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Vortex pinning by columnar defects in $Bi_2Sr_2CuO_y$ thin films: A detailed study of the directional effect

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We present experimental results on the angular dependence of the magnetoresistance and critical currents of $Bi_2Sr_2CuO_y$ thin films irradiated by 1 GeV Pb ions along the *c* axis with a matching field of $B_\phi = 2$ T. When the magnetic field is applied parallel to the defects, we observe, for $0.1\,\mathrm{T} < \mu_0 H < 1.4\,\mathrm{T}$ and $1.5\,\mathrm{K} \leqslant T < T_c$, a minimum of magnetoresistance or a peak of critical current that can be explained in terms of localization of vortices into defects as predicted in the Bose-glass theory. Two regimes of pinning are found: for $\mu_0 H < 1$ T vortices are pinned individually into the defects. However, the field dependence of the macroscopic pinning force indicates that due to the random distribution of defects, not all the vortices are pinned even in this low field regime. Above $\mu_0 H \sim 1.2$ T, vortex interactions become important and the directional effect disappears sharply at $\mu_0 H \sim 1.4$ T, i.e., well below the matching field. Pinning is found to be optimal for a field of the order of $B_\phi/2$. The comparison with earlier results on $Bi_2Sr_2CaCu_2O_8$ thin films and $Bi_2Sr_2CaCu_2O_8/Bi_2Sr_2CuO_y$ multilayers allows us to argue that for thin films, anisotropy is the parameter which controls the occurrence of the above directional effect. Thus, columnar defects can be seen as a sensitive probe of vortex dimensionality.

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I. INTRODUCTION

An efficient way to increase pinning in high-temperature superconductors is the creation of columnar defects (CD's) by heavy-ion irradiation. It has been proven that their linear geometry enhances the vortex correlations along the *c* axis leading to new and completely unexpected vortex states after irradiation which are controlled by the interplay between the several energies involved (*c*-axis correlations, in-plane vortex interactions, thermal fluctuations, entropy, vortex-lattice elastic energy, etc.).[1,2] This is one of the reasons why this technique has deserved in the last few years much experimental and theoretical work in highly anisotropic compounds as $Bi_2Sr_2CaCu_2O_8$ (Bi-2212).

One of the most striking features observed in heavy-ion irradiated superconductors is the presence of a minimum in the magnetoresistance or a peak in the critical current when the magnetic field is applied parallel to columnar defects.[3–6] Both features show that the presence of correlated defects, as the CD's, induces a uniaxial increase of pinning along the direction of the tracks which has been also seen in ac screening,[7] irreversibility line,[8,9] flux transformer,[9] and Josephson plasma resonance[10,11] measurements. This anisotropic pinning, predicted by the Bose-glass theory,[2] is attributed to the alignment of vortices into the CD's and to the consequent increase of *c*-axis coherence. Thus, vortices behave as 3D flux lines instead of 2D pancakes. Obviously vortex localization into CD's is also possible at angles tilted away from the direction of the tracks as long as the gain in condensation energy can compensate the energy cost of tilting the vortex into the CD's. The study of this effect should let us obtain interesting information about both energies. An angular width for the decrease of dissipation was derived from the Bose-glass theory for the case of one single vortex accommodated on a single defect.[2] This accommodation angle was compared to the experimental results on $YBa_2Cu_3O_7$ (Ref. 5) and $Tl_2Ba_2CaCu_2O_8$ (Ref. 3) compounds and two main difficulties were found to arise: firstly, close to the critical temperature (where the minimum in magnetoresistance is observed) the role of thermal fluctuations could be very important and, in fact, it seems to be this energy which controls the accommodation, thus masking the interplay between elastic and pinning energies. Secondly, for high magnetic fields, vortex interactions cannot be neglected, individual vortex pinning is no longer a valid approximation to the problem and an evaluation of the accommodation angle in terms of vortex lattice elastic energy should be required.

The directional effect was observed both in Bi-2212 single crystals[4,6,7] and in Bi-2212 tapes.[12] In contrast, in all the reported results on heavy-ion irradiated Bi-2212 thin films, it was found that pinning induced by the CD's is always isotropic.[13–17] Several possibilities have been considered to explain these different behaviors: characteristic thin film geometry, strong influence of other defects in thin films, etc. However, none of these hypotheses leads to a satisfactory answer and the reasons for these differences between thin films and single crystals remain unclear.

