Surface vortex depinning in an irradiated single crystal microbridge of $Bi_2Sr_2CaCu_2O_{8+\delta}$: Crossover from individual to collective bulk pinning

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Current–voltage characteristics have been performed on an irradiated microbridged $Bi_2Sr_2CaCu_2O_{8+\delta}$ single crystal at low temperature ($T=5$ K) in a magnetic field applied parallel to the c axis. The evolution of the I–V characteristics that leads to a peak in the differential resistance $r_d(I)=dV/dR(I)$ in the vicinity of the "peak effect" in the critical current was investigated. The analysis of the current-dependent differential resistance curves shows that the dynamics of the vortices in the vicinity of B_ϕ is dominated by the plastic flow of interstitially pinned vortex around regions of flux lines strongly pinned at the columnar defects. The pinning is found to be individual at low magnetic fields and collective when the vortex–vortex interactions are involved.

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The enhancement of critical current in superconductors through irradiation by heavy ions has been well established.[1,2] The first theory of pinning by straight parallel columns was proposed by Nelson and Vinokur,[3] showing that the behavior in the low-temperature region is identical to that of the Bose glass[4] with flux lines strongly localized on the columnar defects (CDs), resulting in zero dc resistivity. However, as later seen, another theory came out, raising another way to consider the location of critical currents. According to the latter one, the statics and dynamics of the Abrikosov vortex lines and two-dimensional (2D) pancake vortices in layered superconductors were formulated within the continuum approximation in terms of an equation of motion of the current density J inside an unirradiated superconductor.[5,6] By applying this theory of Brandt *et al.*[5] and Lazard *et al.*[6] for irradiated samples, Indenbom *et al.*[7] investigated the vortex depinning in irradiated yttrium barium copper oxide (Y-123) single crystals by the magnetization measurements and pointed out that the vortex motion from the columnar defects is limited by the nucleation of vortex kinks at the surface of the sample. Thus, the critical current, which is necessary for a kink nucleation, only flows at the surface even if it is in the low field regime so that all the vortices are pinned individually along their entire length by parallel tracks.

The present paper reports on the pinning–depinning mechanism and the dynamics of vortices in the irradiated $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi2212) single crystals. Magnetotransport measurements were performed at $T=5$ K, which can be considered as zero for the fluctuation point of view. We argue that, even if the mechanism is dominated by localization along the columnar defects, a crossover occurs from an individual to a collective depinning when vortex–vortex interactions (VVIs) occur. Finally, we show that despite a surface depinning, the pinning in an irradiated Bi2212 single crystal exhibits real bulk behavior. Moreover, a change from an individual to a collective behavior is present depending on the balance between the VVIs and vortex-CD interactions.

The samples used in this study are unsubstituted Bi2212 single crystals ($TC=84$ K). They were grown by a self-flux technique, as described elsewhere.[8,9] Two samples (1 and 2) were extracted from the same single crystal and the thick microbridge was created by using a laser method ($w\times l\times t=50\times 100\times 20\ \mu m^3$).[10,11] The advantage of this technique is to make it possible to reach low temperature and to get a better homogeneity of the current flowing in the sample. The resulting sample was post annealed by using an appropriate chemical treatment under a flow of oxygen gas.

The samples were irradiated with a beam of 5.8 GeV Pb ions (which traversed over the entire specimen) at the heavy-ion facility GANIL (Caen, France). In this Brief Report, the density of irradiated defects corresponds to a matching field B_ϕ of 1 T, corresponding to an average distance $d_\phi \approx 440$ Å between the tracks. Electrical contacts, with a low resistance of about 1 Ω, were made before the irradiation by using a top configuration. Using a standard dc four-probe method, I–V characteristics were obtained with a voltage resolution of 1 nV and a temperature stability better than 5 mK. The magnetic field was aligned with the ion tracks using a well-known dip feature occurring in dissipation for the field parallel to the columnar defects.

