the case of the pure 2212 phase. Up to now, no detailed and systematic magnetotransport studies have been performed on such multilayers. The data will be analyzed in terms of 2D angular scaling laws so as to reveal the effective dimensionality of the system. We will show that a specific layering allows one to approach an ideal 2D behavior.

Multilayers $(2212)_m/(2201)_n$ have been prepared by reactive rf magnetron sputtering on heated MgO substrates, and the crystalline quality of the films and the structure of the multilayers were studied by x-ray diffraction [13]. The 2201 phase was grown in conditions which produce oxygen overdoped 2201 single layers, metallic in their normal state and superconducting below 5 K. Multilayer SL1 [$(m = 1, n = 2) \times 10$, spatial period $\Lambda_1 = (40.3 \pm 0.4)$ Å] has a $T_c$ of 94 K and SL2 [$(m = 2, n = 2) \times 10$, spatial period $\Lambda_2 = (55.2 \pm 0.5)$ Å] has a $T_c$ of 86 K. The 2212 film SF is 1500 Å thick with $T_c = 81$ K. The samples were patterned by photolithography and chemical etching into a narrow bridge, 120 $\mu$m long and 25 $\mu$m wide. The critical currents are measured by a dc four probe technique, and a constant voltage criteria of 0.5 or 2.5 $\mu$V is used for $J_c$ determination. Note that, for the multilayers, the critical current density has been determined using the total thickness of the sample.

The magnetic field is applied in a direction always perpendicular to the current and tilted at an angle $\theta$ with respect to the $(a,b)$ planes. This angle has been varied from $-90°$ to $90°$ with an accuracy of 0.1° for the low magnetic field measurements ($H < 1$ T) and 0.05° for the high magnetic field ones ($1 < H < 20$ T). The high magnetic field measurements have been performed at the Laboratoire des Champs Magnétiques Intenses at Grenoble. The temperature was varied from 1.3 K to $T_c$ and regulated with a capacitance thermometer, with a precision $\Delta T/T$ better than $10^{-3}$.

Let us consider first the critical currents measured under magnetic field for SL1. In Fig. 2, we present the measurements of the angular dependence of the critical current densities $J_c$ at $T = 4.2$ K and $H = 1$ and 20 T, and at 70 K and $H = 5$ and 20 T. As expected in layered systems, there is a peak in $J_c(H)$ when $H$ approaches the direction of the $CuO_2$ planes ($\theta = 0°$). The important new result is the fact that $J_c$ measured for $H$ applied parallel to the $CuO_2$ planes stays equal, within experimental accuracy, to the value measured in zero magnetic field, as indicated by the solid line,

$$J_c(H, \theta = 0°) = J_c(H = 0)\,. \qquad (1)$$

Relation (1) is satisfied for all temperatures in the range: $4.2 \leq T \leq 81$ K and for $H$ ranging from 0 to 20 T, as demonstrated in Fig. 3. This figure displays the maximum values of $J_c(\theta)$, obtained for $\theta = 0$, and measured at given field and temperature. Because of the limitation of the angular precision and of the rapid decrease of $J_c$ in a transverse magnetic field, the

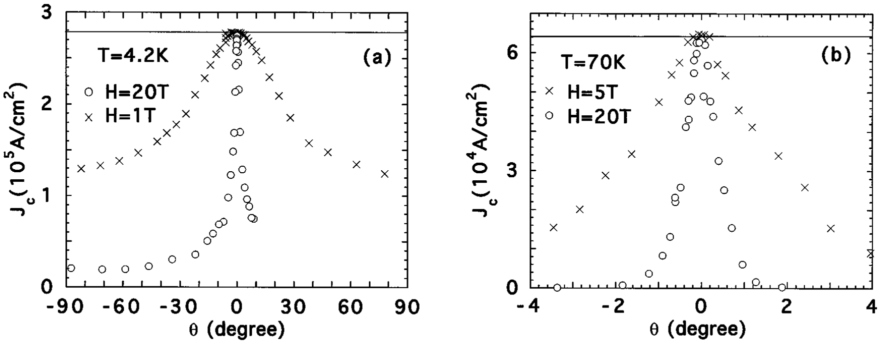

FIG. 2. Critical current density measured on multilayer SL1, for two magnetic field magnitudes, at $T = 4.2$ K ($H = 1$ and 20 T) (a) and $T = 70$ K ($H = 5$ and 20 T) (b), as a function of the orientation $\theta$ of $H$ with respect to the $CuO_2$ planes. The solid line indicates the value of $J_c(H = 0)$.

