Dimensionality and pinning of magnetic vortices in the c-axis aligned $Bi_2Sr_2CaCu_2O_{8+\delta}$ and $(Bi,Pb)_2Sr_2Ca_2Cu_3O_{10}$/Ag tapes irradiated by 5.8-GeV Pb ions

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(Received 23 May 1996)

Powder-in-the Ag tube processed $Bi_2Sr_2CaCu_2O_{8+\delta}$ and $(Bi,Pb)_2Sr_2Ca_2Cu_3O_{10}$ tapes were irradiated with 5.8-GeV Pb ions along the tape normal for the ion fluences of 0.68, 1.0, and 2.0×10^{11} cm^{-2}. The angular (θ) dependence of critical current densities $J_c(\theta,B,T)$ for these tapes was measured at temperature $T=27$ K and 55–80 K. Cusplike sharp peaks in $J_c(\theta,B,T)$ were observed for $T\geqslant55$ K when the applied magnetic field B is oriented parallel to the direction of the irradiation (θ=90°), and $J_c(\theta)$ did not scale with the perpendicular component of B, ($B_\perp=B\sin\theta$). Based on this evidence, it was concluded that the magnetic vortices behave as linelike (three-dimensional) rather than the pancakelike [two-dimensional (2D)] objects in these irradiated superconductors. However, at 27 K, neither the peaks in $J_c(\theta)$ nor the scaling of $J_c(\theta)$ with $B_\perp$ was observed. We attribute this to the increased strength of the isotropic pinning by the small irradiation-induced defect debris relative to that of the columns and due to the increased interlayer coupling strength at reduced temperature, but not as evidence for the pancakelike 2D vortices at low temperatures. Also, for $T\geqslant55$ K, the enhancement in the pinning strength qualitatively followed the theory by Nelson and Vinokur [Phys. Rev. Lett. **68**, 2398 (1992); Phys. Rev. B **48**, 13 060 (1993)]. [S0163-1829(96)01438-5]

I. INTRODUCTION

The mixed state of high-temperature superconductors provides a number of very interesting areas of investigations. Access is available to a wide range of temperature and magnetic-field space due to their short superconducting coherence lengths, large magnetic-field penetration lengths, and extremely large electronic mass anisotropies along the crystallographic axes in combination with large temperature ranges provided by high critical temperatures T_c. One of the consequences of these properties is the appearance of a boundary in the T-B plane, well below the upper critical magnetic field $B_{c2}(T)$ line, which separates the area into two distinct regimes depending on the dynamic behavior of the vortex lines. Above this line, the vortex lines are considered to be liquidlike, while below they act as a solidlike object. This demarcation line is often called the irreversibility line or the vortex liquid-solid phase boundary depending on how it is determined or defined.[1] Since the vortices are easily moved by the Lorentz force and motion results in dissipation above the irreversibility line, the location of this line in the T-B plane has a very practical significance for the application of these superconductors to large scale devices. This is of a particular concern for $Bi_2Sr_2CaCu_2O_{8+\delta}$; [hereafter Bi(2:2:1:2)] and $Bi_2Sr_2Ca_3Cu_3O_{10}$; [Bi(2:2:2:3)] which have irreversibility lines at low fields. This is associated with the fact that the electronic mass anisotropy along the a-b plane relative to the c axis is extremely large and the vortex lines in these materials behave as weakly coupled (by Josephson currents and the magnetic field) pancakelike objects.[2–5]

It was shown for $YBa_2Cu_3O_7$ that heavy ion irradiation at very high energy create small (several nanometers in diameter) columnar amorphous defects in the superconductor, and these defects can effectively pin the vortices at high temperatures through localization of the vortices at these columns.[6] The irreversibility line is thus moved to higher fields and temperatures relative to a unirradiated specimen.[7] A similar effect was also shown for single crystals of Bi(2:2:1:2).[8] The result was interpreted as an evidence for the pinning of the quasi-two-dimensional (2D) vortices by the columnar defects since the magnetization loops at 20 K were nearly the same size for the applied field directions parallel to and 60° off to the irradiation tracks. (In this experiment, the direction of the irradiation was 30° off the c axis of the crystal.) This interpretation is based on the expectation that the 2D vortices can freely move in the a-b planes and they will locate at the columnar defects irrespective of the direction of the columns relative to the magnetic-field direction. In similar experiments at higher temperatures, $T\geqslant60$ K, however, the size of the loops was found to be very different depending on the relative orientation of the columns and applied magnetic fields. In fact the hysteresis was the largest when the direction of the magnetic fields was along the columnar defects. Since this implies that the pancakelike vortices can no longer be freely be moved in the *a*-*b* planes, this effect was interpreted as an indication of the formation of the linelike vortices induced by the presence of the columnar defects.[9]

