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Columnar defects in heavy-ion-irradiated $Bi_2Sr_2CaCu_2O_{8+\delta}$ single crystals: new phase transition in vortices

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Abstract

To improve the superconducting properties, columnar defects have been introduced into $Bi_2Sr_2CaCu_2O_{8+\delta}$ single crystals by heavy-ion irradiation. It has been well known that an irreversibility is raised towards higher temperatures and higher magnetic fields by the columnar defects. Recently, by the measurements of Josephson plasma resonance, we have found the new phase boundary in the reversibility region close to the irreversibility line at the magnetic field around 1/3 of the matching field. The Monte Carlo simulations show this phase boundary in both irreversibility and reversibility region irrelevant to temperature, at which vortices transform suddenly a line-like structure from a liquid state in the reversible region, and into a decoupling state in the irreversibility region, with increasing magnetic field. In the irreversibility region, this boundary has been actually confirmed as a peak effect by DC magnetization measurements. Therefore, it is concluded that the introduction of the columnar defects by the heavy-ion irradiation causes not only an improvement of the superconducting properties, but also invokes a new physics in vortex matter.

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Keywords: Heavy-ion irradiation; High T_c superconductors; Bi(2 2 1 2) single crystal; Columnar defects; Josephson plasma resonance; DC magnetization

1. Introduction

High-temperature superconductors (HTS) have layered structures consisting of super-conducting layers of the Cu–O planes and the non-superconducting ones. Between the layers, a weak Josephson coupling occurs through the non-superconducting ones. This two-dimensional character of the layer-structure in HTS causes some peculiar phenomena, for example, the characteristic vortex states [1]. For the application of HTS, critical current density is an important factor. In HTS, a finite critical current density can be obtained only in the irreversibility region. In the reversibility region, there exists no critical current. Furthermore, the critical current density of the materials becomes larger than that of the conventional metallic superconductors only at lower temperatures, when a magnetic field is applied perpendicular to the layers. Schematic phase diagrams of

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$Bi_2Sr_2CaCu_2O_{8+\delta}$ Bi(2 2 1 2) single crystals are shown in Fig. 1(a) without columnar defects and Fig. 1(b) with columnar defects, respectively, in the magnetic field parallel to the *c*-axis. It is well understood from Fig. 1(a) that Bi(2 2 1 2) has a variety of magnetic phases in the vortex states. The irreversibility line rises up steeply at lower temperatures. When the temperature becomes higher, however, the line lies at lower magnetic fields. So, the efforts to raise the line towards higher temperatures and higher magnetic fields have been made by introducing pinning centers such as impurities, twinning and crystal defects. Columnar defects are one of the candidates for them, by irradiating heavy ions into HTS [2,3]. Fig. 1(b) shows the enhancement of the line, schematically. It is seen that the line raises up to around the matching field B_ϕ towards higher temperatures. Here $B_\phi = \Phi_0 n_{cd}$ is the matching field of the vortices to the columnar defects with the density of n_{cd} and Φ_0 is the flux quantum. This irreversibility region consists of the glassy phase of vortices at lower temperatures, which are so called as a Bose-glass phase [4]. This phase was predicted to melt as a second-order phase transition. This phase has also been studied experimentally. The vortices are confined into the defects, because of the large pinning potential energy of about 300–800 K [5]. In the reversibility region, so called a vortex liquid (VL) phase, the effect of the columnar defects in magnetization has been studied intensively [5–7]. The magnetization curves show a minimum at B_ϕ. Theoretical analysis of the magnetization curves has been made by Bulaevskii et al. [7]. Nevertheless, there is some discrepancy between the theory and experiments, and the nature of VL has still been unclear.