Isothermal $V(I)$ curves have been recorded for different applied magnetic fields ranging from 0.01 to 9 T at low temperature ($T=5$ K). Figure 1 shows an example of $V(I)$ curve measured on sample 1 at a fixed magnetic field and temperature. One can notice that the electrical field, due to the vortex motion, cannot be described by the functional form $E(J)=\rho_0 J\exp[-E_K/K_BT(J_c/J)^\mu]$ with μ ranging from 1/3 to 1, as predicted for the different relevant excitations of the Bose-glass phase (variable range hopping or half loop).[3,12] These curves present the usual form $V\approx(I\text{-}I_C)$ with I slightly higher than the critical current I_C (see the inset of Fig. 1). Thus, considering both the absence of measurable creep phenomena and the fact that the depinning is rather abrupt, the critical current was studied versus the magnetic field B. The value of the critical current I_C was determined by considering the nonlinear V(I) curves and using a criterion of $V=1$ nV. Furthermore, we have compared the effects of an

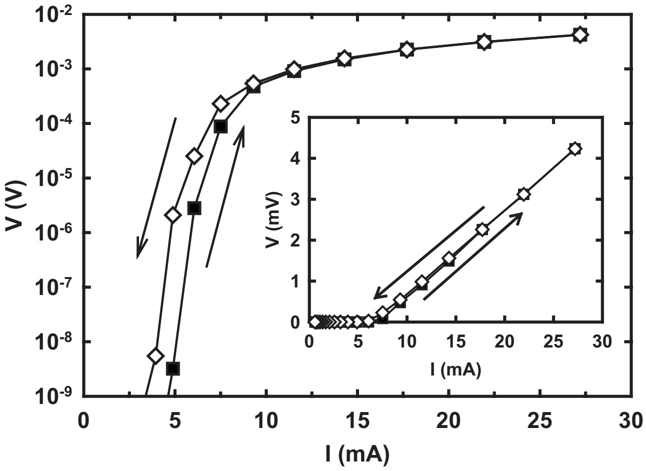

FIG. 1. Typical linear-log plot of $V(I)$ curves measured on sample 1 for $T=5$ K and $B=0.4$ T with both increasing (filled square) and decreasing (open diamond) currents. Inset: Linear-linear plot of the same curves.

increase in the magnetic field B (IB process: $B=0$ T, and $B=B_{\mathrm{meas}}$), as well as a decrease in B (DB process: $B=0$ T, $B=9$ T, and $B=B_{\mathrm{meas}}$) on the depinning threshold.

Figure 2 shows the critical current I_c for IB and DB processes as a function of magnetic field. Both reach a pronounced peak at B_{max} and decrease rapidly to zero. This phenomenon is known as the "peak effect," which is usually associated with a transition from elastic to plastic depinning.[13] One should notice that both IB and DB processes give the same dissipation for both high ($1\ \mathrm{T}\geq B \leq 9$ T) and low magnetic fields ($B\leq 0.035$ T). In contrast, when a magnetic field is increased, different behaviors were observed in a restricted region of the phase diagram ($B_0 =0.035\ \mathrm{T}\leq B\leq B_1=0.6$ T). As a typical example, the $V(I)$ curves measured on sample 1 for $B=0.4$ T for both increasing and decreasing currents are shown in Fig. 1. One can see that a higher value of the critical current may be obtained with the IB process. This effect has been previously observed in pulsed-current experiments and in nonirradiated Bi-2212 crystals,[15] and the state corresponding to a high value of the

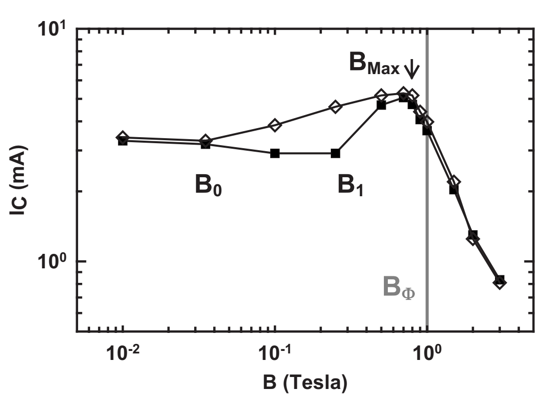

FIG. 2. Magnetic field dependence of the critical current I_C at $T=5$ K measured on sample 2. B varies from 0.03 to 3 T for IB (open diamond) and DB processes (filled square). The gray line corresponds to $B=B_\phi$.