More recently, a number of additional experiments were performed to study the dimensionality of the vortices in these highly anisotropic superconductors which were irradiated with high-energy heavy ions.[10–14] These experiments have clearly demonstrated that, *at high temperatures*, the vortices in these irradiated highly anisotropic superconductors conduct as a 3D system. However, essentially all of the studies were carried out by the magnetization measurements on single crystals[9–11,13] or by the transport current techniques at low currents on films[12] and single crystals.[14] Also, the question of the dimensionality of the vortices in the irradiatated Bi(2:2:1:2) at lower temperatures, e.g., $T \leqslant 50$ K, has not been addressed in detail. Furthermore, because of the unavailability of single crystals of Bi(2:2:2:3), there has not been any detailed study on the effects of high-energy heavy ion irradiation on the dynamics of the vortices except for a set of the critical current measurements reported recently.[15]

Thus, we have investigated in detail the effects of irradiation on the vortex dynamics, i.e., the phase diagram in the B-T plane, critical currents, and the dimensionality of the vortices under large Lorenz forces in Ag-sheathed Bi(2:2:1:2) and Bi(2:2:2:3:) tapes to which large transport currents can be applied. In this paper, we show that at higher temperatures, the angular dependence of the critical current density, i.e., a $J_c(\theta,B,T)$ vs θ plot, exhibits cusplike peaks when θ is near 90°. (Here θ is the angle between the direction of applied magnetic field and the tape plane and is changed keeping the directions of the field and the current always perpendicular.) This is a clear indication for linelike behavior of vortices. However, this directional vortex pinning along the amorphous columns is lost at low temperatures, e.g., $T=27$ K. Based on the study of the scaling of $J_c(\theta)$ with the perpendicular component $B_\perp$ of applied fields, it is shown that this loss of the directional pinning is not due to the vortex system becoming a 2D-like, as previously concluded from magnetization measurements.[8] When temperature is lowered, the loss of the anisotropic pinning is rather due to the facts (1) that the vortex system has increasingly become 3D due to the increased interplanar electronic coupling and (2) that the irradiation-induced defect debris between the amorphous columns provide strong *isotropic* vortex pinning centers, comparable to those for the columns. We will also provide evidence for the existence for small defect debris in addition to the often discussed columnar defects in the irradiated superconductors and show that these small defects contribute to vortex pinning as well as reduction of the directional pinning along the columns as temperature is lowered. In addition, as a part of understanding the change in the dimensionality, we will discuss the enhanced critical currents in these tapes as a function of the irradiation fluence for $\theta=90°$ in terms of the Bose glass theory by Nelson and Vinokur.[7]

II. EXPERIMENTAL PROCEDURE

The single cored tape specimens used for this experiment were fabricated by the standard powder-in-the-tube process. For the Bi(2:2:2:3) tapes, three sets of the tapes were prepared each having approximate critical current densities of 2.6×10^4, 2.0×10^4, and 1.6×10^4 A/cm^2 at the criteria of 1 μV/cm and at 77 K in the self-magnetic field. They are identified as specimen groups, A, B, and C, respectively. There were three specimens of similar current densities in each group and two each out of each group were irradiated at the same fluence while the third was kept unirradiated. The overall thicknesses of the entire tapes were $\sim$130 μm and those of the superconducting cores were approximately 70 μm. The width of the tapes was approximately 0.3 cm. For the Bi(2:2:1:2) tapes, only one set of the tapes, Group D, with J_c of 1.2×10^5 A/cm^2 at 4.2 K, was used. The thicknesses of the Bi(2:2:1:2) tape and the superconducting core were approximately 90 and 25 μm, respectively. It is well known that the Bi cuprates in these tapes consist of the c-axis-aligned crystalline platelets with the c axis approximately parallel to the plane normal of the tape. In order to assess the degree of the alignment, rocking curves of each types of the tapes were determined by transmission x-ray-diffraction measurements at the National Synchrotron Light Source at Brookhaven National Laboratory.[16] The half width at the half maximum of the rocking curves of the (200) line of the tapes were approximately 4.1 and 13.1 degrees for the Bi(2:2:1:2) and Bi(2:2:2:3) tapes, respectively.[17] Also, the critical temperatures T_c for these tapes before the irradiation were 79 and 108 K, respectively (Superconducting onset temperatures as determined by a superconducting quantum interference device magnetometer using an applied magnetic field of 0.2 mT).

All of the irradiations were performed at room temperature at Grand Accelerateur National d'Ion Lourds (GANIL, Caen, France). The direction of the ion beam was parallel to the plane normal of the tapes, i.e., nearly parallel to the c axis of the crystalline platelets. These specimens were irradiated with 5.8-GeV Pb ions for intended fluences of 0.5, 1.0, and 2.0×10^{11} ions/cm^2, for Group B, A, and C of the Bi(2:2:2:3) tapes, respectively. Note that these fluences correspond to the so-called matching magnetic fields B_ϕ of approximately 1, 2, and 4 T, respectively (Matching field is determined by multiplying the fluence by the flux quanta ϕ_0, 2×10^{-8} Wb.) Also, a set of Bi(2:2:1:2), Group D, was irradiated to an intended fluence of 1.0×10^{11} ions/cm^2. The true fluence for each specimen was determined by measurements of the density of the amorphous columnar damage using the images taken by transmission electron microscopy (TEM). Densities were 0.68, 1.0, 2×10^{11}, and 1×10^{11} ions/cm^2 for the specimen B, A, C, and D, respectively. However, we will use the intended fluences for convenience in the following discussion unless the precise value is important. The amorphous columns were approximately 7 nm in diameter. At this energy level, the Pb ions exiting the bottom surface of the superconducting core retain an energy of over 1 GeV. Thus, the defect columns are essentially uniform across the superconducting core. The onset critical temperatures of the irradiated specimens were unchanged for $B_\phi \leqslant 2$ T but it was reduced to 98 K for the irradiation of $B_\phi=4$ T.