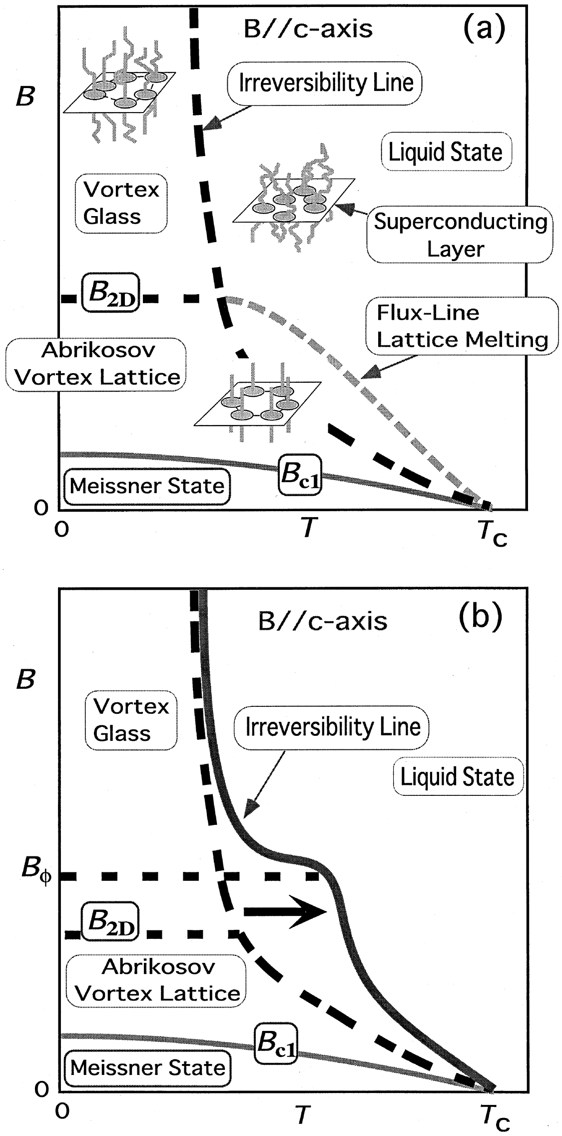


Fig. 1. Schematic illustration of magnetic phase diagram on $Bi_2Sr_2CaCu_2O_{8+\delta}$ single crystal without (a) and with columnar defects (b), when the magnetic field (*B*) is applied along the *c*-axis as a function of temperature (*T*). The irreversibility line (solid line) is raised towards higher temperature, or, higher magnetic field. The columnar defects are made along the *c*-axis.

In this paper, we report a new phase boundary in both irreversibility and reversibility region of Bi(2 2 1 2) with columnar defects. Recent findings of the new phase boundary in Bi(2 2 1 2) single crystals with columnar defects have put forward the understanding of the VL states in HTS, which was for the first time observed by Josephson plasma resonance (JPR) measurements [8,9]. There can be clearly seen a phase boundary to distinguish the VL phase between coupling and decoupling of the vortex lines around $B_\phi/3$. Furthermore, by the Monte Carlo simulations, a distinguished phase boundary could be found at the characteristic magnetic field around $B_\phi/3$, independent to temperature [10]. The boundary exists both in the irreversibility and reversibility region. The boundary was also confirmed by DC magnetization measurements as a peak effect and maximum of the magnetization curves in the irreversibility [11] and reversibility region [12], respectively. It will be shown that, by the presence of the columnar defects, the vortex states in HTS changes dramatically and a new phase transition is proposed in the physics of vortex matter.

2. Experimental

Single crystals of Bi(2212) have been grown by the traveling-solvent floating zone method [13,14]. The grown single crystals with small rectangular pieces from two production sources of Refs. [13,14] were irradiated with the heavy-ion of 3.1 GeV Bi ions at RIKEN and 5.8 GeV Pb ions at GANIL in Caen, respectively. The former