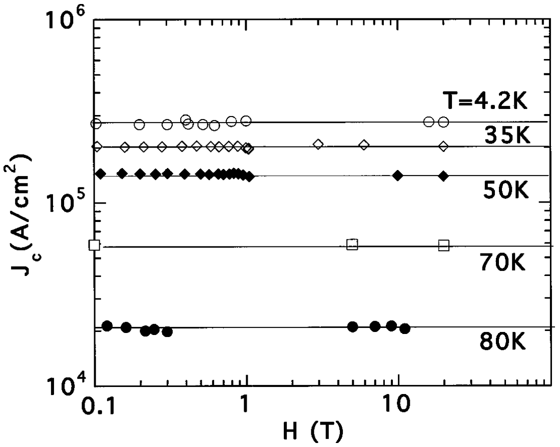

FIG. 3. Dependence of the critical current density measured on multilayer SL1 as a function of the magnetic field parallel to the $CuO_2$ planes ($\theta = 0$), at a given temperature, between $T = 4.2$ and 81 K ($T_c = 92$ K).

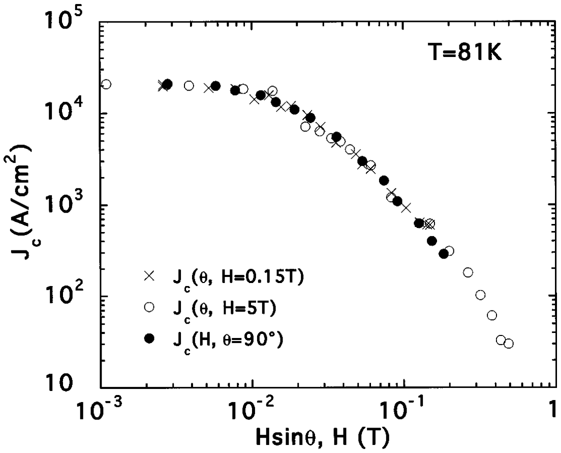

FIG. 4. Angular scaling of the critical current density as a function of $H \sin\theta$, shown at $T = 81$ K for multilayer SL1. The full circles correspond to the measurements performed in the transverse magnetic field configuration ($\theta = 90°$ or $H$ parallel to the $c$ axis).

measurements of $J_c(\theta)$ at high temperature are difficult. For example, at $T = 81$ K and $H = 5$ T, all the variation of the critical current takes place in a very narrow angular window: 0.5°.

From the measurements of $J_c(H,\theta)$ and following the 2D model proposed by Kes *et al.* [14], we can scale for a given temperature the variation of $J_c(H,\theta)$ with the component of $H$ along the $c$ axis and compare this variation with that of $J_c$ measured directly under a transverse magnetic field. This model states that for a 2D superconductor the dissipation is governed only by the component of $H$ perpendicular to the $CuO_2$ planes. As a consequence of relation 1, the 2D angular scaling law is satisfied for any value of the magnetic field and temperature.

$$J_c(H,\theta) = J_c(H \sin\theta)\,. \tag{2}$$

The scaling described by Eq. (2) is perfectly satisfied even for temperatures near $T_c$. Figure 4 shows such a scaling at $T$ equal to 81 K ($T/T_c = 0.9$).

We have carried similar measurements on SL2 and the 2212 single phase film SF (Fig. 5). For SL2, relation (1) is also satisfied for magnetic fields $0 < H \le 20$ T for temperatures up to 60 K. For higher temperatures, $J_c(H,\theta = 0)$ starts to decrease for a magnetic field $H > H_0$ with $H_0$ less than 20 T. $H_0$ is lower for higher temperature (3 T at 75 K) as shown in Fig. 5. The 2D angular scaling law [relation (2)] is perfectly satisfied for $T \le 60$ K. Above this temperature, this law is still valid as long as $H \sin\theta$ is less than $H_0$.

Finally, Fig. 5 presents also the parallel field dependence of $J_c$ for sample SF (2212 phase) for $T \ge 35$ K. A decrease of $J_c$ with increasing $H$ appears at 35 K and $H > 10$ T. It is more and more pronounced as $T$ increases ($H_0 = 10$ T at 35 K, less than 3 T at 70 K) [15].