The critical currents $J_c(\theta,B,T)$ of the specimens were measured as a function of the angle θ between the tape plane and the direction of applied magnetic field by a standard four-probe method in liquid oxygen for temperatures between 54.5 and 77.5 K. The voltage taps were placed across the central 1.0 cm of the tapes (the uniformly irradiated area was 2 cm long). The current contacts were made outside this area. Similarly, the measurements of $J_c(\theta,B,T)$ at 27 K were carried out in liquid neon. (The rotating platform for the critical current measurements was made such that the specimens were transferred from one probe to another without resoldering the specimen at the current contacts.) The direction of the current along the tape was always perpendicular to the applied magnetic field. Since the transport critical currents for these tapes can be quite large at these temperatures, e.g., over 100 A at 27 K, liquid cryogens were chosen (rather than gas or conduction cooling) for the temperature controlling media. We have found that the temperature of liquid oxygen can remain extremely stable once a desired temperature is attained. The criteria for the critical current was 10^{-7} V/cm.

III. RESULTS AND DISCUSSION

A. The dimensionality of the vortices at elevated temperatures ($T \geqslant 55$ K)

In the following, we will first discuss the question of the dimensionality of magnetic vortices (for $T \geqslant 55$ K) in these Bi cuprate tapes irradiated by high-energy heavy ions. In order to do this, we will focus our discussions on the two particular aspects of the present measurements, i.e., (1) the presence (or the absence) of a peak in $J_c(\theta)$ around $\theta=90°$ in $J_c(\theta)$ vs θ plots (At this angle, the defect columns and the c axes of the Bi cuprate platelets are approximately parallel to the direction of applied magnetic fields B), and (2) the scaling (or nonscaling) of the $J_c(\theta)$ with the perpendicular field component $B_\perp$ to the plane of the tapes. We focus on these two aspects of the measurements since (1) the absence of anisotropy in $J_c(\theta)$ with respect to the direction of the columns has been used as one of the defining means for the pancakelike or 2D vortices,[8–14] and (2) the scaling of the critical currents $J_c(\theta)$ by the perpendicular component of B is also used as an experimental confirmation for the 2D-like vortices[4] (since the parallel component of the field will not contribute to the dissipative motion of the vortices in a 2D vortex system). However, it is important to recognize that the identification of the dimensionality of the vortices being 2D or 3D could depend on the method that is used to define it, and the present method, J_c measurement, is a tool with rather strong Lorentz forces on the vortices in comparison with some of other methods in probing the dimensionality such as a resistivity measurement.

It is also important to point out that the temperature region in this study was below T_0 [=66 and 89 K for Bi(2:2:1:2) and Bi(2:2:2:3), respectively]. Here, T_0 is defined as the temperature at which the size of the coherence length becomes approximately equal to the radius of the amorphous column and it is given by $c_0=\sqrt{2}\,\xi_0(1-T_0/T_c)^{-1/2}$ where c_0 is the radius of the amorphous core of the defect column.[7] Below this temperature, the vortex-vortex interaction is assumed to be negligibly small for B less than B_ϕ.

In order to examine the first of the above two criteria for the dimensionality of the vortices, the dependences of $J_c(\theta)$ on the angle θ are presented in Figs. 1(a) and 1(b) for a Bi(2:2:1:2) tape, specimen D-1, and a Bi(2:2:2:3) tape, specimen A-2, respectively. Both of these specimens were

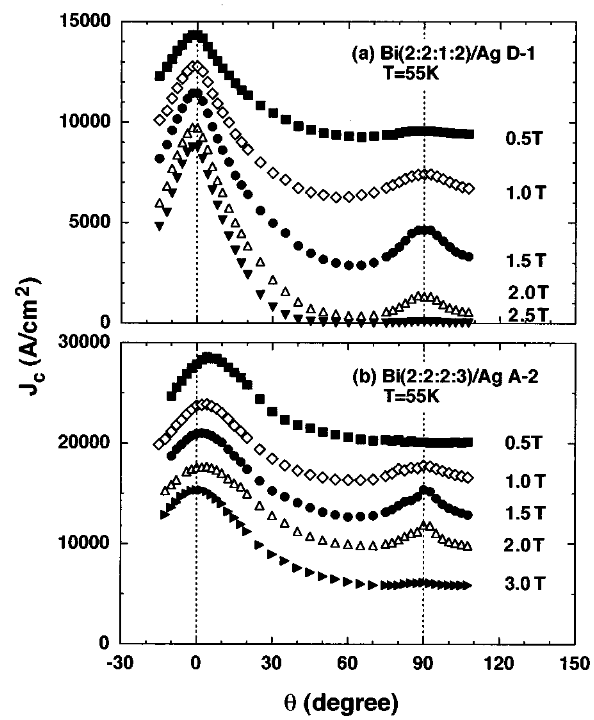

FIG. 1. The angular dependences of the critical current densities at 55 K are shown for the Ag-sheathed tapes of (a) Bi(2:2:1:2) and (b) Bi(2:2:2:3), respectively, which were irradiated with 5.8-GeV Pb ions to a fluence of 1.0×10^{11} ions/cm^2. θ is the angle between the direction of applied magnetic fields and the plane of the tape.