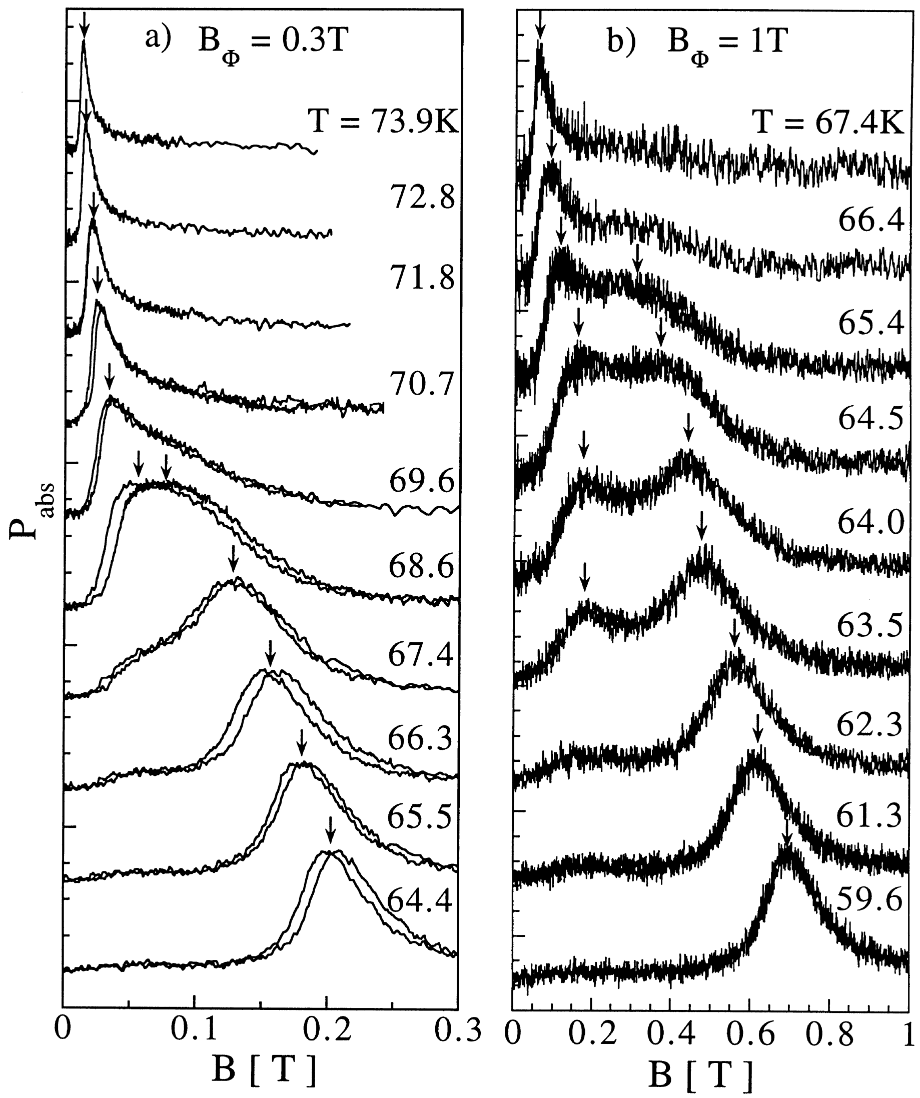


Fig. 2. Josephson plasma resonance at 45 GHz of (a) $B_\phi = 0.3$ T and (b) 1 T, as a function of magnetic field B at various temperatures. The arrows indicate the resonance peaks. Splitting of the resonance peak can be seen clearly in a narrow range of temperature.

was used for DC magnetization measurement [11] and the latter for Josephson Plasma resonance [8,9] and DC magnetization measurement [12]. Actual density of the columnar defects was examined by transmission electron microscope. Details of the measurements are described in the references.