The main aim of this work is to present a detailed angular study of the pinning enhancement induced by columnar defects in $Bi_2Sr_2CuO_y$ (Bi-2201) thin films. Bi-2201 compounds are much less studied in the literature than other copper oxide superconductors such as, for instance, Bi-2212 and, therefore, their physical properties (anisotropy or vortex matter, for example) are almost unknown. We will show that, unexpectedly, Bi-2201 compounds present a vortex pinning behavior quite different from that observed for other Bi-based thin films. For this study, we have performed angular measurements of magnetoresistance and critical currents in widely varying applied magnetic fields and temperatures. First, in Sec. III we will show that an uniaxial increase of pinning can be observed in Bi-based thin films in the vortex liquid state as well as in the solid state. The low critical temperature of these compounds ($T_c \sim 4$ K after irradiation) reduces the importance of thermal fluctuations and allows us to carefully study the temperature and magnetic field dependence of the accommodation angle just in terms of *interplay between pinning energy and elastic energy* (Sec. IV A). The behavior of the macroscopic pinning force, which has been derived from the critical current measurements, will be discussed in Sec. IV B. Finally, we will compare the results on Bi-2201 thin films with our previous results on heavy-ion irradiated Bi-2212 thin films and Bi-2212/Bi-2201 multilayers where no directional effects were observed. This comparison will help us to clarify the abovementioned differences between Bi-based thin films and single crystals.

II. EXPERIMENTAL DETAILS

The experiments have been performed on several $Bi_2Sr_{2-x}La_xCuO_y$ thin films with $x=0$ (Bi-2201) or $x=0.05$ [Bi(La)-2201] grown by *in situ* rf sputtering.[18] Samples were irradiated at their optimally doped state with critical temperatures T_c (defined as the temperature at which the resistance vanishes) of 15 K for the Bi-2201 films and 20 K for the Bi(La)-2201 thin films. Irradiations were performed at GANIL with 1 GeV Pb ions with the beam perpendicular to the *ab* planes of the samples. Details of irradiation experiments are similar to those given by van der Beek *et al.*, in Ref. 19. In this work the matching field B_ϕ, i.e., the induction at which the density of vortices equals the density of tracks, was chosen to be 2 T. After irradiation T_c decreased to ~4 K for Bi-2201 and to ~10 K for Bi(La)-2201. Recently, we have shown that this T_c-decrease is due to the interplay between the material damage and a doping effect induced by the heavy-ion irradiation.[20] Thus, after irradiation samples are overdoped with a typical normal-state $R(T)$ behavior which follows the empirical law $R(T)=A+BT^n$ (n being of the order of 1.2).

Magnetoresistance $R(T,H)$ and transport critical currents $J_c(T,H)$ were measured for $1.5\,\mathrm{K}<T<T_c$ using a standard dc four-point contact method. Voltage resolution was better than 10 nV. Films (~2000 Å thick) were patterned by optical lithography and wet etching into two striplines: one 100 μm wide and 625 μm long for R measurements and the other one 20 μm wide and 100 μm long for J_c measurements. Measurements have been performed at constant temperature in a flow cryostat equipped with an 8 T superconducting coil and a one-axis rotating sample holder. We have performed measurements as a function of the field-sample (*ab* planes) angle θ at constant H or as a function of field applied parallel to the c axis (for the pinning force measurements). The angle θ was measured with a Hall sensor with an accuracy better than 0.05°. Temperature was controlled with a CERNOX thermometer and measured with a carbon-glass resistor. The regulation of temperature ensures a stability better than 15 mK.

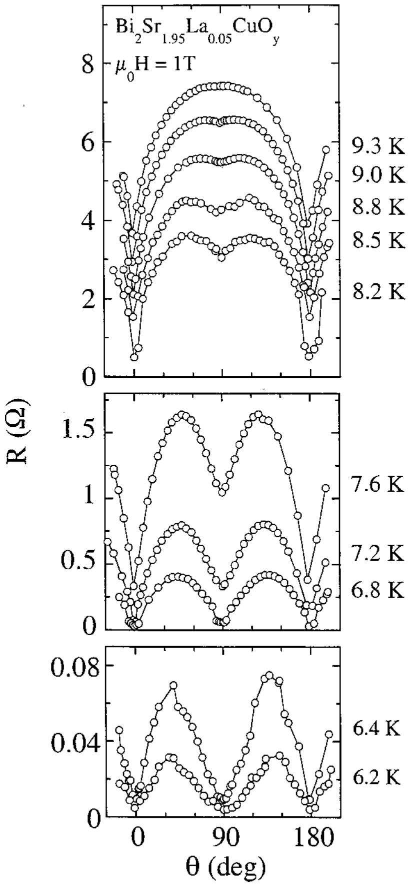

FIG. 1. Magnetoresistance as a function of field-sample (ab planes) orientation for a heavy-ion irradiated $Bi_2Sr_{1.95}La_{0.05}CuO_y$ thin film, showing the evolution of the $R(\theta)$ minimum from the critical temperature $T_c=9.3\,\mathrm{K}$ to the irreversibility temperature $T^* \sim 6$ K. Measurements were made at constant field $\mu_0H=1$ T $=B_\phi/2$. Columnar defects are parallel to the c axis ($\theta=90°$). Solid lines are a guide to the eye.