We can now propose a possible scenario to explain the different dissipative behavior in parallel magnetic field of SF, SL1, and SL2. The mechanism of dissipation in parallel field for strongly anisotropic layered superconductors with Josephson coupling between the layers has been theoretically studied in Ref. [16]. The resistive behavior is related to the activated hopping of segments of Josephson vortices to the neighboring layers and to the subsequent motion of the vortex kinks along the layers. This mechanism is thermally activated with an activation energy linearly dependent on the distance $d$ between the superconducting layers. In the case of the 2212 film SF, with the shortest $d$ value, the dissipation shown in Fig. 5 can be ascribed to this mechanism. The Josephson penetration length in the $ab$ plane is $\lambda_j = \gamma d$, $\gamma$ being the

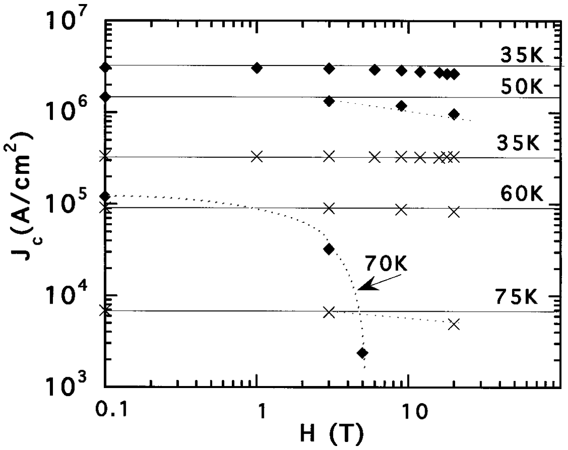

FIG. 5. Dependence of the critical current density measured on both multilayer SL2 (crosses, $T_c = 86$ K) and film SF (full diamonds, $T_c = 81$ K), as a function of the magnetic field parallel to the $CuO_2$ planes, at a given temperature, between $T = 35$ K and $T_c$. The dotted lines are guides to the eye, indicating the decrease of $J_c(H)$, compared to its zero field value (solid line).

anisotropy parameter. In the case of pure 2212 phase the anisotropy parameter is found to be of the order of 250 [17], which is comparable with the crossover value $\gamma_{\rm cr} \sim 100-200$, with $\gamma_{\rm cr} = \lambda_{ab}/d$. For $\gamma$ larger than $\gamma_{\rm cr}$, the Josephson coupling is strongly reduced. Now we consider the multilayers, which can be characterized as extremely anisotropic systems. By introducing separating 2201 layers between 2212 layers, the interlayer spacing $d$ becomes more important (Fig. 1) and the anisotropy parameter is greatly enhanced ($\gamma \gg \gamma_{\rm cr}$). The results obtained for multilayer SL1, composed of the smallest quantity of the 2212 phase (half a unit cell) separated by one unit cell of the 2201 phase, show that for $\theta = 0$ the parallel magnetic field has no effect on the critical current up to 20 T, even for temperatures close to $T_c$. In multilayer SL1 with $CuO_2$ bilayers 40 Å apart, we may suppose that a parallel magnetic field is not screened and penetrates freely through the separating 2201 layers which are transparent to the magnetic field. It appears that the $CuO_2$ blocks are almost completely decoupled. In this situation, no parallel vortices can penetrate such thin $CuO_2$ bilayers ($H_{c1}$ infinite). There are no Josephson vortices and consequently there is no creation of pancake vortices in $CuO_2$ bilayers, induced by the motion between neighboring layers of Josephson vortices. Therefore, there will be no dissipation added by a strictly parallel magnetic field.

Multilayer SL2 shows a behavior intermediate between SL1 and SF. In a parallel magnetic field, we may have Josephson vortices in the 2212 layers of the superlattice. The probability of segment hopping or of double kink nucleation appears to be comparable at a temperature between 60 and 75 K in SL2 and 35 K in SF according to the difference of activation energy, related to the difference of hopping distance [16] and in agreement with experimental results.

In conclusion, we have demonstrated that in the limiting case of a multilayer composed of one half a unit cell, i.e., the smallest thickness, of the 2212 phase (high $T_c$) separated by one unit cell of 2201 phase, the artificially built sample behaves like a perfect 2D system. When the magnetic field $H$ is strictly parallel to the $CuO_2$ planes, there is no observable effect on the critical currents. This has been verified for fields ranging from 0 to 20 T and temperatures from 4.2 K up to 81 K $= 0.9T_c$. Furthermore, it was also found that the parallel field magnetoresistance measured very close to $T_c$ ($T/T_c = 0.98$) is only dependent on the transverse component of the magnetic field and stays equal to zero in a parallel magnetic field [17]. In this situation, the $CuO_2$ double planes appear to be completely decoupled, and there is no screening of the magnetic field.

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