irradiated to the fluence of 1.0×10^{11} ions/cm,[2] or $B_\phi=2$ T, Measurements were taken at 55 K for various magnetic-field strengths. In Figs. 1(a) and 1(b), the values of $J_c(\theta)$ exhibit cusplike peaks for both of the tapes up to $B=2$ T, equivalent to the matching field B_ϕ, about the angle $\theta=90°$. The magnitude of the peak drastically diminishes although similarly shaped peaks exist for $B>B_\phi$. This is expected from the fact that the vortices outnumber the columns beyond $B=2$ T,[7] as will be discussed below. Also, in the case of Bi(2:2:1:2), the critical currents were truly independent of the angle for $|\theta-90°|\leqslant 2.5°$ at all experimental ranges of temperatures and magnetic fields. This is taken as clear evidence for the lock-in vortices in the columnar defects within the full width of 5°. The fact that a similar lock-in behavior was not observed for Bi(2:2:2:3) is likely due to the larger misorientation angles for Bi(2:2:2:3) platelets in this tape than that for Bi(2:2:1:2). [The other large peaks at $\theta=0°$ are due to the alignment of the field direction with the a-b planes and are obviously higher than that at $\theta=90°$ due to the strong inter-CuO planar pinning. These peaks are sharper for the Bi(2:2:1:2) than for the Bi(2:2:2:3) tape, again, reflecting the difference in the degree of the alignment of the platelets.] Similar results were obtained at higher temperatures for these tapes as well as other Bi(2:2:2:3) tapes with different levels of the irradiation. Thus, the anisotropic pinning along the direction of the amorphous columns clearly establish that the vortices in the heavy ion irradiated Bi cuprates become the linelike objects, as previously shown by magnetic and low-current measurements on the single crystals and films of

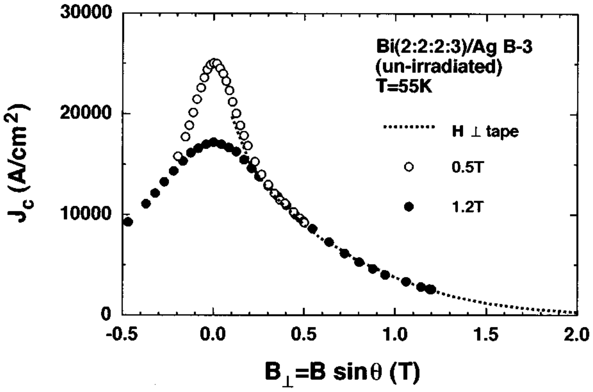

FIG. 2. The scaled critical current densities $J_c(B_\perp)$ with the perpendicular component of the applied magnetic fields, $B_\perp = B\ \sin\theta$, are shown for the unirradiated Bi(2:2:2:3) tape.

Bi(2:2:1:2).[9–14] These figures also show that the vortices in the irradiated Bi(2:2:2:3) behave essentially identically to those in the Bi(2:2:1:2).

In the above observations, it was clearly shown that the vortices conduct as 3D objects when the alignment of the vortices and the columns are within approximately 30°. However, these results do not address the question of the dimensionality when vortices are tilted further away from the columns beyond 30°, the so-called accommodation angle.[7,13] Thus, in the following, we will examine the dimensionality of the vortices by studying the scalability of the critical current densities $J_c(\theta)$ with the perpendicular component $B_\perp$ of applied magnetic fields. First we give an example of scaling for an unirradiated Bi(2:2:2:3) tape, specimen B-3, in Fig. 2. Here, $J_c(\theta)$ was measured at 55 K. For clarity, only three sets of the data $J_c(B,\theta)$ for $B=0.5$ and 1.2 T and J_c $(B,\ \theta=90°)$, are shown in the figure where $B_\perp = B\ \sin\theta$. As shown previously,[18,19] $J_c(B_\perp)$ scales very well above $B_\perp=0.2$–0.3 T, illustrating that at high temperatures the vortices are very weakly coupled along the c axis and that the small misalignment, (halfwidth at half maximum=13.1°), of the platelets along the c axis is not important for the scaling. In the low-field region, $J_c(\theta)$ no longer scales with $B_\perp$. This is due to the presence of the weakly connected grain boundaries which can transport currents at low fields but not at high fields and also to the misalignment of the platelets which limit the maximum current of a tape by introducing the perpendicular component of applied magnetic fields to the platelets even though the field is parallel with the tape face.[18,19] For comparison with Fig. 2, those data for $J_c(\theta)$ in Figs. 1(a) and 1(b) were replotted as a function of $B_\perp$ in Figs. 3(a) and 3(b). These results of Figs. 3(a) and 3(b) demonstrate that $J_c(B_\perp)$ does not scale with $B_\perp$ for this set of the specimens. The nonscaling behavior of $J_c(\theta)$ has become even stronger at a higher irradiation fluence, $B_\phi=4$ T. As shown in Fig. 4, however, for the lowest irradiation level, $B_\phi=1$ T, the scaling for the entire field range was observed except for θ close to 90° and at very low fields where the weak grain boundaries can play a role in carrying the currents as mentioned above. These results demonstrate that the vortices are still like the