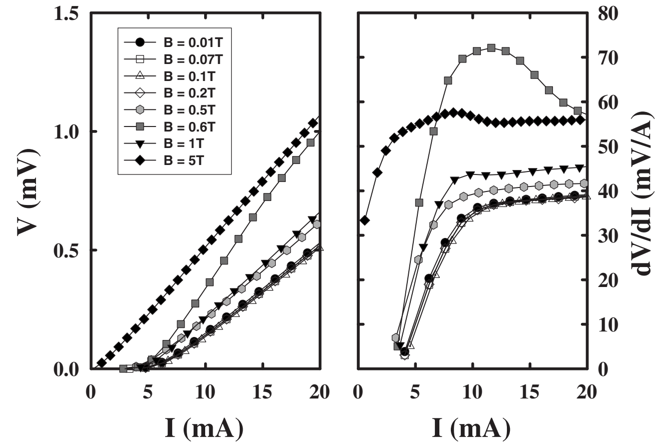

FIG. 3. $V(I)$ curves recorded at $T=5$ K for different magnetic fields measured on sample 2 (left) and current dependence of the differential resistance, $r_d(I)=dV=dI(I)$, obtained from I-V curves at different fields near the peak regime (right).

critical current has been identified to be a metastable state with a very long relaxation time.[14] Similar metastability has also been observed in $2H$-$NbSe_2$ (Ref. 16) and in Nb (Ref. 17). Although it is easy to reach and stabilize an out-of-equilibrium state, it is also possible to recover the more stable state with a smaller I_C. In fact, this assumption is confirmed by measuring $V(I)$ curves for the increasing current I and then for the decreasing current. The presence of the metastable state is probably due to the existence of a distribution in the pinning energies,[18,19] as well as the competition between the pinning ability of the CDs and the elastic properties of the vortex lattice. The vortex spacing is larger than the penetration length λ (typically 2000 Å) at low magnetic field. Thus, the weak VVI leads to an individual pinning of each vortex on one CD (i.e., $B\leq B_0$). On the contrary, at high magnetic field, the vortices outnumber the CDs, leading to the presence of interstitial vortices pinned by the interactions with those localized on CDs. The peak effect at a filling factor, $f=B/B_\phi \approx 0.6\sim 0.8$, in the $I_C(B)$ curve corresponds to the magnetic field at which the first interstitial vortex appears. This result is in good agreement with the previous work of Wengel and Täuber.[20] Their simulation showed that at least 10% of the vortices are weakly pinned by a filling factor, $f=0.65$, when $\lambda/d_\phi \approx 5$ (in our case, $\lambda/d_\phi \approx 4$).[21] A simple but realistic calculation was proposed by Wahl *et al.*[22] They found that the interaction between two vortices below B_ϕ is completely screened out by the presence of the columnar defects. This explains the anomaly of the reversible magnetization and also explains why the vortex system appears to be individual pinning below the matching field.

The crossover between these behaviors can be better illustrated by the results of the differential resistance, $r_d(=dV/dI)$, versus I (Fig. 3). Below the peak regime, for $B\leq 0.5$ T, r_d grows monotonically with the increasing current up to the flux flow of resistance (i.e., the I–V curve becomes quasilinear). In the vicinity of the peak regime for $B=0.6$ T (*i.e.,* $B\approx B_{\mathrm{Max}}$), r_d develops a peak whose value exceeds the asymptotic flux flow of resistance at the intermediate Lorentz forces. In numerical simulations, this peak in r_d is usually ascribed to the plastic vortex depinning followed by the dynamic ordering of the lattice.[23–25] Marchetti *et al.*[23] and Olson *et al.*[24] pointed out that a purely elastic medium description of the flux line lattice (FLL) is inadequate. They found that the quenched disorder generates defects in the FLL and the onset of motion is due to the plastic flow rather than a coherent motion of an elastic medium. The presence of this peak in $r_d(I)$ at intermediate current confirms the plastic behavior due to "free" vortices moving through the forest of vortices pinned by the CDs. This behavior presents a sharp distinction with the behavior that is exhibited at low field where the flux flow is quasimonotonous [see the *plateau* of $I_C(B)$]. It must be noticed that the plastic behavior due to the moving vortex incoherently disappears at $B=1$ T when an equal distribution of localized and interstitial vortices is present in the sample.