III. RESULTS

A. Magnetoresistance

Figure 1 shows the magnetoresistance at $\mu_0H=1T \sim B_\phi/2$ as a function of field-sample orientation θ for a Bi(La)-2201 thin film at different temperatures $T^*<T<T_c$, T^* being the irreversibility temperature. Similar results were obtained for Bi-2201 samples. The main feature of these $R(\theta)$ curves is the presence of *a minimum in the magnetoresistance* when the magnetic field is applied parallel to the columnar defects. This minimum appears just below T_c and it is deeper and deeper as temperature decreases down to T^* where the resistance falls below our experimental resolution. Similar features have been previously observed in other compounds such as $Tl_2Ba_2CaCu_2O_8$,[3] $YBa_2Cu_3O_7$,[5] and Bi-2212 single crystals[6] and they were successfully explained in terms of vortex-line behavior as predicted by the Bose-glass theory.[2] In this framework the presence of correlated disorder (columnar defects) promotes the localization of vortices along the defects increasing c-axis coherence and thus leading to a directional pinning enhancement. However, we should note that, to our knowledge, this is the first time

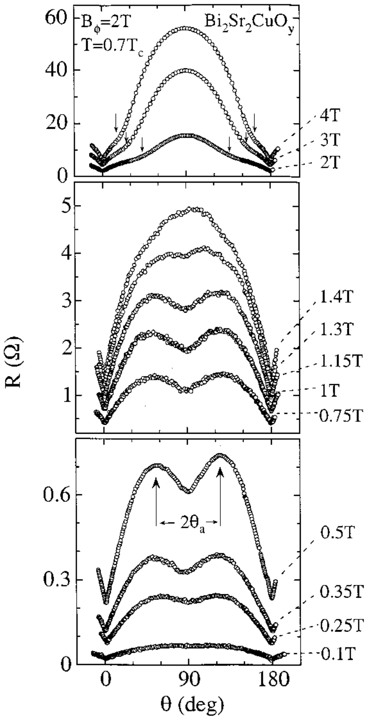

FIG. 2. Magnetoresistance as a function of field sample (ab planes) orientation of a heavy-ion irradiated $Bi_2Sr_2CuO_y$ thin film showing the evolution of the $R(\theta)$ minimum from $\mu_0H=0.1$ T to $\mu_0H=4$ T. Measurements were made at constant temperature $T=2.8\,\mathrm{K}\sim0.7T_c$. Columnar defects ($B_\phi=2$ T) are parallel to the c axis ($\theta=90°$). Arrows in the top figure correspond to $\mu_0H_z=\mu_0H\sin\theta=1.4$ T and they show the inflection in the $R(\theta)$ curves which are the reminiscence at high fields of the $R(\theta)$ minimum. The definition of the accommodation angle θ_a is illustrated in the bottom plot. Solid lines are a guide to the eye.

that such effect is reported in Bi-based *thin films*. As was said in the Introduction all the previous results reported on Bi-2212 thin films showed no signatures of angular pinning selectivity.[13–17] So, the results of Fig. 1 are very exciting and they suggest that the absence of directional effects in Bi-2212 thin films is not related to film geometry nor to the high natural defects density. We will discuss this issue more carefully in Sec. IV C where we will show that differences are related to different sample anisotropy.

We have also investigated the evolution of this $R(\theta)$ minimum as a function of applied magnetic field. Typical results are shown in Fig. 2. Here $R(\theta)$ of a Bi-2201 film ($B_\phi=2$ T) is plotted at constant temperature $T/T_c=0.7$ and for magnetic fields ranging from 0.1 to 4 T. We can see three different regimes associated with the $R(\theta)$ minimum.

(a) $R(\theta)$ minimum is well pronounced for applied fields in the range $0.25<\mu_0H<1.2$ T. The depth of this minimum, which can be defined as $\Delta R/R_{\max}=(R_{\max}-R_{\theta=90°})/R_{\max}$, seems to be field independent for $0.5<\mu_0H<1.15$ T. In fact, these $R(\theta)$ curves can be scaled into a single one just by normalizing the resistance by its maximum value (not shown). As we will see later such behavior suggests individual vortex pinning in this range of fields.