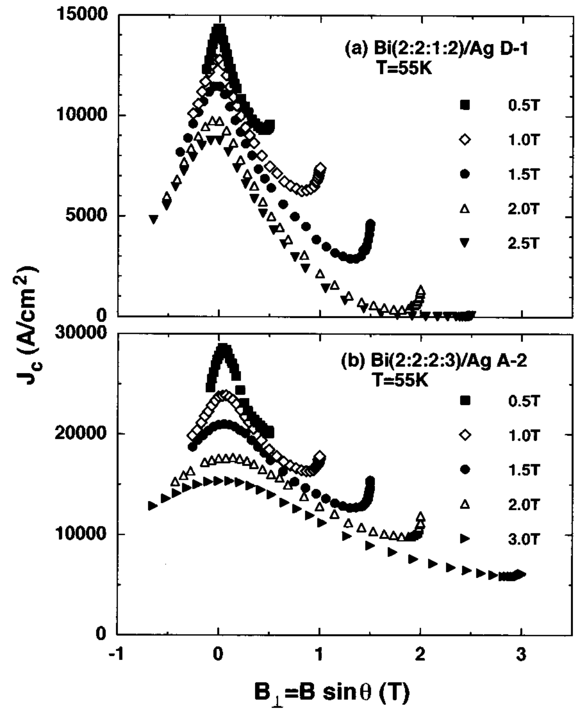

FIG. 3. The scaled critical current densities $J_c(B_\perp)$ with the perpendicular component of the applied magnetic fields $B_\perp$ are shown for the data in Fig. 1 for (a) Bi(2:2:1:3) and (b) Bi(2:2:2:3). Both of these were irradiated to $B_\phi=2$ T.

2D pancakes for low level irradiation ($B_\phi \leqslant 1$ T except for $\theta \approx 90°$) if a relatively low magnetic field is applied at sufficiently high angles θ relative to columnar defects and the c axis. However, at very high irradiation fluences, the vortices behave as 3D for the nearly entire angular range, particularly at high magnetic fields. Thus, these results further illustrate that the line-like nature of the vortices are enhanced by both higher irradiation levels and magnetic fields in these specimens, even in the case where the applied magnetic fields make a large angle with the columnar tracks.

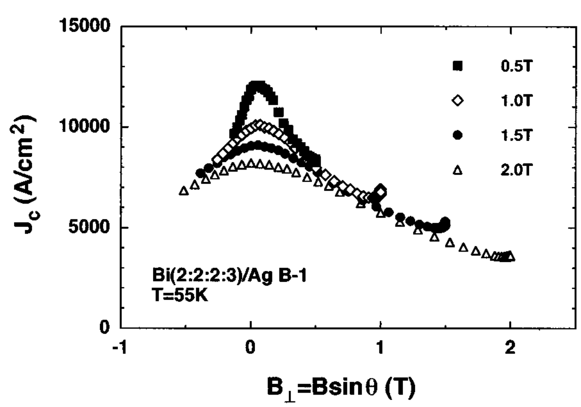

FIG. 4. The scaled critical current densities $J_c(B_\perp)$ with the perpendicular component of the applied magnetic fields $B_\perp$ are shown for the Bi(2:2:2:3) tape with $B_\phi=1$ T.

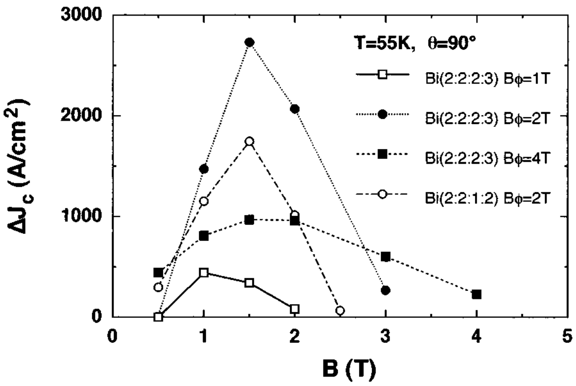

FIG. 5. The excess critical current densities $\Delta J_c(\theta=90°)$ at 55 K are plotted as a function of applied magnetic fields for the irradiated Bi(2:2:2:3) tapes for fluence $\phi=0.5$, 1.0, and 2.0×10^{11} ions/cm^2 and the Bi(2:2:1:2) tape for $\phi=1.0\times10^{11}$ ions/cm^2.

