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Parallel and crossed columnar defects aligned at 45° to the c axis in $Bi_2Sr_2CaCu_2O_x$ tapes

Y. Kazumata
Nihon Advanced Technology Co., Tokai-mura, Naka-gun, Ibaraki-ken, Japan 319-1106

S. Okayasu and M. Sataka
Japan Atomic Energy Research Institute, Tokai-mura, Naka-gun, Ibaraki-ken, Japan 319-1195

H. Kumakura
National Research Institute for Metals, 1-2-1, Sengen, Tsukuba, Ibaraki-ken, Japan 305-0047

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Exactly the same number of parallel and crossed columnar defects were introduced into $Bi_2Sr_2CaCu_2O_x$ tapes irradiated by 180 MeV Cu^{11+} ions. Parallel columnar defects were tilted by 45° for the c axis, while crossed columnar defects consisted of the two subsystems of columnar defects crossing each other at right angles. A substantial enhancement of the irreversibility field (H_{irr}), was observed for the parallel columnar defects (PCD's) and crossed columnar defects (CCD's). The angular dependence of H_{irr} for the PCD's showed a peak in the direction of the columnar defects and another peak for the CCD's was found in the mid-direction between the two subsystems of the CCD's. When the external field was applied parallel to the ab plane, H_{irr} decreased exponentially with an increase of temperature for the three specimens, i.e., prior to irradiation, containing PCD's, and containing CCD's. This exponential decrease of H_{irr} was attributed to the motion of kinks trapped at lattice defects. Three distinct temperature regimes were found in the temperature dependence of H_{irr} for the PCD's in the applied field parallel to the direction of columnar defects. These temperature regimes followed the temperature dependence of the accommodation field B^* for the single-vortex strong pinning regime. H_{irr} for the CCD's showed rather a smooth function of temperature, which indicated the motion of kinks with diverse activation energies. The directional property of J_c for the PCD's and CCD's was measured at several temperatures at the directions in applied fields for $\theta=45°$, 90°, and 135°. The two-dimensional pancake model was appropriate at 5 K and the directional property appeared above 30 K. The field dependence of J_c at $\theta=90°$ (the applied field parallel to the c axis) for the PCD's nearly coincided with that of J_c at $\theta=45°$ (perpendicular to columnar defects), but that for the CCD's showed the same value of J_c as at 135° (the direction of the larger number of columnar defects) at temperatures between 30 and 50 K. It is inferred from the field dependence of J_c that the irregular distribution of defect density hinders the stable pinning for vortices, and resulted in smaller J_c at high fields. [S0163-1829(98)00733-4]

I. INTRODUCTION

The enhancement of the critical current density in a magnetic field is an essential problem for the practical application of high-T_c superconductors. The critical current density is tightly correlated with thermal and static disorders of vortices.[1–3] The influence of thermal disorder or thermal fluctuation is observed in the reversible region in the temperature dependence of magnetization near T_c (Refs. 4–6) and also in giant flux creep.[7,8] Random and correlated disorders are static disorders. Random disorder forms a vortex-glass state in a vortex configuration.[9] The low-temperature vortex glass transforms into the high-temperature vortex-liquid phase at a glass-liquid transition temperature with a second-order phase transition. A characteristic correlation length and the relaxation time of the fluctuation of the glass order parameter diverge at the glass-transition temperature. Scaling laws based on the second-order phase transition hold for the regions above and below the glass-transition temperature, for example, the current-voltage scaling law.[10–14] It should be noted that a vortex-glass state should not occur in a two-dimensional (2D) flux-line lattice.[15–17] Correlated disorder, such as twin boundary and columnar defects, on the other hand, form a Bose-glass state in a vortex configuration.[18] The Bose-glass state for columnar defects also shows a second-order phase transition similar to that for the vortex glass, but with different critical exponents in the scaling functions.[19–23] Theoretically, the infinite tilt modulus below the Bose-glass transition temperature is a distinct feature for the Bose glass state when the columnar pins outnumber flux lines.[18] Based on the theory by Nelson and Vinokur,[18] Zech *et al.*[24] proposed a temperature-field phase diagram in the state with columnar defects, in which the irreversibility line is not identified with a shifted melting line (the Bose-glass melting line), but follows the accommodation field B^* separating the single-vortex strong pinning regime from the collective weak pinning regime.

Krusin-Elbaum *et al.*[25] pushed forward with a study of the controlled splay configuration of columnar defects in a $YBa_2Cu_3O_x$ (YBCO) single crystal after the establishment of the effectiveness of the uniform splay which was installed with the fission products produced by 0.8 GeV protons in a $Bi_2Sr_2CaCu_2O_x$ film, and also with the small divergence of columnar tracks by 0.58 GeV Sn ions in a YBCO single crystal.[26,27] The largest persistent current J was obtained for a parallel distribution of columnar defects with a splay angle of ±5°, but the J in the Gaussian distribution of ±4.47° was less effective compared to the parallel distribution. Their conclusion for this result was that the flux pinning by the Gaussian distribution is controlled by large-angle tails of the distribution which enhances thermal creep rate. This experiment supports the theoretical prediction for splayed-columnar defects by Hwa *et al.*[28] Prozorov *et al.*[29] measured the irreversibility temperature (T_{irr}) for the parallel and crossed columnar defects in a YBCO single crystal with the onset of the third harmonic in the ac response. T_{irr} depends on the trapping angle, which is the angle between the external field and the defects, and is also the angle for vortices starting to be partially trapped by the columnar tracks. When the external field is aligned to the parallel columnar defects in the direction of the c axis, a dip or a slight downward shift is observed in T_{irr} for the parallel columnar defects (PCD's), but a peak is found in T_{irr} for the crossed columnar defects (CCD's). The following explanation is given for this result. A vortex captured by the PCD can nucleate a double kink which can easily slide out resulting in a displacement of a vortex on a neighboring column, and the resultant increase of the creep rate yields the dip in T_{irr}. Vortices for the crossed columnar defects, on the other hand, can depin only via nucleation of multiple half loops, of which the characteristic size depends upon current density. The formation of multiple half loops results in an additional barrier for vortex depinning, which even diverges at zero current. A comparison between parallel and crossed columnar defects for flux pinning was made by Schuster *et al.*[30] from magneto-optics experiments. The critical current density for the CCD's was up to a factor of 14 larger than for the PCD's in irradiated $DyBa_2Cu_3O_x$. In a $Bi_2Sr_2CaCu_2O_x$ (Bi-2212) single crystal, on the other hand, the ratio of the critical current of CCD's to PCD's was about 1.5, and is temperature independent in the range $5\ K < T < 80\ K$. Their conclusion was that flux motion in a Bi-2212 crystal proceeds by depinning of single pancake vortices, and the difference in J_c between CCD's and PCD's is due to the geometrical arrangement of the line defects. However, several authors reported a line nature of the vortices captured in columnar defects for even Bi-2212 crystals,[31–35] and the line nature of vortices in Bi-2212 is inconsistent with the result derived from magneto-optics mentioned just above.