(b) For low fields $\mu_0H\sim0.1$ T no signature of pinning by columnar defects was observed within the experimental resolution. This behavior is quite different from that reported in Bi-2212 single crystals where the $R(\theta)$ minimum seems to be deeper at low magnetic fields.[6] Recently, we have shown that pinning by the CD's in the vortex liquid phase of irradiated Bi-2212 thin films and Bi-2212/2201 multilayers is driven by the interplay between entropy and vortex interactions.[21] Pinning by the CD's is only observed in a well-defined range of magnetic fields $0.25B_\phi<\mu_0H<B_\phi$. Thus, the absence of directional effect at low fields in Bi-2201 could have a similar *field-driven* origin but further work is necessary in order to clarify this important issue.

(c) The minimum disappears progressively for $\mu_0H>1.2$ T and it is no longer observed at $\mu_0H>1.4$ T well below the matching field ($B_\phi=2$ T). This is also different from the results reported for single crystals where the directional effect is visible up to fields of the order of B_ϕ.[5,6] However, we should note that, in our case, this absence of a minimum does not mean an absence of pinning due to the CD's at high fields. In fact, for higher fields, $\mu_0H>1.4$ T, there is still a feature in $R(\theta)$ characterized by an inflection in the $R(\theta)$ curve as indicated by the arrows in Fig. 2 (top). The angular position of this slight decrease of dissipation approaches the *ab* planes as magnetic field increases but, surprisingly, it always occurs at the orientation for which the c-axis component of the field $H_z=H\sin\theta$ is equal to $\mu_0H_z=1.4$ T, exactly the *same value* as for the suppression of the $R(\theta)$ minimum. Thus, we can look at this high-field feature as a reminiscence of the minimum observed at low fields.

Finally, note that similar results to those shown in Fig. 2 were seen for several temperatures in the range $T^*<T<T_c$: the $R(\theta)$ minimum always was observed for $0.25<\mu_0H<1.4$ T. These results suggest that 1.4 T ($B/B_\phi\sim0.7$) corresponds to the maximal matching (in the sense of maximal filling) between the vortex lattice and the CD's.

B. Critical currents

In order to investigate the vortex solid state we have measured the critical current density J_c at our lowest available temperature of $T\sim1.5\,\mathrm{K}\sim0.3\,T_c$. Figure 3 shows the angular dependence of J_c at different applied magnetic fields for the same Bi-2201 film as in Fig. 2. In addition to the common feature of intrinsic peaks for H parallel to the ab planes ($\theta=0°$ and 180°) an additional peak was observed at $\theta=90°$, i.e., for field applied parallel to the columnar defects. This confirms, for the vortex solid state, the directional effect described above in the vortex liquid state. Similar directional pinning was reported for $YBa_2Cu_3O_7$ thin films[22] but, as in the case of the $R(\theta)$ minimum, it was not seen in Bi-2212 *thin films*. Also, the field dependence of this effect is analogous to the above one for $R(\theta)$, i.e., the directional effect occurs in a well-defined range of applied magnetic fields $0.25<\mu_0H<1.5$ T. However in this case we cannot find at high fields any reminiscence of the J_c peak due to the CD's. Also, as can be seen from the data taken at $\mu_0H=0.1$ T, in Fig 3, there is no CD's peak in the low-field regime. One explanation for this absence comes from the different low-

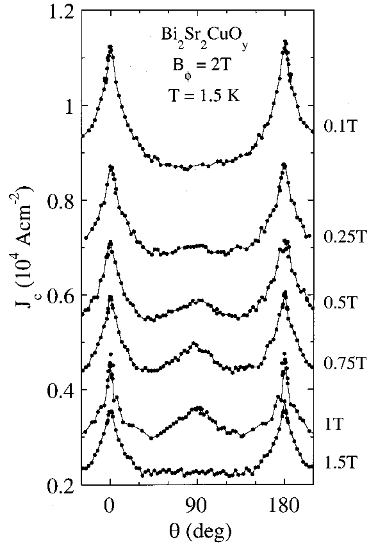

FIG. 3. Critical current density as a function of field sample (ab planes) orientation of the same heavy-ion irradiated $Bi_2Sr_2CuO_y$ thin film as in Fig. 2, showing the evolution of the second J_c peak from $\mu_0 H = 0.1$ T to $\mu_0 H = 1.5$ T. Measurements were made at constant temperature $T = 1.5\,K \sim 0.3 T_c$. Columnar defects ($B_\phi = 2$ T) are parallel to the c axis ($\theta = 90°$). Solid lines are a guide to the eye.

field dependences of the critical current with H parallel to the CD's or parallel to the ab planes. If the intrinsic pinning at low fields is much stronger than the pinning by CD's (i.e., $J_{c\|ab} \gg J_{c\|CD's}$) then the latter one could be masked. We should note that an absence of anisotropic pinning induced by heavy-ion irradiation at very low fields and low temperatures was reported in YBaCuO and Bi-2212 crystals irradiated at 45° off the c axis.[23,24] This was explained in terms of pinning efficiency of the CD's: when this pinning efficiency is very large (as is the case if temperature is low enough) it may counterbalance the elastic energy due to vortex distortions. Therefore, even if a magnetic field is applied perpendicular to the CD's, vortices are able to accommodate on the tracks (flux-flop). The pinning efficiency in the perpendicular and in the parallel configurations are quite similar which leads to a merging of critical currents at very low fields and, as a result, to the absence of directional effect.