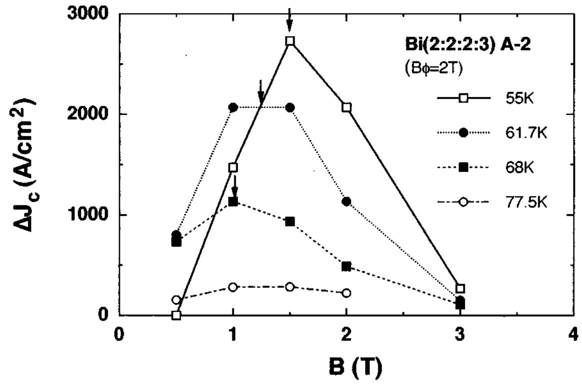

FIG. 6. The excess critical current densities $\Delta J_c(\theta=90°)$ at 55, 61.7, 68.0, and 77 K are plotted as a function of applied magnetic fields for the irradiated Bi(2:2:2:3) tapes for $\phi=1.0\times10^{11}$ ions/cm^2.

B. The irradiation enhanced vortex pinning

Before discussing the results of the measurements of $J_c(\theta)$ at 27 K, we will discuss the heavy ion irradiation enhancement of J_c in these tapes. As described below, this becomes important in understanding the results of $J_c(\theta)$ and the dimensionality of the vortices at low temperatures. Returning to Fig. 1, we note that the strength of the peaks at $\theta=90°$ varies significantly depending on the values of B. We will examine the variations in detail by plotting the excess critical current density ΔJ_c at $\theta=90°$ above the minimum background values of $J_c(\theta)$ in Fig. 5. Note that the value of the ΔJ_c can also be considered as the strength of an amorphous column for pinning a single vortex, since $F_L/n\phi_0=J_c$, where F_L is the Lorentz force per unit volume and $B=n\phi_0$. In order to understand these variations in $\Delta J_c(B)$, it is helpful to refer to the Bose glass picture of the enhancements in critical current densities by the columnar pinning centers.[7] According to Nelson and Vinokur,[7] one expects that the pinning strength is a maximum at $B=B_\phi$ where all of the pinning centers are occupied, and excited half loops of the vortices cannot move into neighboring sites. For B less than B_ϕ, the pinning strength will be lower as the vortices can jump from one occupied site to an unoccupied site assisted by sufficiently large Lorentz forces and thermal excitations for nucleation of the half loops. On other side of the peak where B is greater than B_ϕ, the extra vortices at the interstitial sites among the trapped vortices will be easily moved by the Lorentz forces, causing a diminished value of the excess critical current, ΔJ_c. This is essentially what is observed in Fig. 4 and is in qualitative agreement with the Bose glass picture. However, it should be noted that the peaks in ΔJ_c are at somewhat lower values of B than at B_ϕ. In order to understand this, we examine the temperature dependence of the peak in ΔJ_c as a function of B. As shown in Fig. 6, the values of B at which ΔJ_c is a maximum (indicated by the arrows) decrease with increasing temperatures. Thus, this suggests that the reason for the peak in ΔJ_c being lower than B_ϕ is that the temperature is too high for ΔJ_c to match with B_ϕ. Thus, if ΔJ_c is measured at some what lower temperature, e.g., at $T<50$ K, it is likely that we would observe the maximum in ΔJ_c at B_ϕ, the matching field.

Interestingly, it was also observed in Fig. 5 that the magnitudes of the J_c peaks at $\theta=90°$, ΔJ_c, for the low fluence irradiation, are much lower than those with higher levels of the irradiation. For an examples see the Bi(2:2:2:3) tapes with the lowest irradiation level, $B_\phi=1$ T. This may indicate that the vortices are less linelike than those for the higher irradiation. A similar conclusion was also made in the scaling of $J_c(B)$ for the specimen with the lowest irradiation, i.e., $J_c(\theta)$ scaled relatively well with $B_\perp$ except for θ near 90°. This may imply that the linelike behavior of the vortices in the irradiated tapes is assisted by the magnetic interaction among the trapped vortices in the columns. Thus, in the case where the density of the amorphous columns is relatively low, e.g., $B_\phi=1$ T, the trapped vortices are far apart and their interaction is weaker than for the case where they are closely packed. This results in the vortices retaining more of the pancakelike (2D) nature, particularly when the applied fields are tilted away from the direction of the columns, i.e., a softer tilt modulus along the c axis for the specimens with the lower fluence than for those with the higher fluence. Also, the peak heights ΔJ_c are reduced for the specimens with the highest irradiation fluence, i.e., $B_\phi=4$ T (C-1), relative to those with $B_\phi=2$ T. This is believed to be due to the extensive overlapping damaged areas at this level of irradiation as indicated in the reduction in T_c as well as observed in the TEM images. However, for this specimen, the vortices are strongly linelike even when applied magnetic fields are tilted away from the columns by large angles.

