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Reentrant pinning effect in the vortex liquid phase of a quasi-two-dimensional $Bi_2Sr_2CaCu_2O_8/Bi_2Sr_2CuO_6$ multilayer with columnar defects

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The ab-plane magnetoresistance $R(H)$ is studied for an extremely anisotropic $Bi_2Sr_2CaCu_2O_8/Bi_2Sr_2CuO_6$ multilayer with columnar defects (CD's). In a well-defined range of H and T, $R(H)$ exhibits slope changes due to the pinning of vortices by CD's. Angular measurements reveal that the dissipation is still determined by the motion of two-dimensional pancakes proving that the occurrence of this feature is controlled by a field-driven competition between intralayer vortex repulsion and entropy. We draw the contour of a reentrant pinned liquid region in the (H,T) phase diagram where CD's decrease the dissipation.

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$Bi_2Sr_2CaCu_2O_8$ (Bi-2212) oxide superconductors in magnetic field H perpendicular to CuO_2 layers have a phase diagram characterized by the existence of a large region with a vortex liquid state (VL) bounded by the irreversibility line $H^*(T)$ and the upper critical field line $H_{c2}(T)$. According to the angular scaling of resistivity ρ and magnetization with the c axis component of H, this liquid state consists of two-dimensional (2D) pancake vortices instead of the usual vortex lines (for a review see Ref. 1). This behavior is a consequence of the large anisotropy parameter γ of these layered materials and of the importance of thermal fluctuations. The introduction of columnar defects (CD's) by heavy-ion irradiation is a very efficient way to increase vortex pinning even in the VL as it was reported from transport measurements in irradiated Tl-based thin films[2] and, later on, in Bi-2212 single crystals.[3] These measurements demonstrated an uniaxial decrease of the magnetoresistance when H is applied parallel to CD's suggesting the restoring of vortex lines. Evidence of strong interlayer correlation in the VL was also found in flux-transformer geometry experiments[4,5] and in Josephson plasma resonance (JPR) experiments.[6–9] Recently, it was reported a dip in the c axis resistivity $\rho_c(H)$ of irradiated Bi-2212 single crystals.[10] Associated with this dip it was observed a breaking of the angular scaling of $\rho_c(H)$.[11] This was explained in terms of a field-driven coupling transition[12,13] at $B\sim 0.3B_\Phi$ (B_Φ being the magnetic flux density at which the number of vortices equals the number of defects). These results contrast with torque and superconducting quantum interference device measurements of the reversible magnetization in Bi-2212 crystals[14] and with transport measurements in Bi-2212 thin films[15] when enhanced pinning by the CD's was found to be isotropic.

In this work we report measurements of the in-plane magnetoresistance in the mixed state of a heavy-ion irradiated artificial superlattice constituted by a stack of half-unit-cell thick (15 Å) Bi-2212 layers separated by one-unit-cell thick (25 Å) $Bi_2Sr_2CuO_6$ (Bi-2201). In this system the CuO_2 bilayers are 40 Å apart. Consequently, the $(\text{Bi-2212})_1/(\text{Bi-2201})_2$ multilayer (ML) is an extremely anisotropic system ($\gamma > 2000$) and it can be considered as a nearly pure 2D system with *negligible Josephson interlayer coupling*.[16–18] The main goal of this paper is to show that even for this extremely anisotropic system there is a pinning effect due to the CD's in the VL. This effect leads to an anomaly in the ab-plane resistance similar to the one previously reported for $\rho_c(H)$.[10] However, in our case, 2D angular scaling is conserved after irradiation even in the region where anomaly occurs. Our results demonstrate that the in-plane repulsion between pancake vortices is responsible for this feature. In addition, we established a (H,T) phase diagram with a reentrant region in the liquid phase where pinning by the CD's is noticeable. For comparison, similar results for irradiated Bi-2212 thin films ($\gamma\sim 250$) are also reported.