In a theoretical work, Fisher,[26] in analogy with static critical phenomena, proposed that by focusing on the nonlinear dynamics above the onset of motion, a scaling behavior between the applied force (current) and the velocity (voltage) is expected: $V\sim(I\text{-}I_C)^{\zeta}$, where ζ is the critical exponent. Two types of behaviors can be distinguished: the "elastic flow," where the elastic medium distorts but does not break, and the "plastic flow," where the motion breaks up the channels and, therefore, the flow is intrinsically inhomogeneous. Figure 4 shows a typical logarithmic plot of these fits close to the critical current. The exponent ζ has been determined using the linear part of the I–V curves at low $[(I\text{-}I_C)/I_C]$ values. We show different power law scaling respectively below ($B=0.1$ T), and in the vicinity of the peak regime ($B=0.5$ and 1 T) with respect to $\zeta\approx1.39\pm0.02$ and $\zeta\approx1.50\pm0.02$. Varying the value of I_c changes the value of ζ that best fits the data near the onset of vortex motion and allows an estimate of the error in ζ. A power law fit to the data is poor in the peak regime. Note that the exponents in these two regimes present different physical phenomena. One can notice that in the vicinity of I_C, there is a difference in the vortex dynamics between the depinning of vortices localized on the CDs below $B<B_{\phi}$ and the depinning of the ones that are submissive to the "cage" potential in the vicinity of B_{ϕ}.

Radzihovsky[27] proposed in his cage model that, for a high vortex density (i.e., $f>1$), interstitial vortices could be pinned due to the VVIs with the vortices localized on CDs. For $f>0.5$, our magnetotransport measurements are in agreement with such a depinning process that gives a true plastic response. The two regimes, $B<B_{\phi}$ and in the vicinity of B_{ϕ}, are characterized by qualitatively different spatial distributions of vortex velocities. Evidence for this comes from some previous numerical studies of the dynamics of a two-dimensional flux lattice driven by a uniform current through random pinning centers at zero temperature.[28] It was established that there is a correlation between the qualitative features of the velocity's distribution and the shape of the macroscopic I-V characteristics. Following the results of Faleski *et al.*[28] for a stronger disorder, the response near the depinning threshold should be plastic with vortices flowing around the pinned regions. In this plastic flow regime, the distribution of vortex velocities near the threshold has a clear bimodal structure. The bimodal structure of the velocity distribution reflects the coexistence of the pinned and flowing regions in the vicinity of the peak in the differential resistance r_d, and is proposed as a quantitative signature of plastic flow. The change in the distribution of vortex velocities near the threshold in the vicinity of the peak in r_d seems to be a possible cause of the onset of the plastic flow of vortices and leads to the peak effect in these samples.