In Figs. 1 and 5, the peaks in $\Delta J_c(90°)$ at 55 K and at $B=0.5$ T have completely disappeared for the Bi(2:2:2:3) tapes with $B_\phi=1$ and 2 T and it has diminished to a barely observable level for the Bi(2:2:1:2) tape. Although the size of the peak at $B=0.5$ T at higher temperatures was generally smaller than those at higher fields, the peaks were clearly observable for all of the specimens. One possibility for this absence of irradiation-induced anisotropic pinning at $\theta\approx90°$, particularly at lower temperatures ($\leqslant55$ K), is due to the vortices becoming more like ''2D'' objects as suggested earlier by the magnetization measurement.[8] This is a possibility where the weak $J_c(B_\perp)$ scaling is observed at low values of the perpendicular component $B_\perp$ of the applied fields as shown in Fig. 2 for the specimens irradiated to $B_\phi=2$ T. This scaling was more apparent for the specimen irradiated to a lower fluence of $B_\phi=1$ T as shown in Fig. 4. However, in addition to this, there appears to be another factor involved in the disappearance of $\Delta J_c(90°)$ peaks. This is based on the fact that the values of J_c are higher for the irradiated ($B_\phi=1$ and 2 T) tapes than the virgin ones even when the tapes are tilted far away from $\theta=90°$ to the extent that the directional pinning by the columns is no longer effective. This suggests that there may be small irradiation-induced defects between the amorphous columns which are isotropic (with respect to the crystal axis and the direction of the columns) in pinning the vortices and become effective pinning centers at low temperatures, e.g., $T\leqslant55$ K. The enhanced pinning from these defects can contribute to the diminished peak heights ΔJ_c. Presumably, the strength of the isotropic pinning by these defects increases faster relative to the anisotropic pinning by the columnar defects at lower temperatures.

Before examining further the possibility that the small noncolumnar irradiation induced defects play a role in the diminished ΔJ_c and $J_c(\theta)$ at low temperatures, we will discuss possible sources of the defects which are believed to be contributing to isotropic pinning. In general, when the effects of high-energy heavy ion irradiation is considered in relation to the behavior of the vortices in high-T_c superconductors, only the volume or the size of the amorphous columns are considered. However, as it was previously shown,[19–21] the area damaged by the irradiation extends substantially beyond the region of the amorphous columns. Actually, the damaged volume in $YBa_2Cu_3O_7$ is approximately twice as large as that of the amorphous region as determined by the measurements of the pre-edge strength (the hole density) of the oxygen K-edge absorption spectra by electron-energy-loss spectroscopy in a transmission electron microscope. Superconductivity can be reduced outside of the amorphous region due to the small defect debris which could be created during quenching of the molten material after the passage of high-energy ions.[20] The instantaneous columnar molten region formed after the passage of the ions is greater than the frozen amorphous area. As described in detail in Ref. 20, a part of the molten region epitaxially grows back before the formation of the amorphous zone during the freezing process. Although these hypothesized small defects are not seen in high-resolution electron microscopy, it is reasonable to expect that there will be small defects, e.g., oxygen disordered regions, which are created during this very rapid quench process. These defects are likely to be the cause the decreased carrier density out side of the columns and can be strong *isotropic* pinning centers at reduced temperatures.

It is also shown that there exists a substantial strain field around the columns with a diameter extending to 3–4 times that of the size of the amorphous columnar region. This strain field is a result of the increased volume in the amorphous columns relative to the crystalline volume before it was converted in amorphous and this strain could also cause the reduction of the carrier density outside of the amorphous region.[22] However, since the strain is circumferential to the amorphous columns, this will only enlarge the apparent size of the columnar pinning centers, but will not contribute to the increased *isotropic* pinning strength by lowering temperature.

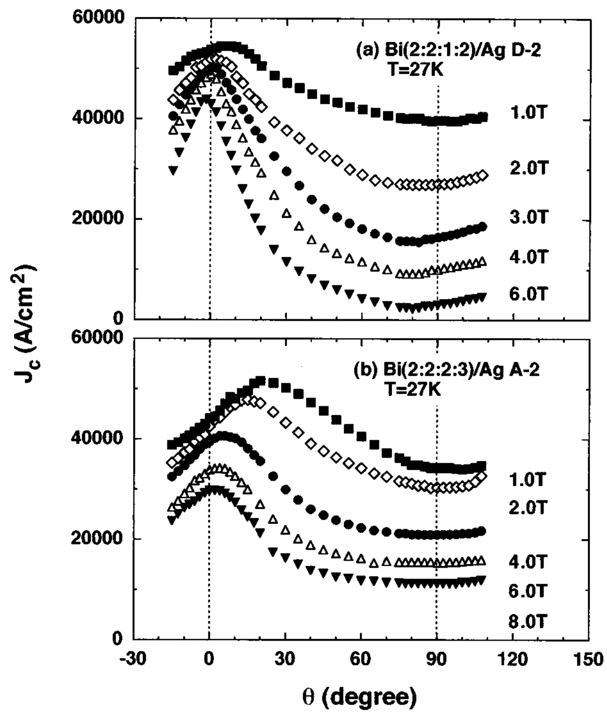

FIG. 7. The angular dependences of the critical current densities at 27 K are shown for the tapes of (a) Bi(2:2:1:2) and (b) Bi(2:2:2:3), respectively, which were irradiated to $\phi=1.0\times10^{11}$ ions/cm^2.