Samples are a Bi-2212/Bi-2201 multilayer as well as Bi-2212 single-phase thin films grown by *in situ* rf sputtering.[19] The critical temperatures T_c, defined as the inflection point in the $R(T)$ curve, were 91 K for ML and of the order of 87 K for the Bi-2212 films. The thickness of the films ranged from 600 Å for ML to 5000 Å for the thickest Bi-2212 sample. The films were patterned by optical lithography and wet etching into a suitable stripline 100 μm wide and 625 μm long. The magnetoresistance was measured with a four point contact method using a low current level ($j \leqslant 10$ A/cm^2) and with a voltage resolution better than 10 nV. Measurements have been performed in a flow cryostat equipped with an 8 T superconducting coil and a rotating sample holder. The field-sample (ab planes) angle θ was measured with a Hall sensor, to an accuracy better than 0.05°. Measurements were performed at constant temperature ($30\text{ K} \leqslant T \leqslant T_c$) as a function of the field at given θ. We have also measured $R(\theta)$ at constant T and H. Films were irradiated at GANIL (Caen, France) with 1 GeV lead ions. For one of the Bi-2212 thin films, the angle θ_i between the ion tracks and the ab planes was chosen to be 45°. In all the other films, the tracks were parallel to the c axis, i.e., $\theta_i = 90°$. The films contain a certain amount of natural defects, yielding irreversibility lines much higher than those of virgin Bi-2212 crystals. To overwhelm these natural defects, we have chosen relatively high irradiation doses, $B_\Phi \sim 2-2.5$ T. These doses induced a slight reduction of T_c in the samples (~3–5 K).

Figure 1(a) shows a set of $R(H)$ curves, normalized by the normal-state resistance at $T = 300$ K, measured on the

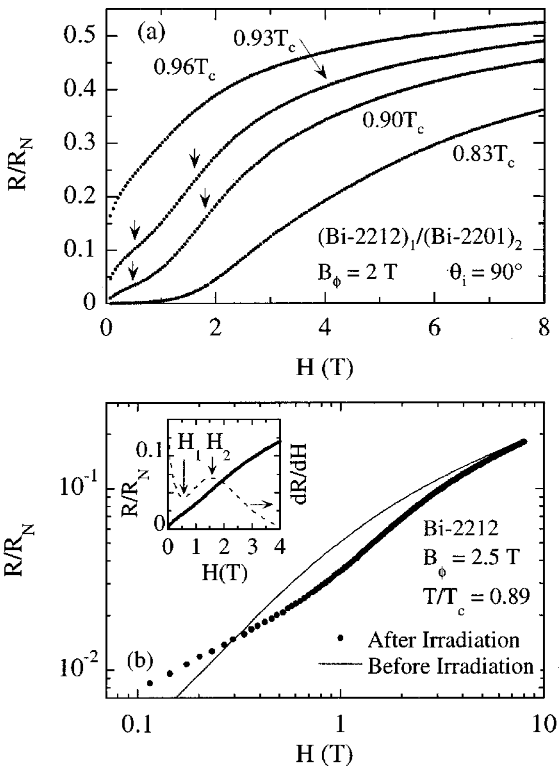

FIG. 1. (a) In-plane resistance normalized by $R(T=300\ \mathrm{K})$ as a function of transverse magnetic field measured at different T for a Bi-2212/Bi-2201 multilayer showing the inflection (arrows) due to the pinning by the CD's. (b) The same in log-log representation for a Bi-2212 thin film at $T/T_c=0.89$. The pristine behavior of $R(H)$ is also plotted (solid line). The inset in (b) illustrates the determination of H_1 and H_2 by using the derivative of $R(H)$, dR/dH.