IV. DATA ANALYSIS AND DISCUSSION

A. Accommodation angle

As we said before, the results in Figs. 1–3 may be explained in terms of localization of vortices into the columnar defects when the magnetic field is applied along the direction of the tracks. This alignment enhances c-axis correlation and vortices behave as flux-lines instead of 2D pancakes. Then, these pinned vortex lines induce a decrease of dissipation that is experimentally observed as a minimum of $R(\theta)$ or as a peak in $J_c(\theta)$. If the magnetic field is tilted away from the direction of the tracks, the vortices will accommodate to the defects via the formation of kinks. The vortices will adjust in this way up to a given accommodation angle θ_a above which the gain in condensation energy cannot compensate for the cost in elastic energy due to the kinks.

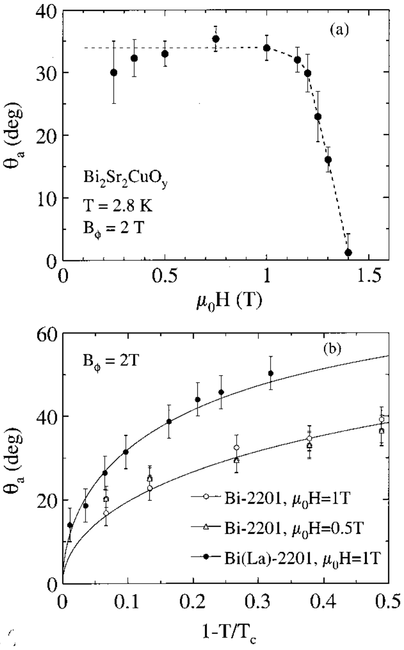

FIG. 4. (a) Accommodation angle θ_a determined at $T = 2.8$ K from the results of Fig. 2, as a function of applied magnetic field for a $Bi_2Sr_2CuO_y$ thin film irradiated at $B_\phi = 2$ T along the c axis. Dashed line is a guide to the eye. (b) Accommodation angle θ_a determined at $\mu_0 H = 1$ T as a function of reduced temperature for the same $Bi_2Sr_2CuO_y$ thin film as in (a) (open circles) and for the same $Bi_2Sr_{1.95}La_{0.05}CuO_y$ thin film as in Fig. 1 (closed circles). For completeness, data obtained at $\mu_0 H = 0.5$ T for the $Bi_2Sr_2CuO_y$ film are also plotted (open triangles). Solid lines are the best fits of Eq. (2) to the experimental data.

This accommodation angle can be defined experimentally as the angular half width between the two resistance maxima (as illustrated by arrows in Fig. 2, bottom). From the data in Figs. 1 and 2 we can analyze the field and temperature dependence of θ_a which are shown in Fig. 4(a) and 4(b), respectively.

First, we observe from Fig. 4(a) that θ_a is almost field independent up to magnetic fields of the order of $\mu_0 H \sim B_\phi/2 = 1$ T. For $\mu_0 H > 1$ T, θ_a is dramatically reduced and it goes to zero for $\mu_0 H = 1.4$ T. We can explain this behavior in terms of the Bose-glass theory. In this framework, the accommodation angle is determined from the ratio between the pinning energy U_p and the single vortex tilt energy ε_1:[2]

$$\theta_a = \left(\frac{U_P}{\varepsilon_1} \right)^{1/2}. \tag{1}$$

For high values of the angle θ_a we must replace it by $\tan \theta_a$.[4] Now, by using the usual expressions[2] for $U_p \sim \varepsilon_0 (c_0/\xi_{ab})^2$ (which is valid if $c_0 \ll 2^{1/2} \xi_{ab}$, see below) and $\varepsilon_1 \sim \varepsilon_0 \gamma^{-2} \ln \kappa$, we get

$$\tan \theta_a = \gamma \frac{c_0}{2\xi_0} \frac{1}{\sqrt{\ln \kappa}} \left(1 - \frac{T}{T_c} \right)^{1/2} \tag{2}$$

which is field independent. This expression is valid for small magnetic fields as long as vortex interactions are irrelevant. In fact, this is the experimental behavior found at low fields [see Fig. 4(a)]. So, we can conclude that, for $H < 1$ T, vortices are pinned by the CD's almost independently and the physics is the same as for one single vortex accommodating to a single column.