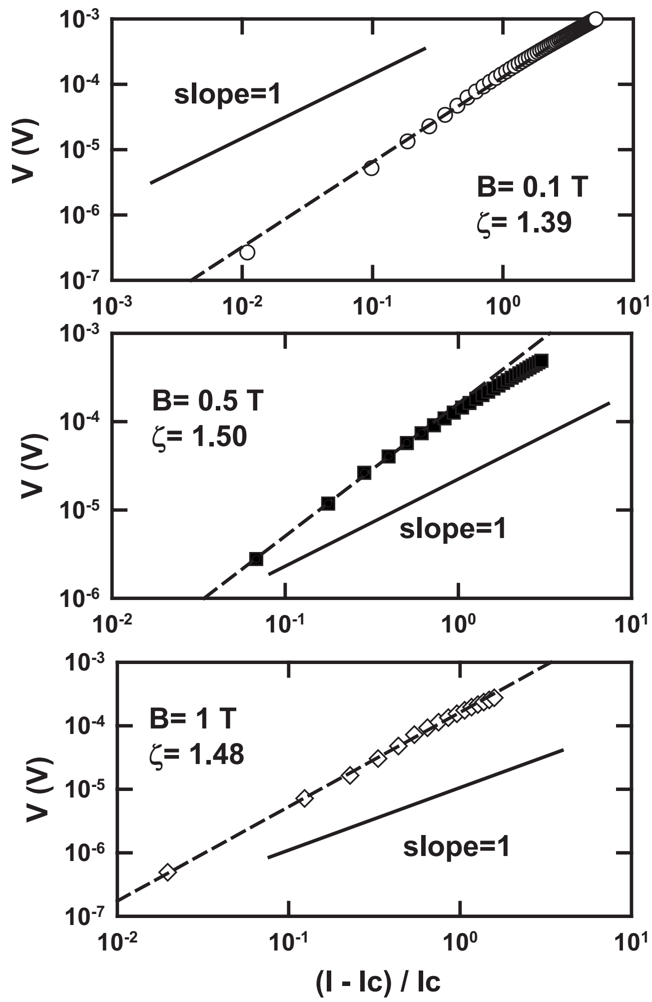

FIG. 4. Typical scaling plots for the I-V curves at fields below ($B=0.1$ and 0.5 T) and in the vicinity of the peak regime ($B=0.5$ and 1 T).

Our main findings, the peak effect in the critical current and the evolution of the differential resistance with increasing B resemble those observed in the experiments on a "quasi-two-dimensional" (2D) and a "three-dimensional" (3D) flux-line lattice in the unirradiated layered low-T_c superconductor 2H-$NbSe_2$.[29,30] In these two papers, Bhattacharya and Higgins[29,30] described the experiments on the nonlinear transport properties of the FLL in this system. They used a magnetic field dependence of the critical current and differential resistance to investigate the crossover of the dynamics from an interaction-dominated regime elastic flow to a disorder that might dominate the plastic flow. They found that the dimensionality effects are more pronounced in the disorder-dominated regime (where $\zeta\approx1.3$ and 1.8 in the 2D and 3D cases, respectively). In this regime where the disorder dominates, ζ presents the nonuniform filamentary motion of a defective FLL and the growth of a tenuous structure of connected paths that is similar to percolation. In contrast, the flow's behavior in the interaction-dominated regime weakly depends on dimensionality, $\zeta \approx 1.2$, and the exponent measures the collective motion of the FFL. The apparent exponent in the elastic regime is close to what is typically found for the charge-density-wave systems ($\zeta \approx 1.23 \pm 0.07$),[31] and it is in agreement with the numerical simulation investigations of the dynamics of the 2D vortex system ($\zeta \approx 1.11 \pm 0.05$).[32]

Additionally, it was suggested that an important distinction between plastic and elastic responses could be found in the correlations of the time-averaged velocity length, which characterizes the spatial inhomogeneity of a moving FLL.[33] Indeed, in a model where dislocations are forbidden and the response is therefore elastic, the time-averaged velocity will be spatially homogeneous and correlated over the whole system. In contrast, in a system that exhibits a plastic flow, the time-averaged velocity will be spatially inhomogeneous and it yields a bimodal structure of the corresponding histogram. The scaling behavior in the field regime below and above the peak suggests that the vortex lattice pinning and dynamics at low temperature (5 K) in the irradiated Bi2212 with an applied field close to the matching field are more similar to what is currently observed, and is much closer to B_{C2} in $NbSe_2$. However, there are still two discrepancies. The first difference is that a dramatic change in the *I-V* curves by varying magnetic fields is attributed to the plastic flow of interstitially pinned vortices around the regions of flux lines strongly pinned at the defects. The second is, in $NBSe_2$, the peak effect and the associated metastable effects usually appear close to B_{c2}; while in our case, it is restricted to a low field value. Since the applied temperature is very similar in both experiments, the explanation for these differences should be explained by the large difference between the electronic anisotropies.