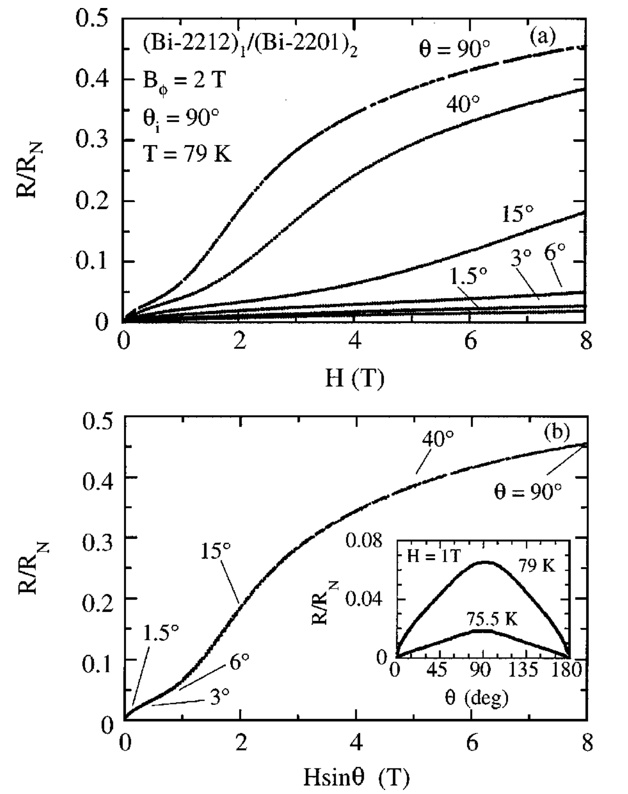

FIG. 2. (a) In-plane resistance vs H at different orientations for the Bi-2212/Bi-2201 multilayer. (b) Angular scaling of the curves shown in (a) by using the c-axis component of H, $H\sin\theta$. All the curves collapse into $R(H,\theta=90°)$, i.e., with H parallel to c axis and to CD's. Inset in (b): Normalized resistance as a function of angle showing the absence of any directional effect, in particular of a minimum in $R(H)$ when H is parallel to CD's.

irradiated ML at constant T in a magnetic field perpendicular to the ab planes. The remarkable feature of these curves is the presence of an anomaly signaled by successive changes of the slope of $R(H)$ (see arrows). This effect is visible in a *well-defined* range of T and H. It was also observed in all the Bi-2212 irradiated samples and is more pronounced for the most anisotropic sample. We have performed measurements with different current densities without any significant modification of this feature. In Fig. 1(b) we compare in logarithmic representation $R(H)$ at $T/T_c=0.89$ of a Bi-2212 film before and after a c-axis irradiation ($B_\Phi=2.5$ T). We can see that for the pristine sample, $R(H)$ increases monotonically without any anomaly.[20] Therefore the inflection observed after irradiation can be attributed to the presence of CD's even in a quasi-2D system as the ML where Josephson interlayer coupling is negligible. As no theory is available to calculate $R(H)$ we can only make a qualitative description and discussion of the facts. Concerning the H dependence we observe that, when the dissipation sets in, there is a first rise of the resistivity, even faster than before irradiation and at a certain characteristic field H_1, the rate of increase slows down. At a higher field H_2, there is another change in the slope of $R(H)$ and the behavior before irradiation is recovered. We determined quantitatively H_1 and H_2 from the position of the extrema in $dR(H)/dH$. This is illustrated in the inset of Fig. 1(b) where H_1 and H_2 are indicated by arrows. Other criteria, such as subtraction of $R(H)$ after and before irradiation, were also considered giving similar results. This $R(H)$-feature was observed for T ranging from $T\sim0.98T_c$ to the temperature, $T_0\sim0.8T_c$ for which the irreversibility field is of the order of $0.25B_\Phi$. At high T, very close to T_c, the anomaly is washed out and $R(H)$ follows the pristine behavior. On the other hand, below T_0, the first change in the slope of $R(H)$, i.e., the minimum in dR/dH, is lost and only H_2 can be determined. At even lower T (not shown), of the order of $0.6T_c$, dissipation appears for $B\geqslant2\ B_\Phi$ and no signature of the CD's is observed in $R(H)$.