The situation is quite different at high fields where the interactions between flux lines become important and should be taken into account. In this case, the accommodation angle is controlled by the competition between pinning energy and the elastic deformation energy of the vortex lattice. To our knowledge there is no theory which deals with this problem. However, as a first approximation, we can use the analogy with the case of vortex pinning by twin boundaries where the accommodation angle for strong fields is given by[1]

$$c_{44}\theta_a^2 = \frac{U_p}{a_0^2} f, \tag{3}$$

f being the fraction of trapped vortices, $a_0 \sim (\phi_0/B)^{1/2}$ the intervortex distance, and c_{44} the tilt modulus. Now, by assuming that $f \sim a_0/(d_\phi \gamma^{1/2})$ with $d_\phi \sim (\phi_0/B_\phi)^{1/2}$ the average distance between CD's, we get for θ_a the following expression:

$$\theta_a(H) \approx \left(\frac{U_p}{\varepsilon_1}\right)^{1/2} \left[\ln\left(\frac{\kappa}{\gamma}\right)\left(\frac{B}{\gamma B_\phi}\right)^3\right]^{1/2}. \tag{4}$$

So, $\theta_a(H)$ vanishes if $B/B_\phi \sim (\kappa^2/\gamma^5)^{1/3}$. Experimentally, we have observed that the directional effect disappears for $\mu_0 H \sim 1.4$ T, i.e., $\theta_a(H) = 0$ for $B/B_\phi \sim 0.7$. By using $\kappa \sim 100$, we get $\gamma \sim 8$ which is a reasonable value for Bi-2201.[25] We should note that Eq. (4) cannot explain the behavior of θ_a around $\mu_0 H = 1.4$ T. In fact, this sharp disappearance reflects that vortex interactions play a very important role in pinning by the CD's as was recently suggested in Refs. 15, 19, and 21. Then we can look at $B \sim 1.4$ T as the maximum trapping field above which the presence of interstitial vortices and collective effects are important leading to a strong diminution of pinning. A more detailed theory, which will consider the many-body effects in these systems, is required to explain quantitatively the observed $\theta_a(H)$ dependence and to investigate the accommodation of a vortex lattice to the CD's.

We now turn our interest to the temperature dependence of θ_a which is shown in Fig. 4(b). We can see that θ_a vanishes at T_c as expected from Eq. (2). Also, there is no sign of saturation in θ_a at low temperatures. Such saturation was observed in the case of YBCO single crystals and it was explained as the crossover from vortex-core pinning at high temperatures (where vortices are larger than CD's) to electromagnetic pinning at low temperatures (with vortices smaller than CD's). We may assume that the depth of the $R(\theta)$ minimum, $\Delta R/R_{\max}$ provides a qualitative indication of the temperature dependence of the pinning energy. From the results of Fig. 1, we have found $\Delta R/R_{\max} \propto U_p \sim U_p(0)(1 - T/T_c)^2$. This T dependence exactly corresponds to the one expected for vortex-core pinning and it confirms the adequacy of our above calculation with Eq. (2). Thus, in our case, vortices are larger than CD's in all the studied range of temperatures. Solid lines in Fig. 4(b) are the best fits of θ_a data to expression (2). If we take $\gamma \sim 8$ for both samples and $c_0 \sim 35$ Å then we get $\xi_{ab}(0) \sim 35$ Å for Bi-2201 and $\xi_{ab}(0) \sim 22$ Å for Bi(La)-2201. The same kind of analysis can be made from the J_c peak for H parallel to the CD's of Fig. 3. Similar results are obtained.

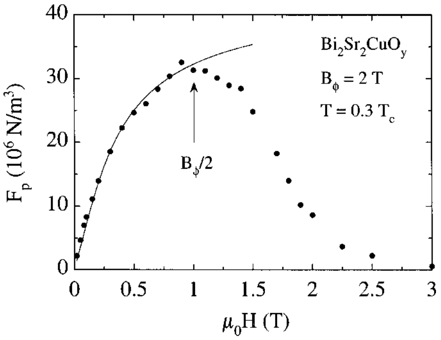

FIG. 5. Macroscopic pinning force, $F_p = j_c B$ at $T = 0.3T_c$ as a function of applied magnetic field (parallel to the defects) for the same Bi$_2$Sr$_2$CuO$_y$ thin film as in Fig. 3. The solid line is the best fit of Eq. (6) to the experimental data. Optimal pinning is achieved for $\mu_0 H \sim 1$ T, i.e., well below the matching field $B_\phi = 2$ T.