In this paper, we described the parallel and crossed columnar defects, which were directed to +45° and ±45° from the c axis, respectively, in Bi-2212 tapes irradiated by 180 MeV Cu^{11+} ions. The irreversibility field (H_{irr}) is considerably enhanced by the introduction of PCD's and CCD's as compared to that prior to irradiation. In the angular dependence of H_{irr} at 55 K, the PCD's had a peak in the direction of the columnar defects and another peak was found for CCD's in the direction of the c axis, which is the mid-direction between the two subsystems of columnar defects. The peak for the CCD's indicates the breaks of line vortices. The trapping angle for vortices is estimated to be 48°, which is nearly the same value as that for YBCO. When the external field is applied in the ab plane, H_{irr} decreases exponentially with an increase of temperature for the three specimens; prior to irradiation, containing PCD's, and containing CCD's. This exponential decrease of H_{irr} is described in relation to the motion of kink pairs, vortices, and antivortices trapped in lattice defects. The temperature-field phase diagram obtained from H_{irr} for the PCD's showed three distinct temperature regimes, which are inferred to be due to the temperature dependence of the accommodation field B^* on the basis of the theory by Nelson and Vinokur.[18] The temperature dependence of H_{irr} for the CCD's, on the other hand, is a smoothly decreasing function with increase of temperature. This fact indicates the contribution of kinks with diverse activation energies for the flux motion of CCD's. From the comparison of J_c for three different orientations of the applied field, the pancake vortex model is confirmed to be adequate for PCD's and CCD's at 5 K, but above 30 K the orientation difference of J_c indicates the line nature of the vortices. The flux-flop phenomenon is discussed from J_c at low fields for the PCD's. A considerable enhancement of J_c for the CCD's is observed at high temperature and at high fields in the field dependence of J_c. J_c at 5 K for the CCD's is larger below 2 T, but is slightly smaller above 2 T than that prior to irradiation in the applied field parallel to the c axis. The smaller J_c above 2 T is ascribed to the irregular distribution of defect density for the CCD's.

II. EXPERIMENTAL PROCEDURES

The specimens used in this experiment were grain-oriented Bi-2212 tapes prepared by the doctor blade method.[36] The tapes were cut into $0.4\times 0.3\ cm^2$ shapes for irradiation. The thickness of the specimens was about 15 μm. They were irradiated with 180 MeV Cu^{11+} ions at room temperature using the tandem Van de Graaff accelerator at Japan Atomic Energy Research Institute. Irradiation was performed by two processes. In the first process, the surfaces and the c planes of the two specimens were inclined at an angle of 45° counterclockwise to the incident beams and both specimens were irradiated with a dose of $7.8\times 10^{10}\ Cu^+/cm^2$ at the same time. In the next, one of the specimens was placed at 45° clockwise to the beam direction, and both specimens were again irradiated to a dose of $5.8\times 10^{10}\ Cu^+/cm$. Therefore, the total fluence of both specimens was exactly the same. One of them had parallel columnar defects in the amount of $1.36\times 10^{11}\ Cu^+/cm^2$, which corresponded to a dose equivalent matching field $B_\phi = 2.8\ T$, in the direction 45° away from the c axis in clockwise rotation (this direction is defined as 135°, as shown in Fig. 1(a), for the angle between the direction of the defects and the ab plane). The other had crossed columnar defects with $B_\phi = 1.2\ T$ at 45° and 1.6 T at 135°, respectively.

All the measurements were performed using a Quantum Design model MPMS superconducting quantum interference device (SQUID), which allowed a rotation of the specimen relative to the applied magnetic field.

III. EXPERIMENTAL RESULTS AND DISCUSSION

A. Angular dependence of the irreversibility line

The angular dependence of the irreversibility field (H_{irr}) is shown in Fig. 1(b) for the three specimens; prior to irradiation, containing columnar defects, and containing crossed columnar defects, where θ is the angle between the applied