In order to investigate the possible linelike behavior of the vortices we have performed angle-resolved measurements. Figure 2(a) shows a set of normalized resistance curves for the ML taken at constant T and different θ, ranging from H close to being parallel to the CuO_2 layers to H parallel to the c axis. It is clear that the $R(H)$-anomaly depends strongly on the orientation of the applied magnetic field. In particular, when H approaches the ab planes, it is enlarged and shifted to higher values of H (beyond our available range of H at very small angles). In fact, this just reflects the typical angular behavior of quasi-2D samples. In Fig. 2(b) we plot the R values of Fig. 2(a) as a function of the c-axis component of the field, $H\sin\theta$. Now, as it was the case before irradiation,[17] all the measured $R(H)$ curves collapse onto a

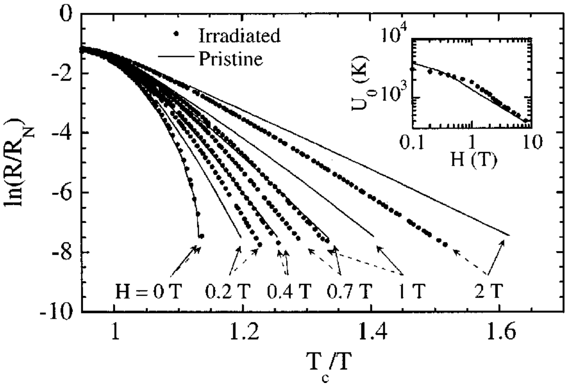

FIG. 3. Arrhenius plot of $R(T,H)$ for the same Bi-2212 film as in Fig. 1(b). The Arrhenius behavior of $R(H)$ is still observed after irradiation but the narrower spacing between curves for 0.4 T$<H<2$ T reflects the pinning by the CD's. The inset shows the activation energy before and after irradiation as a function of H.

single one, namely, the one measured with H perpendicular to the ab planes. The arrows indicate the end of each curve of Fig. 2(a), i.e., the data point corresponding to $H=8$ T. As a further check we have also measured R as a function of θ at T and H fixed. An example for the ML is given in the inset of Fig. 2(b) for two selected temperatures and $H=1$ T. Two comments should be made from these results. First, we note that there is no decrease of the resistance when H is applied parallel to CD's (see inset), in contrast to the effect observed by other groups in *Tl*-based thin films[2] or in Bi-2212 single crystals.[3] We have exhaustively scanned over a wide range of H and T for all the samples studied here and no directional effect was found.[21] Second, the $R(\theta)$ curves also follow the 2D angular scaling, i.e., $R(H \sin \theta)$ coincide with $R(H,\theta=90°)$. This scaling was also observed for the Bi-2212 film irradiated at $\theta_i=45°$. In this case the dissipation was found to be the same when H was applied parallel to CD's or perpendicular to them. Angular studies demonstrate that vortices are able to accommodate onto the CD's at any angle θ, i.e., behave as stacks of pancakes. Thus, CD's decrease dissipation but *no angular selectivity was found*. This angular scaling of $R(H)$ in the VL agrees with that reported for the reversible magnetization in irradiated Bi-2212 crystals.[14]

We have also studied the $R(T)$ curves measured at constant H. Figure 3 shows the Arrhenius plots for the magnetoresistance of the same Bi-2212 film as in Fig. 1(b) before (line) and after (circles) irradiation. We can see that the onset of $R(T,H)$ is well described by an Arrhenius-like behavior, $R \sim R_0 e^{-U_0/T}$ with U_0 the activation energy. Hence after irradiation the dissipation is still due to thermally activated creep of pancakes even in the region where the anomaly in $R(H)$ occurs. In Fig. 3 we may notice that the spacing between curves obtained at different fields is smaller after irradiation for $H<B_\phi$ (for example, comparing the curves at 0.2 T and 0.7 T). In fact this reflects the H behavior of U_0 shown in the inset of Fig. 3. After irradiation, $U_0(H)$ strongly increases ($\Delta U_0/U_0 \sim 1.4$ for $H=B_\phi/2$) for $H>0.4$ T which coincides fairly well with H_1 determined as in Fig. 1. This suggests the presence of a field-driven mechanism controlling all the features of the dissipation. At higher fields ($H>3$ T), $U_0(H)$ tends to recover the pristine behavior.