3. Results and discussions

3.1. Josephson plasma resonance

Fig. 2 shows the results of the JPR of the sample: (a) $B_\phi = 0.3$ T and (b) 1 T, irradiated with Pb-ions. The intensity of the microwave absorption with 45 GHz in the samples is plotted as a function of magnetic field at characteristic temperatures. There appears a double peak in the spectrum in a narrow range of temperature. Without the columnar defects, only a single peak can be observed, and the resonant magnetic field B_p has a temperature dependency of inversely proportional to temperature in the VL phase [15]. This is well understood by the Koshelev's theory [16], based on the high temperature expansion. The lower peak B_{LF} in magnetic field has a similar temperature dependence, as explained in the theory. So, it is suggested that the vortex state at higher temperatures above the irreversibility line is in a VL phase at lower magnetic fields. However, the higher peak B_{HF} does not have such a temperature dependency. These two peaks show a quite different feature in angular dependency of the resonant field.

Fig. 3 shows the angular dependence of the resonant fields B_{LF} and B_{HF}. In Fig. 3(a), although the higher peak B_{HF} shows no angular dependence, the lower peak B_{LF} changes significantly. The resonance field B_{LF} is well scaled by the field component $B_{LF}\cos\theta$ to the c-axis at lower angles, as shown in Fig. 3(b). This indicates that the vortices are decoupled in this magnetic field and temperature range [17]. Therefore, it is strongly suggested that the vortices are in a coupled state at higher magnetic fields, confined into the columnar defects. With increasing magnetic field at the fixed temperature above the irreversibility line, the vortex state becomes a coupled VL from decoupling VL. This is schematically drawn in the magnetic phase diagram of Fig. 4. The solid line indicates the coupling line inferred from the JPR measurements. With increasing a magentic field above B_ϕ, the influence of the columnar defects becomes negligible and the decoupled liquid phase appears again. From the results of JPR, the coupling line is suggested in the VL phase.

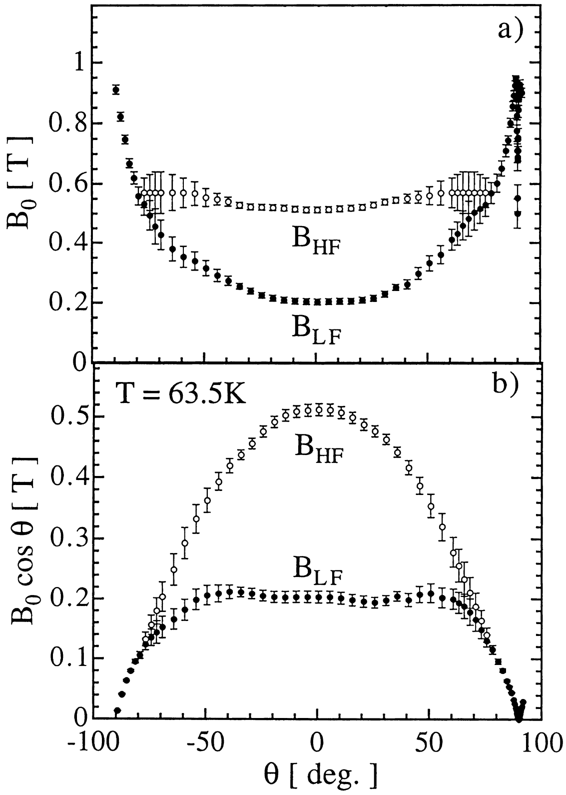


Fig. 3. Angular dependence of the higher (B_{HF} open circles) and the lower (B_{LF} filled circles) resonance fields at 63.5 K (a). θ is the angle between the c-axis and the magnetic fields. (b) shows the same data as a function of the field parallel to the c-axis.

3.2. Monte Carlo simulations

Fig. 5 shows the results of the Monte Carlo simulation [10], based on the Lawrence–Doniach model [18]. Fig. 5(a) shows the determination of the Bose-glass melting transition temperature T_{BG},