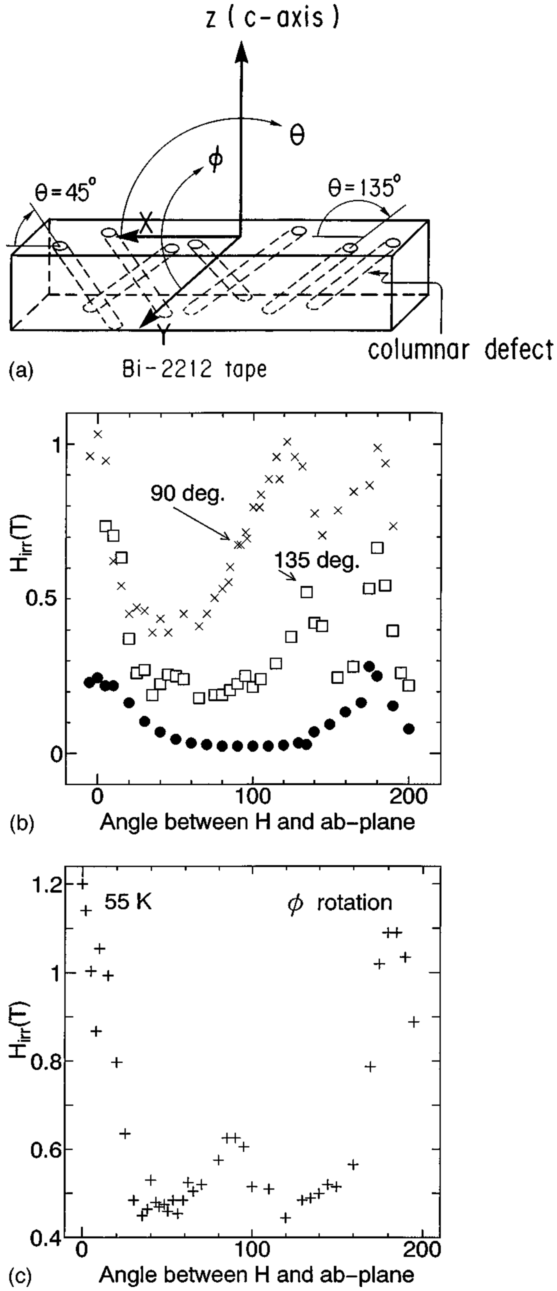

FIG. 1. (a) Definition of the angles for the angular dependence of irreversibility field (H_{irr}). θ: Angle in the xz plane between the external applied field and the ab plane of a Bi-2212 tape. The angle of $\theta=135°$ is the direction of columnar defects for PCD's. ϕ: Angle in the yz plane between the external applied field and the ab-plane. (b) Angular dependence of H_{irr} at 55 K for θ rotation. Solid circles: prior to irradiation. Squares: PCD's, crosses: CCD's. (c) Angular dependence of H_{irr} for CCD's for ϕ rotation.

field and the ab plane of the tape as depicted in Fig. 1(a). H_{irr} was estimated from the measurements of hysteresis loops and was defined as the field at the critical current density $J_c=1\times10^2$ A/cm^2. As already reported,[37] remarkable enhancement of H_{irr} by irradiation is observed around 55 K. For the specimen prior to irradiation, two maxima can be seen in Fig. 1(b) at 0° and 180°, which are caused by intrinsic pinning between CuO_2 layers. The angular dependence of H_{irr} can be written as

$$H_{irr}(T,\theta)=H_{irr}(T,\theta=90)/\varepsilon(\theta),$$

$$\varepsilon(\theta)=[\gamma^{-2}\cos^2\theta+\sin^2\theta]^{1/2}, \tag{1}$$

where γ^2 is the ratio of effective mass, m_c/m_{ab} for a single crystal, while it depends upon the average misalignment angle of grains in Bi-2212 tapes. By applying the above equation to the experimental curve, γ was estimated to be 10, which is almost the same value as that in (Bi, Pb)$_2$Sr$_2$Ca$_2$Cu$_3$O$_x$ (Bi-2223) tapes.[38,39]

For the parallel columnar defects, a peak is found in the direction of the defects 135° and H_{irr} is enhanced in all directions of the applied field. Further enhancement of H_{irr} is caused by CCD's. The peak at 125° deviates somewhat from the direction of the defects 135° and a bulge is observed at 90° (H parallel to the c axis) in the shoulder of the peak. The bulge is recognized as a peak by ϕ rotation [see Fig. 1(a)] as shown in Fig. 1(c). This peak is a salient feature of CCD's and evidence of the breaking of vortex lines, since such a peak cannot be expected for pancake vortices and also is not observed in PCD's.

A similar peak in the angular dependence of the irreversibility temperature was also found in a YBCO single crystal with CCD's in the direction of $\pm45°$ to the c axis by Prozorov *et al.*[29] They pointed out that the collective action of the CCD's led to enhancement of the pinning strength along the mid-direction between the two subsystems of CCD's. The irreversibility temperature was determined by the temperature-dependent trapping angle, which is the angle between the external field and the CCD, and also is the angle of vortices starting to be partially trapped by CCD's. The trapping angle in their experiments was 50°. From Fig. 1(c) the critical angle for trapping vortices in Bi-2212 is estimated to be 48°, since the full width of half maximum of the peak is about 20° and then the angle is given by cos(48) $=$cos(45)cos(20). Consequently, the trapping angle in Bi-2212 is nearly the same as in YBCO, which is derived from the equation $\tan(\theta_t)=[2\varepsilon_r/\varepsilon_1]^{1/2}$. Here, θ_t is the trapping angle and ε_r and ε_l are the potential energy of a columnar defect and the line tension, respectively. Not much difference is found in either ε_r or ε_l between Bi-2212 and YBCO.

Schuster *et al.*[30] showed from magneto-optics experiments in DyBa$_2$Cu$_3$O$_x$ that vortices are more strongly pinned by CCD's than by PCD's. The ratio of the critical current densities flowing in PCD's and CCD's increased with an increase of temperature from unity to about 6 for single kinks (depinning mode A in Fig. 1 in Ref. 30) and up to a factor 14 for kink pairs (depinning mode B in the same reference). In a Bi-2212 single crystal in their report, however, the ratio was temperature independent in the range from 5 to 80 K, which was attributed to an equal activation energy due to the pancake vortices. In our experiments in Figs. 1(b) and 1(c), the vortices show directional behavior in the angular dependence of H_{irr}. Hardy *et al.*[35] also reported that the crossover from isotropic to directional behavior of vortices was found at about 40 K in a Bi-2212 single crystal. The directional behavior of the critical current density for PCD's and CCD's will be described in Sec. III C.