C. The dimensionality of the vortices and J_c at $T=27$ K

In order to investigate the possibility that the disappearance of the peaks in ΔJ_c or of the anisotropic pinning at $\theta=90°$ is due to the increased pinning strength of the small defects at low temperatures, the angular dependence of J_c at 27 K was measured for the tapes, Bi(2:2:1:2), D-2 and Bi(2:2:2:3), A-2. The results are shown in Figs. 7(a) and 7(b). In both cases, no peak in $J_c(\theta)$ was observed at $\theta=90°$ at any magnetic field. [As noted, the peaks at $\theta=0°$ are shifted and the appearance of the plot for the Bi(2:2:2:3) tape becomes somewhat complicated. This is due to the fact that the values of $J_c(B)$ become hysteretic for the increasing and the decreasing fields at lower magnetic fields and temperatures. This hysteresis causes the shift in the peaks in $J_c(\theta)$ near $\theta=0°$ and is associated with the presence of the weakly coupled grain boundaries[23] which may become more noticeable after the irradiation.]

Is the absence of the peak in $J_c(\theta)$ at 90° an indication that the vortices become pancakelike objects at lowering temperatures? In order to investigate this, a second test for the dimensionality of the vortices, i.e., the scaling of $J_c(\theta)$ with $B_\perp$, is shown in Fig. 8 for Bi(2:2:1:2) with $B_\phi=2$ T. [It was difficult to use the scaling for Bi(2:2:2:3) tape in Fig. 7(a) since the J_c hysteresis has extensively distorted the $J_c(\theta)$ curves.] This figure clearly exhibits that the scaling of $J_c(\theta)$ is not valid at $T=27$ K. Thus, it is clear that the diminished anisotropic pinning by the columnar defects at these low temperatures, i.e., $T\leqslant40$ K,[24] is not due to the vortices becoming quasi 2D objects. Furthermore, the $J_c(\theta)$ scaling by the perpendicular component of the applied magnetic fields was not observed for either of these tapes,

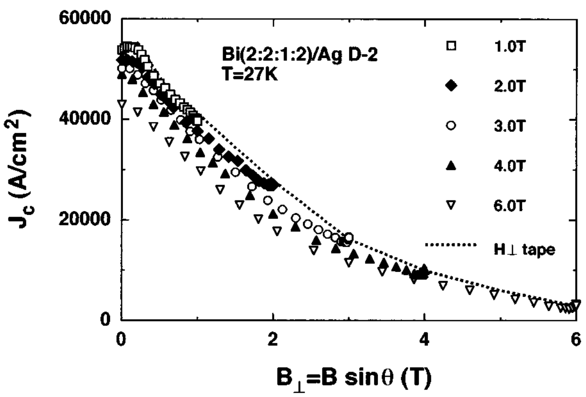

FIG. 8. The scaled critical current densities $J_c(B_\perp)$ for the data shown in Fig. 7 [a Bi(2:2:1:2) tape at 27 K].

Bi(2:2:1:2), D-3 and Bi(2:2:2:3), B-3, even *without irradiation*. This indicates that the interlayer coupling in these superconductors is sufficiently strong so that the magnetic field in the ab planes contributes to the dissipation in the tapes, i.e., the vortices behave as a 3D linelike object at these temperatures except perhaps at the very low fields. This 3D-like state of the vortices in a highly anisotropic superconductor was previously called an incipient 3D state.[24,25] Obviously, this effect is significantly smaller in Bi(2:2:1:2) than Bi(2:2:2:3). Also, the increased tilt moduli with decreasing temperatures are consistent with the sharply increased irreversibility fields at low temperatures, below ~30 K for Bi(2:2:1:2) and ~50 K for Bi(2:2:2:3). Thus, the disappearance of ΔJ_c or of the anisotropic pinning along the columnar defects at 27 K is due to the increased interlayer coupling strength and the increased isotropic pinning strength of the small defects around and between the columns relative to that of the amorphous columns.

IV. SUMMARY

At high temperatures, e.g., $T \geqslant 55$ K, the magnetic vortices become linelike objects when amorphous columnar tracks are introduced in Bi(2:2:1:2) and Bi(2:2:2:3) by high-energy heavy ion irradiation. The linelike behavior is accentuated with irradiation fluence, indicating that the density of the amorphous columns, which are occupied with the vortices, retards the nucleation of the vortex half loops. At low temperatures, e.g., $T=27$ K, the anisotropic pinning by the irradiation tracks is no longer effective. This is due to the facts that the interplanar coupling strength becomes significant and that the pinning strength by the irradiation-induced small isotropic defect debris between the tracks becomes comparable with that of the amorphous tracks. Variations in the strength of the vortex pinning as a function of the irradiation fluence and B for $\theta=90°$ are well described by the concept of the Bose glass put forward by Nelson and Vinokur.[7]

Note added in proof. A similar conclusion was reached by Hardy *et al.*[26] in regard to the nature of the dimensionality of the vortices in the heavy ion irradiated Bi and Tl cuprate single crystals by the magnetization measurements.

ACKNOWLEDGMENTS

The authors appreciate very helpful discussions with David Welch on many occasions and a very careful reading of the manuscript by A. R. Moodenbaugh. The work was performed under the auspices of the Division of Materials Sciences, Office of Basic Energy Sciences, U.S. Department of Energy under Contract No. DE-AC02-76CH00016.

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