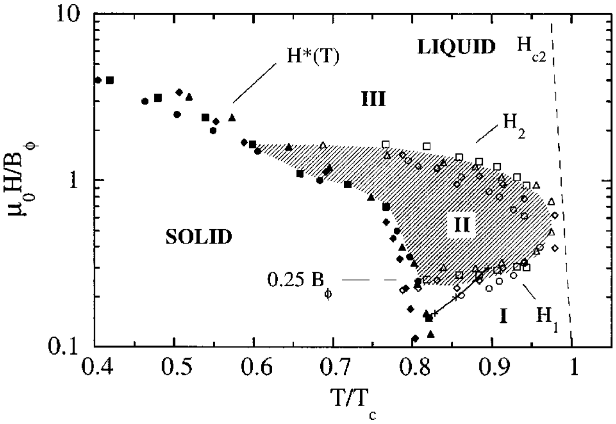

FIG. 4. Semilogarithmic representation of the (H,T) phase diagram for the highly anisotropic Bi-2212/Bi-2201 multilayer and Bi-2212 films in the presence of CD's. Solid symbols represent the irreversibility line. Open symbols are H_1 and H_2 obtained as in Fig. 1(b). Region II corresponds to the presence of the $R(H)$-anomaly induced by the CD's. The other field regions are described in the text. Samples are a multilayer (circles) irradiated at $B_\Phi=2$ T and Bi-2212 films irradiated at $B_\Phi=2$ T (squares), 2.5 T (triangles), and 2.5 T at 45° off the c axis (diamonds). Characteristic fields from JPR data (Ref. 6) are also shown (solid line).

Plotting the fields H_1 and H_2, determined as indicated above for the different samples, we draw a contour in the (H,T) phase diagram delimiting a reentrant region in which the CD's decrease the dissipation. Moreover, if we use B_Φ and T_c as normalization parameters this (H,T) phase diagram becomes universal for the ML and Bi-2212 films.[22] Figure 4 shows this diagram in semilogarithmic representation for all the studied samples. The open symbols correspond to the obtained H_1 and H_2. The solid symbols indicate the irreversibility line $H^*(T)$, delimiting the solid and liquid vortex phases. This was determined from the onset of dissipation above our experimental resolution in $R(T,H,\theta=90°)$. This figure clearly shows the existence of a universal behavior independent of anisotropy after irradiation. First, the $H^*(T)/B_\Phi$ line is almost the same for all the irradiated samples and it is similar to those obtained for Bi-2212 single crystals irradiated at a comparable dose.[5,22] Second, the regions in the VL where the $R(H)$ anomaly induced by the CD's is noticeable coincide (region II in Fig. 4). For comparison, the characteristic fields obtained from JPR data (Ref. 6) are also shown. A very important point is that we have shown that both the 2D angular scaling and the thermally activated pancake creep are still observed after irradiation in the VL. These results indicate that the dissipation is still determined by the motion of 2D pancakes. Pinning in the liquid phase and, therefore all the features of $R(H)$, are controlled by the density of pancakes in the ab plane independently of any recoupling of the vortex. We therefore discuss the physics of this reentrant pinned liquid just in terms of intralayer interactions.

Confinement of vortices on CD's in the VL is controlled by the competition between entropy favoring delocalization, the energy gain obtained by localization onto the CD's and the repulsive intralayer interactions between vortices which increase with H. For large irradiation doses ($B_\phi > 1$ T) and at low fields ($B \ll B_\phi$) it was proved that the entropy term is dominating.[23] Here (region I in Fig. 4), vortices are able to hop easily between the large number of available CD's giving a slightly higher dissipation than in the pristine sample. As H increases, intralayer vortex repulsion becomes more important and, at a given field, $H_1 \sim 0.25\ B_\Phi$, it begins to dominate over entropy giving a reduction of vortex mobility which leads to the slope changes in $R(H)$ curves (region II). At higher fields (region III), $H > H_2 \sim B_\Phi$ the number of vortices greatly exceeds the number of available defect sites, intervortex repulsion also overcomes pinning energy and the dissipation is determined by pancakes that are never localized on CD's. Hence we recover the pristine behavior. At high temperature, close to T_c, the effects of CD's also disappear due to the stronger importance of thermal fluctuations. So, *the competition between intralayer repulsion and entropy* controls the feature observed in $R(H)$.