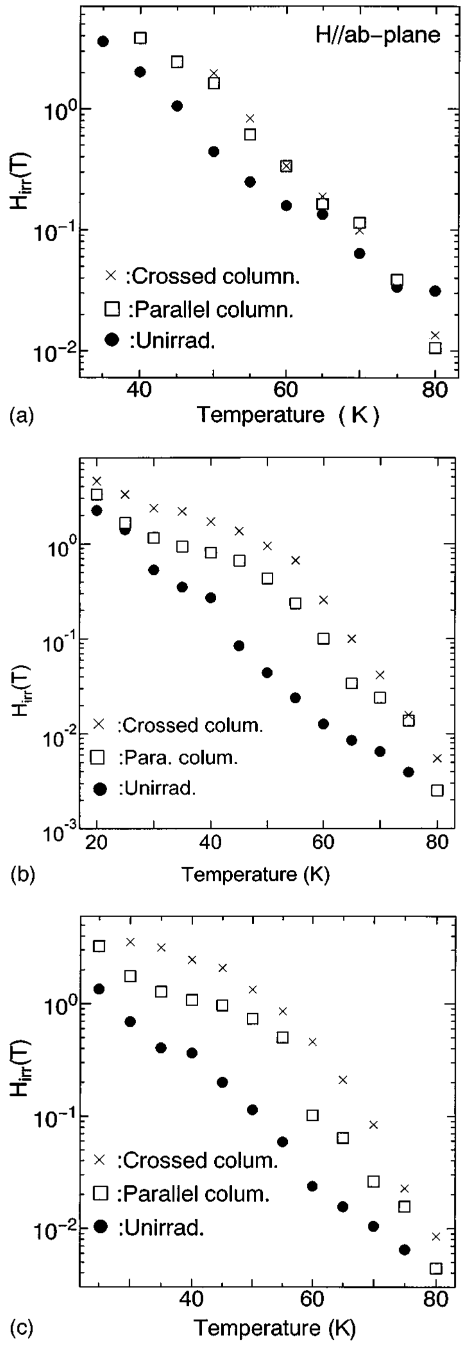

FIG. 2. Temperature dependence of H_{irr}. (a) The external field (H) parallel to the ab plane. (b) H parallel to the c axis. (c) The external field is applied to $\theta = 135°$ away from the ab plane. Solid circles: prior to irradiation, squares: PCD's, crosses: CCD's.

B. Temperature dependence of the irreversibility lines

The temperature dependence of H_{irr} is shown in Figs. 2(a)–2(c) for the field applied parallel to the ab plane, the c axis, and 135° (parallel to the columnar defects) away from the ab plane, respectively. Prior to irradiation, the temperature dependence of H_{irr} for the three directions of the applied field can be written as an exponential function $H_{irr}^{unirrad}(T,\theta) = A(\theta)\exp(-CT)$, where the fitting parameters of A and C are estimated to be 131 and -0.11 for H parallel to the ab plane, 18 and -0.11 for H parallel to the c axis, and 20 and -0.11 for 135°, respectively. These results are quite acceptable because C in the exponent in the function should be independent of the direction of the applied field as predicted by Eq. (1). The angular-dependent part appears only in $\varepsilon(\theta)$, and the ratio of $\varepsilon(0)/\varepsilon(90)$ is estimated to be 10 from the angular dependence of H_{irr} at 55 K as described in the previous section. The corresponding ratio derived from the A value in the above equation is 131/18~7, which is somewhat smaller, but the agreement of the two values is rather fair when the experimental tolerance is taken into account.

After irradiation and for the field applied parallel to the ab plane, H_{irr}'s for PCD's and CCD's show a similar exponential dependence to that prior to irradiation: for instance, $H_{irr} = 1.5\times 10^3 \exp(-0.14T)$ for PCD's. All of these H_{irr}'s should be interpreted as from the same origin. When the field is applied parallel to the CuO_2 layers, vortices are confined between the layers and the movement of the vortices across the layers is hindered by the strong intrinsic pinning. When kink pairs are formed across the layers by the help of grain boundaries in the tapes, vortices and antivortices formed from the kink pairs can move parallel to the layers. Such vortices and antivortices look similar to 2D vortices, and point defects will act as pinning centers against the movement of these 2D vortices. Consequently, the exponential temperature dependence of H_{irr} is due to pinning by point defects.

Next we will consider the temperature dependence of H_{irr}'s for PCD's and CCD's in a field applied parallel to the c axis and 135° away from the ab plane as shown in Figs. 2(b) and 2(c), respectively. These curves have quite different features compared with those prior to irradiation. Three distinct temperature regions are found in H_{irr} for PCD's in Fig. 2(c). (1) $T<30$ K, H_{irr} sharply decreases with an increase of temperature. (2) 35 K$<T<$55 K, a linear decrease of H_{irr}. (3) $T>60$ K, H_{irr} decreases exponentially with increasing temperature.