B. Pinning force

Another quantity of interest is the average pinning force $F_p = j_c B$ when the magnetic field is applied parallel to the CD's. Figure 5 shows the results obtained at $T = 1.5$ K for a Bi-2201 thin film irradiated with $B_\phi = 2$ T. The first remark on these results is that the pinning force F_p exhibits a maximum for a field of the order of 1 T, i.e., close to $B_\phi/2$. So the *optimal pinning field is far away from* B_ϕ as was shown from the directional effect. For higher fields, the pinning force decreases with increasing field, as it is controlled more by lattice distortions than by vortex density. As expected, F_p goes to zero when H approaches the irreversibility field which has been estimated at this temperature to be $\mu_0 H^* \sim 3$ T from resistive measurements. Also, we note that at low fields F_p increases with field but not with a linear dependence as it could be expected[1] for pinning by columnar defects in the regime $B \ll B_\phi$, where all vortices are supposed to be pinned individually in CD's. In this case, the overall pinning force can be written as the sum of all the individual pinning forces, $F_p = j_c B = n(B) f_p$ [where $n(B)$ is the number of pinned vortices and f_p is the field-independent individual pinning force]. If we assume that each vortex is pinned by a CD then $n(B) \sim B$ and we get $F_p = j_c B = n(B) f_p \sim B$ leading to a B-linear dependence of F_p and to a field-independent critical current. However, this is not the experimental situation of Fig. 5 despite the fact that we are well inside the single vortex pinning regime and vortex interactions are not important as was discussed in the preceding section. So, in order to explain the results of Fig. 5 we should assume that not all the vortices are pinned by the CD's. This partial filling of the defects has also been pro-

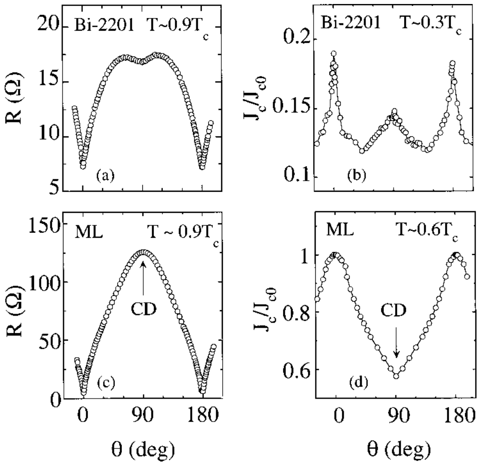

FIG. 6. Angular dependence of the magnetoresistance (a), (c) and critical current (b), (d) as a function of magnetic field sample (ab planes) orientation for a $Bi_2Sr_2CuO_y$ thin film (a), (b) and for an extremely anisotropic $Bi_2Sr_2CaCu_2O_8/Bi_2Sr_2CuO_y$ multilayer (c), (d). Samples were irradiated parallel to c axis at $B_\phi = 2$ T. Measurements were performed at $\mu_0 H = 1$ T and similar reduced temperatures.

posed in several recent works.[26,27] Qualitatively, the number of vortices which are pinned, $n(B)$, will depend on the probability of finding a defect close enough to a vortex so that the gain in condensation energy will be greater than the cost in elastic energy needed to fit the column. As irradiation is a highly random event a vortex is not always able to find an available defect in its neighborhood even at low fields. A simple calculation of $n(B)$ can be derived by assuming a Poisson distribution of defects[28,29]

$$n(B) \propto B_\phi \left(\frac{1 - e^{-\alpha x}}{\alpha x} \right), \tag{5}$$

where $x = B_\phi / B$ and α is a function of the column radius, c_0 and of the in-plane coherence length ξ_{ab}. Then, if we use this expression for $n(B)$, we get that the average pinning force is given by

$$F_p = j_c B = f_p n(B) = A(1 - e^{-\alpha B_\varphi / B}) B, \tag{6}$$

where $A = f_p / \alpha$ is a constant. The solid line in Fig. 5 is the fit of the F_p data in the region $H < 1$ T to Eq. (6) with f_p and α as free parameters. We see that a very good agreement can be achieved with $\alpha \sim 0.6$ and $f_p \sim 43 \times 10^6\ \mathrm{Nm}^{-3}$. We can consider that this f_p value is the individual pinning force exerted on a single vortex of dimension $(\xi_{ab})^2 \xi_c$. So, with typical values $\xi_{ab} \sim 22$ Å and $\xi_c \sim 3$ Å (where this later was obtained by using $\gamma \sim 8$) we can estimate the average pinning energy to be $U_0 \sim 4 \times 10^3$ K, which is comparable to the values reported for Bi-based compounds.[30]