In conclusion, we have shown a field-induced ($H_1 \sim 0.25\ B_\Phi$) decrease in the dissipation of a heavy-ion irradiated quasi-2D ($Bi_2Sr_2CaCu_2O_8$)/($Bi_2Sr_2CuO_6$) multilayer due to the accommodation of vortices onto the CD's. The validity of the 2D angular scaling proves that the magnetoresistance is still controlled by the motion of 2D pancakes. This feature in $R(H)$ delimits a reentrant pinned liquid in a (H,T) phase diagram experimentally established. The origin of this region is due to the competition between entropy, pinning energy, and in-plane vortex repulsion which is driven by the c-axis component of the magnetic field.

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[1] G. Blatter, M. V. Feigel'man, V. B. Geshkenbein, A. I. Larkin, and V. M. Vinokur, Rev. Mod. Phys. **66**, 1125 (1994).

[2] R. C. Budhani, W. L. Holstein, and M. Suenaga, Phys. Rev. Lett. **72**, 566 (1994).

[3] F. Warmont, V. Hardy, Ch. Goupil, Ch. Simon, J. Provost, and A. Ruyter, Physica C **277**, 61 (1997).

[4] W. S. Seow *et al.*, Phys. Rev. B **53**, 14 611 (1996).

[5] R. A. Doyle *et al.*, Phys. Rev. Lett. **77**, 1155 (1996).

[6] M. Sato, T. Shibauchi, S. Ooi, T. Tamegai, and M. Konczykowski, Phys. Rev. Lett. **79**, 3759 (1997).

[7] M. Kosugi *et al.*, Phys. Rev. Lett. **79**, 3763 (1997); Phys. Rev. B **59**, 8970 (1999).

[8] T. Hanaguri, Y. Tsuchiya, S. Sakamoto, A. Maeda, and D. G. Steel, Phys. Rev. Lett. **78**, 3177 (1997).

[9] Y. Tsuchiya *et al.*, Phys. Rev. B **59**, 11 568 (1999).

[10] N. Morozov, M. P. Maley, L. N. Bulaevskii, and J. Sarrao, Phys. Rev. B **57**, R8146 (1998).

[11] N. Morozov, L. N. Bulaevskii, M. P. Maley, J. Y. Coulter, A. E. Koshelev, and T.-W. Li, Phys. Rev. B **60**, 96 (1999).

[12] L. N. Bulaevskii, M. P. Maley, and V. M. Vinokur, Phys. Rev. B **57**, R5626 (1998).

[13] R. Sugano, T. Onogi, K. Hirata, and M. Tachiki, Phys. Rev. Lett. **80**, 2925 (1998); Phys. Rev. B **60**, 9734 (1999).

[14] R. J. Drost, C. J. van der Beek, J. A. Heijn, M. Konczykowski, and P. H. Kes, Phys. Rev. B **58**, R615 (1998).

[15] F. Hillmer *et al.*, J. Low Temp. Phys. **105**, 1153 (1996); Physica C **311**, 11 (1999).

[16] We neglected the role of the electromagnetic coupling as it is only determinant for low magnetic fields. See, e.g., G. Blatter, V. Geshkenbein, A. I. Larkin, and H. Nordborg, Phys. Rev. B **54**, 72 (1996).

[17] H. Raffy *et al.*, Physica C **235-240**, 182 (1994).

[18] S. Labdi, S. F. Kim, Z. Z. Li, S. Metgert, and H. Raffy, Phys. Rev. Lett. **79**, 1381 (1997).

[19] Z. Z. Li, H. Rifi, A. Vaurès, S. Metgert, and H. Raffy, Phys. Rev. Lett. **72**, 4033 (1994).

[20] H. Raffy, S. Labdi, O. Laborde, and P. Monceau, Physica C **184**, 159 (1991).

[21] This is also valid in the vortex solid phase as no directional effects were found for the critical current.

[22] For the Bi-2212 film irradiated at $\theta_i = 45°$ we use $B_\Phi \sin \theta_i$, i.e., the effective number of CD's in the ab plane.

[23] C. J. van der Beek, M. Konczykowski, R. J. Drost, P. H. Kes, N. Chikumoto, and S. Bouffard, Phys. Rev. B **61**, 4259 (2000).