Zech *et al.*[24] proposed a B-T phase diagram for a Bi-2212 single crystal in the presence of columnar defects, led by the theory of Nelson and Vinokur.[18] Their conclusion is that the irreversibility line follows the accommodation field B^* separating the single-vortex strong pinning regime from the collective pinning regime. At low temperatures, where the radius of columnar defects c_0 is larger than the coherence length ξ_{ab} in the ab plane, B^* is equal to B_ϕ, where B_ϕ is the matching field. The characteristic temperature T_0 is defined by the relation $\sqrt{2}\xi_{ab}(T_0) = c_0$. Upon using the relation from mean-field theory $\xi_{ab}(T) = \xi_0(1-T/T_c)^{-1/2}$, T_0 is estimated from the following equation:

$$T_0/T_c = 1 - 2(\xi_0^2/c_0^2). \qquad (2)$$

The estimation by Zech *et al.* was $T_0 = 77$ K with values of $\xi_0 = 25$ Å and $c_0 = 35$ Å. From this result, the first kink in their phase diagram was attributed to T_0. However, T_0 depends very sensitively on the values of ξ_0 and c_0. ξ_0 covers a very wide range between 14.7 and 29.4 Å, calculated from the BCS coherence length ξ_{BCS} of 20–40 Å[1] by the relation $\xi_0 = 0.54\xi_{BCS}$. In addition, the radius of columnar defects depends significantly on the kinds and energies of irradiating ions, and also the chemical and local structures of the materials. The radii reported are distributed in the 25–63 Å range.[40] Consequently, T_0/T_c will be in a broad range between 0.28 and 0.89. In our experiment with irradiation by 180 MeV Cu^{11+} ions, the radius is 26 Å.[41] With this value and $\xi_0=15$ Å, T_0 is estimated to be 30 K, which value is in good agreement with the low-temperature break at 25 K in Fig. 2(c).

In the temperatures between 35 and 55 K, $H_{\rm irr}$ decreases linearly with an increase of temperature, which leads to the relation of $H_{\rm irr}(T)=-AT+B$, where A and B are the parameters determined from the experiments. From Fig. 2(c) these two values of A and B are estimated to be 3.7×10^{-2} and 2.6. According to the theory by Nelson and Vinokur,[18] the accommodation field B^* decreases linearly above the temperature T_0 up to the depinning temperature $T_{\rm dp}$. In this regime,

$$B^*(T)=B_\phi(c_0/2\xi_0)^2(1-T/T_c). \quad (3)$$

In Eq. (3), $A=B_\phi(c_0/2\xi_0)^2/T_c$ and $B=B_\phi(c_0/2\xi_0)^2$ are given. By using the values described above for B_ϕ and c_0 and ξ_0, A, and B are calculated to be 2.5×10^{-2} and 2.1, values which can be compared with those from the experiments mentioned just above.

Above 60 K, $H_{\rm irr}$ decreases exponentially with an increase of temperature. Following Nelson and Vinokur, the accommodation field B^* above the depinning temperature $T_{\rm dp}$, at which temperature a vortex segment wanders to an adjacent columnar by thermal energy, is

$$B^*(T)=[4\varepsilon_r\exp(-T/T_{\rm dp})/\varepsilon_0]B_\phi, \quad (4)$$

where ε_r and ε_0 are the potential energy of a columnar defect and the interaction energy, respectively, and $T_{\rm dp}$ is given by

$$T_{\rm dp}/T_c=[(c_0/4\xi_0)\ln\kappa/{\rm Gi}]/[1+(c_0/4\xi_0)\ln\kappa/{\rm Gi}]. \quad (5)$$

From κ (GL parameter)$=10^2$, Gi (Ginzburg number) $=10^{-1}$, and c_0 and ξ_0 described above, $T_{\rm dp}$ is obtained to be 63 K. The temperature starting the exponential decrease for $H_{\rm irr}$ of the PCD's shows 60 K. Zech *et al.*[24] reported $T_{\rm dp}=81$ K in a Bi-2212 single crystal and the lower value of $T_{\rm dp}=41$ K was obtained in a YBCO single crystal by Krusin-Elbaum *et al.*[42]

As can be seen in Figs. 2(b) and 2(c), $H_{\rm irr}$ for the CCD's are rather smooth functions of temperature without pronounced breaks. Many kinks or bends are formed in vortex lines by crossed columnar defects as is evident from the magneto-optics experiments by Schuster *et al.*[30] The flexibility of vortex lines in high-T_c superconductors originates from the small tilt modulus $C_{44}\sim(m_{ab}/m_z)\varepsilon_0\ln(\lambda_{ab}/\xi_{ab})$ due to the large effective mass ratio $(m_{ab}/m_z)^{1/2}$ of $\frac{1}{5}-\frac{1}{7}$ in YBCO and $\frac{1}{50}-\frac{1}{200}$ in Bi-2212.[1] Schuster *et al.*[30] reported from the experiments on a Bi-2212 single crystal that the ratio of the critical current density of CCD's to PCD's was 1.5 and temperature independent in the range $5\,{\rm K}<T<80\,{\rm K}$, and no difference was observed in the depinning modes A and B in their report. They concluded from this result that vortices in Bi-2212 were arrayed in the pancake structure. In our experiments the ratio of $H_{\rm irr}$ for the CCD's to that for PCD's is 1.5–3.0 and weakly temperature dependent as derived from Figs. 2(b) and 2(c). Further, as seen in Figs. 1(b) and 1(c), and as will also be described in the next section, vortices in the presence of PCD's and CCD's show directional character and cannot be explained by the pancake model. The smooth curves in $H_{\rm irr}$ for the CCD's as seen in Figs. 2(b) and 2(c) are presumably caused by the diverse activation energies due to the motion of the different types of kinks such as proposed by Schuster *et al.*[30]