C. Comparison with Bi-2212 thin films and multilayers

We will now compare the results of Figs. 1–3 with our earlier measurements on heavy-ion irradiated Bi-2212 thin films and Bi-2212/2201 multilayers (ML).[15] This comparison is shown in Fig. 6 where we have plotted the angular dependence of the magnetoresistance (a) and (c) and critical current (b) and (d) in a Bi-2201 thin film (a) and (b) and in a 2212/2201 multilayer (c) and (d). Both samples were irradiated at identical dose $B_\phi = 2$ T and the measurements were performed at similar reduced temperatures and at constant magnetic field $\mu_0 H = 1$ T (i.e., $B_\phi/2$ which corresponds to optimal pinning). We can see that, in contrast to the behavior presented for Bi-2201 thin films, no signatures of pinning angular selectivity [neither a minimum in $R(\theta)$ nor a second peak in $J_c(\theta)$] were observed in the case of the ML (similar results were found for Bi-2212 thin films). We should remark that this absence of directional effects was found in all the (H,T) ranges studied. Also, the 2D scaling laws verified in pristine samples are still valid after irradiation.[21] These results indicate that, in these systems, vortices are able to accommodate into CD's at any orientation, i.e., $\theta_a \sim \infty$. This can be easily explained from Eq. (2) where if we put the typical values for Bi-2212, i.e., $\xi_{ab} \sim 20$ Å, $\kappa \sim 100$, $c_0 \sim 35$ Å, and $\gamma \sim 200$ we get, for $T/T_c \sim 0.9$, an accommodation angle $\theta_a \sim 90°$ and vortices then accommodate at any angle. So, the differences in the angular behavior of pinning by CD's between slightly anisotropic Bi-2201 thin films and highly anisotropic Bi-2212 thin films and multilayers are mainly due to the large difference in vortex dimensionality and anisotropy in these systems. Moreover, this comparison may help us to understand the different behavior of thin films and single crystals or tapes where the directional effect has been observed from transport measurements.[6,12] Several hypotheses have been considered to explain these differences. A first possibility arises from the presence in thin films of a stronger density of as-grown defects which are responsible for the high critical currents before irradiation.[31] These defects will favor the delocalization of vortices thus preventing the alignment into CD's. Another explanation has been suggested by Wirth *et al.*[13] who have attributed the differences to the much smaller thickness of thin films. Here the idea is that, below a threshold thickness, pinning is controlled by surface effects instead of by bulk pinning into the CD's thus avoiding the directional effect. However, these two hypotheses, which have been earlier proposed to account for the differences between films and crystals *cannot be used to explain our results* of Fig. 6. Indeed, as the Bi-2201 and Bi-2212 films (or ML) were grown in similar conditions, their level of natural defects should be of the same order of magnitude. Also, sample thicknesses are comparable in both phases. Thus, the only explanation is, as we said before, that the different sample anisotropy, $\gamma \sim 8$ for Bi-2201 and $\gamma \sim 200$ for Bi-2212,[25] is responsible for the different features of Fig. 6. This is strongly supported by the results on Bi-2212 tapes[12] where a directional effect was found and the authors indicate an anisotropy factor of $\gamma \sim 10$ which is comparable to that of Bi-2201 or YBaCuO. Then, in the light of our results, we may argue that columnar defects induced by heavy-ion irradiation *in thin films* should rather be considered as *a way to probe the sample anisotropy and vortex dimensionality*.

V. CONCLUSIONS

In this paper we have presented experimental results on the angular dependence of the magnetoresistance and critical currents of heavy-ion irradiated $Bi_2Sr_2CuO_y$ thin films. We have shown, that a decrease of dissipation (minimum of magnetoresistance or peak of critical current) can be observed in Bi-based thin films when the magnetic field is applied parallel to the defects. We have performed a detailed study of this directional effect which can be explained in terms of localization of vortices into defects as predicted in the Bose-glass theory. First we focused on the field and temperature dependence of the accommodation angle θ_a. For $\mu_0 H < 1$ T our results are compatible with a regime of individual vortex pinning. Above $\mu_0 H \sim 1$ T vortex interactions become important leading to a reduction of pinning and to the absence of any directional effect for $\mu_0 H > 1.4$ T. The temperature dependence of θ_a indicates that, in our case, vortices are larger than columnar defects. From the results on the pinning force F_p, we have found that, due to the random distribution of columns, optimal pinning is achieved for a magnetic field of the order of $B_\phi/2 = 1$ T, i.e., well below the matching field. Moreover, the field dependence of F_p suggests that not all the vortices are pinned even at low fields (in the regime of individual pinning). Finally, we have compared the present results with our earlier results on heavy-ion irradiated Bi-2212 thin films and Bi-2212/2201 superlattices where no directional effect has been observed. We have proven that differences between these films are related to the different sample anisotropy. In conclusion, we consider columnar defects induced by heavy-ion irradiation as a very sensitive probe of sample anisotropy and vortex dimensionality in high-temperature superconducting thin films.

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