At the threshold of dissipation, we have shown that a scaling law exists between the current and the voltage below and in the vicinity of the peak regime, $V \sim (I\text{-}I_C)^{\zeta}$, with $\zeta \approx 1.39 \pm 0.02$ and $\zeta \approx 1.50 \pm 0.02$, respectively. The pinning is found to be individual at low magnetic fields and collective when the vortex–vortex interactions are involved. The analysis of the shape of the *I-V* characteristic and the current-dependent differential resistance curves shows that the dynamics of the vortices in the vicinity of B_{ϕ} is dominated by the plastic flow of interstitially pinned vortex around the regions of flux lines strongly pinned at the columnar defects. We also show that a magnetic field induced peak effect in the critical current occurs due to the onset of plasticity. The change in the distribution of the vortex velocities near the threshold in the vicinity of the peak in r_d seems to be a cause of the onset of the plastic flow of vortices and leads to the peak effect. Our transport experiments suggest that the vortex lattice pinning and dynamics at low temperature in the irradiated Bi2212 are rather similar to what was observed below the upper critical field, $B_{c2}(T)$, in conventional superconductors.

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[1] D. Bourgault *et al.*, Nucl. Instrum. Methods Phys. Res. B **42**, 61 (1989).
[2] L. Civale *et al.*, Phys. Rev. Lett. **67**, 648 (1991).
[3] D. R. Nelson and V. M. Vinokur, Phys. Rev. Lett. **68**, 2398 (1992); D. R. Nelson and V. M. Vinokur, Phys. Rev. B **48**, 13060 (1993).
[4] M. P. A. Fisher *et al.*, Phys. Rev. B **40**, 546 (1989), and references therein.
[5] E. H. Brandt, Phys. Rev. B **64**, 024505 (2001).
[6] G. Lazard *et al.*, Phys. Rev. B **65**, 064518 (2002).
[7] M. V. Indenbom *et al.*, Phys. Rev. Lett. **84**, 1792 (2000); M. V. Indenbom *et al.*, Physica C **341-348**, 1251 (2000).
[8] A. Ruyter *et al.*, Physica C **225**, 235 (1994).
[9] A. Wahl *et al.*, Phys. Rev. B **60**, 12495 (1999).
[10] A. Ruyter *et al.*, Mater. Sci. Eng., B **104**, 113 (2003).
[11] A. Ruyter *et al.*, J. Phys. IV **114**, 371 (2004).
[12] L. Ammor *et al.*, Phys. Rev. B **69**, 134508 (2004).
[13] Min-Chui Cha and H. A. Fertig, Phys. Rev. Lett. **80**, 3851 (1998).
[14] F. Portier *et al.*, Phys. Rev. B **66**, 140511(R) (2002).
[15] Ch. Simon *et al.*, Pramana **66**, 83 (2006).
[16] W. Henderson *et al.*, Phys. Rev. Lett. **77**, 2077 (1996).
[17] X. S. Ling *et al.*, Phys. Rev. Lett. **86**, 712 (2001).
[18] S. Hébert *et al.*, Nucl. Instrum. Methods Phys. Res. B **146**, 545 (1998).
[19] J.-C. Soret *et al.*, Phys. Rev. B **61**, 9800 (2000).
[20] C. Wengel and U. C. Täuber, Phys. Rev. B **58**, 6565 (1998).
[21] C. Wengel and U. C. Täuber, Phys. Rev. Lett. **78**, 4845 (1997).
[22] A. Wahl *et al.*, Physica C **250**, 163 (1995).
[23] M. C. Marchetti *et al.*, Phys. Rev. Lett. **85**, 1104 (2000).
[24] C. J. Olson *et al.*, Phys. Rev. Lett. **81**, 3757 (1998).
[25] E. Olive and J. C. Soret, Phys. Rev. B **77**, 144514 (2008).
[26] D. S. Fisher, Phys. Rev. Lett. **50**, 1486 (1983); D. S. Fisher, Phys. Rev. B **31**, 1396 (1985).
[27] L. Radzihovsky, Phys. Rev. Lett. **74**, 4923 (1995).
[28] M. C. Faleski *et al.*, Phys. Rev. B **54**, 12427 (1996).
[29] S. Bhattacharya and M. J. Higgins, Phys. Rev. B **49**, 10005 (1994).
[30] S. Bhattacharya and M. J. Higgins, Phys. Rev. Lett. **70**, 2617 (1993).
[31] S. Bhattacharya *et al.*, Phys. Rev. Lett. **63**, 1503 (1989).
[32] Y. Cao *et al.*, Phys. Rev. B **62**, 4163 (2000).
[33] M. J. Higgins and S. Bhattacharya, Physica C **257**, 232 (1996).