C. Critical current density

The unidirectional property of J_c for PCD's and CCD's was measured with the applied field at the three different directions relative to the defects. The difference of J_c in the field applied at $\theta=45°$, 90°, and 135° is shown as a function of magnetic field in Figs. 3(a)–3(c) for the three specimens, prior to irradiation, containing PCD's, and containing CCD's, respectively. In these figures, J_c's were calculated from $J_c=(\Delta M/d)[1/\cos(90-\theta)]$, where ΔM was the difference of measured magnetization between the ascending and descending branches of the hysteresis loops and d is the average radius of the grain size (15 μm) in the tapes. The applied fields are multiplied by $\cos(90-\theta)$ since the irreversible magnetization is always pointed along the c-axis direction whatever the applied field direction. As shown in Fig. 3(a), a slight difference in J_c for the applied fields at $\theta=45°$ and 90° is observed in the specimen prior to irradiation. The difference will be ascribed to the mosaic structure of the crystallites (small orientation irregularity of grains) in the Bi-2212 tape. At 5 K, J_c is described by a power-law dependence on the applied field, but above 30 K, J_c decreases exponentially with the applied field. The power-law dependence of J_c is theoretically derived from 2D pancake vortices in the strong pinning regime, and the exponential decrease of J_c as generally observed in single crystals and high quality thin films is the same dependence as that for the intragranular pinning mechanism.[43] The crossover from a power law to an exponential decrease for J_c on the applied field is also observed in Bi-2223 tapes.[43] As seen in Figs. 3(b) and 3(c), J_c's at 5 K for PCD's and CCD's show a power-law dependence on the applied field and also orientation independence for the three directions of the applied field, which indicates the justification of 2D pancake vortices. In Fig. 3(b) for PCD's, the difference of J_c depending on the direction of the applied field is manifested above 30 K. The unidirectional property of vortices trapped in columnar defects is pointed out by Klein *et al.*[32] and also Hardy *et al.*[35] for Bi-2212 single crystals. They showed that the anisotropy due to the columnar defects depended on the applied field and temperature, and sharply decreased below 40 K.

For PCD's, J_c at $\theta=90°$ shows a similar field dependence to that at $\theta=45°$ (perpendicular direction to the defects). Although vortices at $\theta=90°$ will be partially trapped in PCD's, the energy difference of the vortex arrangement between 45° and 90° will be small. The definite configurations of vortices for the applied field perpendicular to the columnar defects are shown in Fig. 5 of Ref. 35. For CCD's as shown in Fig. 3(c), a difference in J_c for the two directions of the applied field of 45° and 135° is found above 30 K, which is caused by the difference of irradiation fluence for the two directions. The characteristic feature manifested in Fig. 3(c) is that J_c at 90° coincides with that at 135° (the direction of the larger number of the columnar defects),

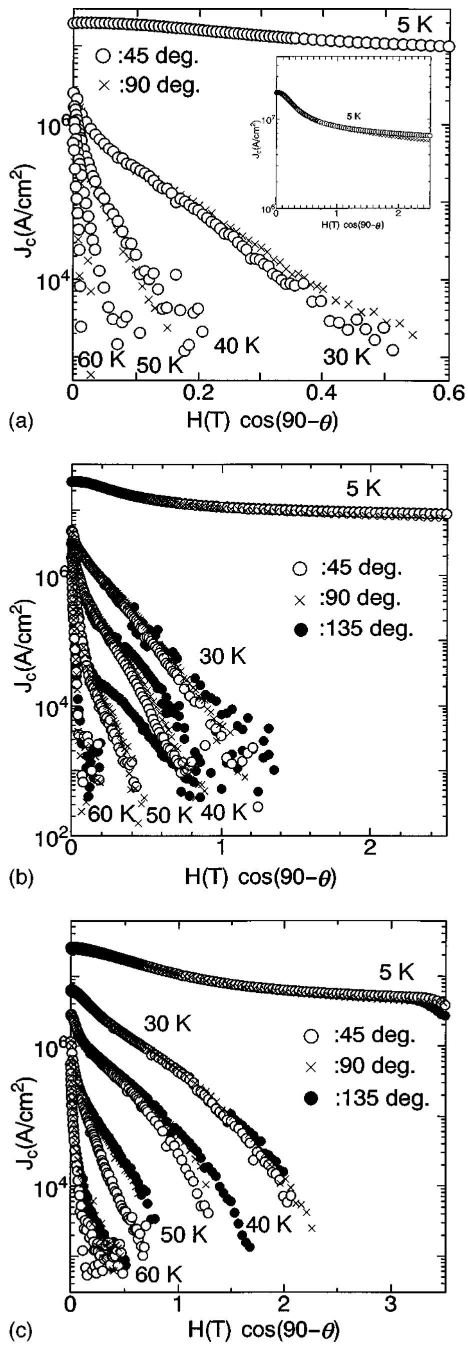

FIG. 3. Orientation dependence of J_c at several temperatures (labeled in the graph) for the three respective applied fields $\theta = 45°$, 90°, and 135°. x axis: $H \cos(90-\theta)$. y axis: J_c calculated from $[\Delta M(\text{measured magnetization})/d]\,[1/\cos(90-\theta)]$. (a) Prior to irradiation. Solid circles: $\theta = 45°$, open circles: $\theta = 90°$. (b) For PCD's. Open circles: $\theta = 45°$, crosses: $\theta = 90°$, solid circles: $\theta = 135°$. J_c's for 90° shows nearly the same value to those for 45° (perpendicular to PCD's). (c) For CCD's. J_c's for 90° mostly coincide with those for 135° (the direction of the larger amount of columnar defects).

which should be compared with the result of 90° configuration for PCD's mentioned just above. The vortices at 90° for CCD's will be arranged in zigzag lines trapped in the columnar defects with directions perpendicular to each other, as is evident from the peak in Fig. 1(c). The stability of the zigzag vortices with respect to thermal energy and magnetic field is presumably the same as that of the straight line configuration of vortices at the field along columnar defects as inferred from Fig. 3(c).

As is evident from J_c at 50 K in Fig. 3(b), J_c's for both 45° and 135° coincide with each other at low fields. This result has been ascribed to a flux-flop phenomenon by Klein *et al.*[44] Below a crossover field, the vortices of the configuration for the applied field perpendicular to the columnar defects flop toward the direction of the defects, and thereby the two vortex states for the parallel and perpendicular to the defects become identical. Hardy *et al.*[35] proposed a formula for the crossover field, where the flux flop takes place, from the free energy calculation:

$$H_{\text{cross}} = \pi\sqrt{2}(1+n)\varepsilon_0(T)[\alpha_c - \alpha_p(T)]/\phi_0. \qquad (6)$$

Here, n is the demagnetization factor, $\varepsilon_0 = [\phi_0/4\pi\lambda_{ab}(T)]^2$, $\alpha_p(T) = \ln[\xi_{ab}(T)/d]$, and $\alpha_c = 0.5$. The temperature dependence of H_{cross} will be mostly governed by $\lambda_{ab}(T)$ because ξ_{ab} is in the logarithmic term. Smaller H_{cross} values are predicted at higher temperatures, which explains the experimental results by Klein *et al.*[44] and by us, mentioned just above. However, the absolute value, 10 G at 50 K, of H_{cross} estimated seems to be too small compared with 1000 G in our experiment, although the flux flop occurs gradually as a function of the magnetic field and it is difficult to point out a specific field, as already reported by Klein *et al.*[44]

The field dependence of the critical current density is shown in Figs. 4(a)–4(c) for the three respective specimens prior to irradiation, containing PCD's, and containing CCD's in the field applied in the three different directions and at the three different temperatures, respectively. The enhancement of J_c for CCD's is remarkable at 30 K, and even at 60 K, J_c for CCD's increases noticeably, as seen in the inset of Fig. 4(a). This result indicates that the enhancement of J_c for CCD's is significant at high temperatures.

At 5 K, as seen in the inset of Fig. 4(b), J_c for CCD's shows the largest value among the three specimens in fields between 0.3 and 1 T, but above 1 T it becomes smaller than that for PCD's, and above 1.8 T it is even smaller than that prior to irradiation. The density of the defects is exactly the same for both PCD's and CCD's, and the only difference can be deduced from the distribution of the defects. Intuitively judging from the parallel beam irradiation, PCD's will be distributed homogeneously, but CCD's will be distributed irregularly because the columnar defects cross each other.

In order to trap vortices into defects, the following condition has to be satisfied: (energy gain by the trapping)$>$(the increase of interaction energy among vortices by the trapping)$+$(elastic distortion energy of vortex lattice by defects). The interaction energy between two vortices is given by $(\phi_0^2/8\pi\lambda^2)K_0(r/\lambda)$, where $K_0(r/\lambda)$ is the zeroth order Hankel function and r is the distance between two vortices.[45] This equation can be approximated to $(\phi_0^2/8\pi\lambda^2)[\ln \lambda/r + 0.12]$ for $r<\lambda$. The approximate form of the elastic distortion energy is $C_{66}d^2 = (\varepsilon_0/4B_\phi)B$, where C_{66} is the local elastic modulus, d the distance between the vortices, and B is the induction field.[18] The interaction energy requires an excess energy for a shorter separation of defects, and the elastic distortion energy increases with an increase of the field

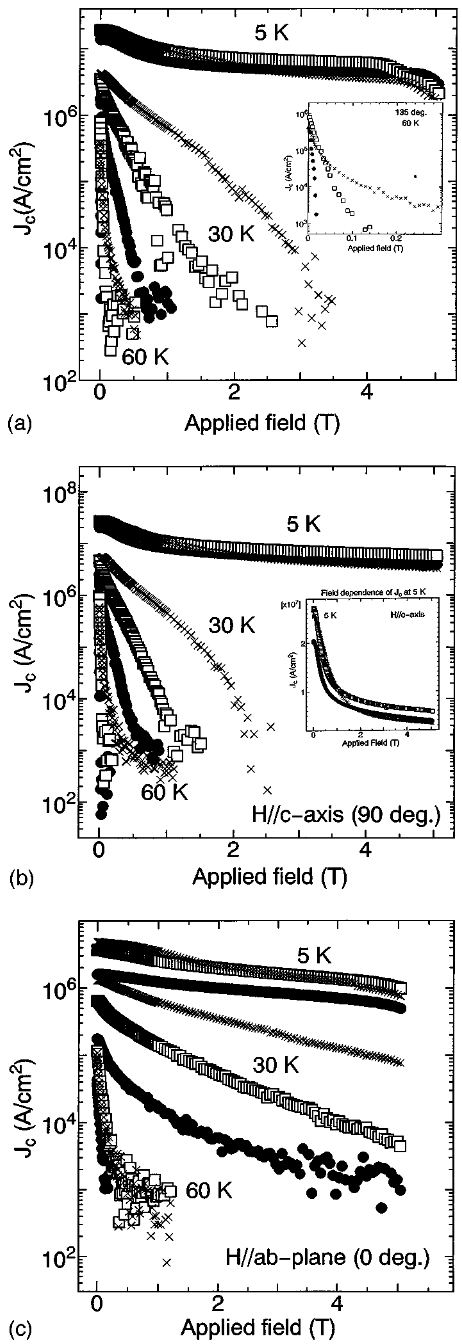

FIG. 4. Field dependence of J_c at several temperatures for the three specimens, prior to irradiation, containing PCD's and containing CCD's. (a) The external field is applied to 135° away from the *ab* plane (parallel to the direction of the columnar defects of PCD's). (b) *H* parallel to the *c* axis. (c) *H* parallel to the *ab* plane. Solid circles: prior to irradiation, squares: PCD's, and crosses: CCD's.

strength. The irregularity of the distribution of defect density yields a shorter separation between the vortices trapped in the defects and an increase of the elastic distortion energy at high fields. Tachiki and Takahashi[46] calculated the repulsive force between two vortices containing a columnar defect. When a vortex lies in close vicinity of the surface outside a columnar defect, the repulsive force acting on the vortex by the other vortex is larger than that in the absence of the defect. When the vortex enters the columnar defect, however, the force is drastically weakened. These considerations will follow the conclusion that the elastic distortion energy at high fields will overcome the energy gain for trapping 2D pancake vortices into the defects because of low binding energy. Further, for vortices outside defects because of the latter's irregular distribution, if the vortices are not trapped, they will reside in an unstable configuration.

J_c for CCD's shows almost the same value as that for PCD's above 1.8 T at 10 K and becomes larger above 20 K in all fields applied. This result may be relevant to the growth of a unidirectional property from the pancake vortices with an increase of temperature.

In the field parallel to the *ab* plane, J_c prior to irradiation decreases exponentially at 5 K in fields between 0.5 and 4 T as shown in Fig. 4(c). In this direction of the applied field, J_c governed by the intrinsic pinning is theoretically given by the formula $J_c \propto (1-B/H_{c2})J_{\mathrm{dp}}$,[46,47] where J_{dp} is the depairing current density. Since $B/H_{c2} \ll 1$ for experimentally accessible applied fields, J_c is almost independent of the field. The experiments on single crystals and high quality thin films support the above theory of the independence of J_c on the field strength.[13,48–50] The exponential decrease of J_c in Bi-2212 tapes with increasing applied field may be caused by another phenomenon, probably due to kink motion occurring at small angle grain boundaries or lattice defects, such as oxygen deficiency. The enhancement of J_c for PCD's indicates the relevance of kinks formed at the lattice defects induced by irradiation. The increase of J_c at low fields below 1 T is significant for PCD's. The exponentially decreasing region for PCD's extends between 1 and 4 T, somewhat narrower than that prior to irradiation. An exponential decrease of J_c with increasing field is shown theoretically for 2D pancake vortices in the weak pinning regime in Bi-2223 tapes in the form $J_c(B) \propto \exp(-\pi B/2n\phi_0)$ for the high pinning center density, where n is the area density of pinning centers.[51] The corresponding form prior to irradiation and for PCD's is $Jc(B) \propto \exp(-0.2B)$. Further enhancement of J_c is observed for CCD's at low fields below 3 T. The exponential region in J_c is narrower and is placed between 3 and 4 T. The enhancement at low field and the narrowness of the exponential region in J_c indicate the increase of the single-vortex pinning regime. The irregular distribution of defect density, as mentioned previously, will increase the strong and single-vortex pinning regime.

IV. SUMMARY

The same number of parallel and crossed columnar defects were introduced into Bi-2212 tapes by bombardment of 180 MeV Cu^{11+} ions. The angular dependence of the irreversibility field (H_{irr}) at 55 K was obtained from the measurements of hysteresis loops for the three specimens, prior to irradiation, containing PCD's, and containing CCD's. The largest enhancement of H_{irr} was found in the specimen with CCD's. A peak in the angular dependence of H_{irr} for PCD's was observed in the direction of the columnar defects, and a distinct feature for CCD's was found in a peak along the mid-direction between the two subsystems of CCD's. The trapping angle, where vortices start to be partially trapped by CCD's, was estimated to be 48°, which is nearly the same as that for YBCO.

When the external field was applied parallel to the ab plane, H_{irr}'s for the three specimens decreased exponentially with an increase of temperature. This temperature dependence was accounted for by the motion of vortices and antivortices trapped at lattice defects, where the vortices and antivortices were formed from the kinks of Josephson vortices at the points across the CuO_2 planes. Three distinct temperature regimes were found in the temperature dependence of H_{irr} for PCD's in the field applied in the direction of the columnar defects: (1) $T<30$ K, (2) 35 K$<T<$55 K, and (3) $T>60$ K. The characteristic temperature T_0, where the radius of the columnar defect matches the coherence length, was estimated to be 30 K. Above T_0, the H_{irr} decreased linearly with an increase of temperature, which agreed with the temperature dependence of the accommodation field as predicted theoretically. The depinning temperature T_{dp}, where the vortices trapped in the columnar defects start to wander to adjacent columnar defects by thermal energy, was estimated to be 60 K. Above T_{dp} the exponential decrease of H_{irr} was observed with the increase of temperature. For CCD's, a rather smooth curve, which is due to kinks with diverse activation energies, was observed in the temperature dependence of H_{irr}.

The directional properties of J_c for PCD's and CCD's were measured for several temperatures in applied field in the directions of $\theta=45°$, 90°, and 135°, respectively. At 5 K, the field dependence of J_c for PCD's and CCD's coincided in the three directions and consequently the isotropic 2D pancake model is appropriate. The directional dependence of J_c appeared above 30 K. The field dependence of J_c for PCD's at $\theta=90°$ (H parallel to the c axis) was nearly the same as that at $\theta=45°$ (perpendicular to columnar defects), but for CCD's J_c for $\theta=90°$ coincided with J_c at 135° (the direction of the larger number of columnar defects) for temperatures between 30 and 50 K.

The field dependence of J_c was compared for the three specimens. The enhancement of J_c for CCD's was substantial at high fields and at high temperatures. When the external field was applied parallel to the c axis, J_c for CCD's was the largest among the three specimens below 1 T, but above 1.8 T it was slightly smaller than that of the specimen prior to irradiation. Since the pancake vortex model was plausible at 5 K for Bi-2212 tapes, the irregular distribution of defect density for CCD's was considered to hinder stable pinning for vortices, and to be responsible for the smaller J_c at high fields.

When the external field was applied parallel to the ab plane, J_c for the specimen prior to irradiation decreased exponentially with an increase of the field, which was different from the result of Bi-2212 single crystals and also from the theoretical prediction. In Bi-2212 tapes, the motion of kinks caused at the points across small angle grain boundaries will govern the behavior of J_c.

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