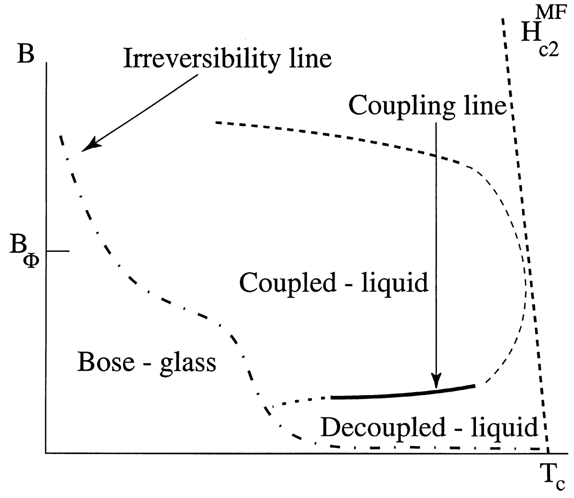


Fig. 4. Magnetic phase diagram are drawn schematically inferred from the results obtained by the Josephson plasma resonance.

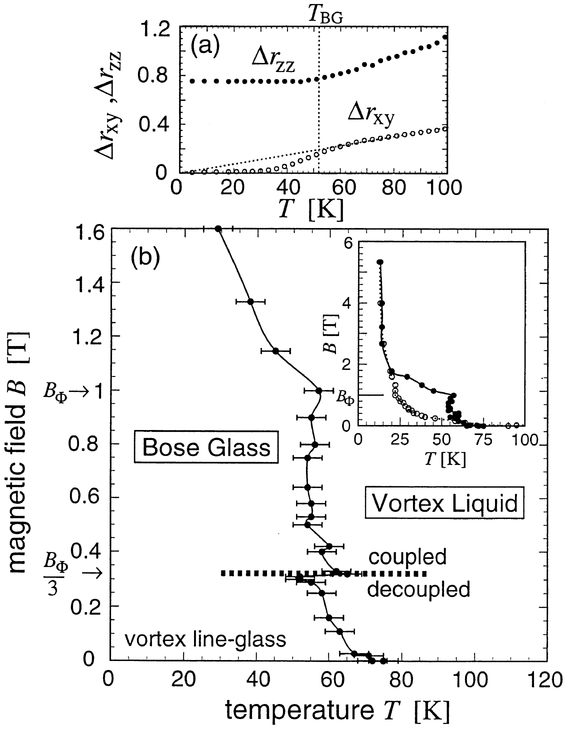


Fig. 5. (a) Temperature dependence of the mean-square deviation of each pancake vortex Δ_{xy} and Δ_{zz} for taking into account in-plane and out-of-plane fluctuations, respectively, at 0.32 T. T_{BG} shows the point where Δ_{xy} and Δ_{zz} change. (b) Magnetic phase diagram obtained from the simulations. The solid curve (solid circles) represents the Bose glass melting. The bold-dotted line shows a coupling transition line at $B \sim B_\phi/3$. Inset shows the over-all profile of the phase diagram. The broken line shows the melting line for a defect free case.

calculating the mean-square deviation of each pancake vortex from the equilibrium position. Detailed calculations are described in Ref. [10]. Fig. 5(b) shows the Bose-glass transition line in a magnetic phase diagram, obtained from the simulations with $B_\phi = 1$ T. Inset of the figure, the melting line without defects are added as a open circles, which was determined by the disappearance of the Abrikosov triangular vortex lattice. To compare these two melting lines, columnar defects are effective for the pinning significantly, and the vortices are well pinned up to the B_ϕ. The melting line is shifted towards higher temperatures below B_ϕ. However, above B_ϕ, two lines approach suddenly to the line without the defects with decreasing a temperature.

Well below the B_ϕ, there is a sharp jump in the Bose-glass melting line around $B_\phi/3$, which is indicated as a bold-dotted lines. At this characteristic magnetic field, the VL phase shows a coupling transition from the decoupled VL with increasing a magnetic field. In the Bose-glass phase, however, a decoupling transition appears from the vortex-line glass at $B_\phi/3$. This can be easily understood in Fig. 6.

Fig. 6 shows (a) the trapping rate p_{trap} of the vortices to the columnar defects. The configuration of vortices is also shown in Fig. 6(b) for $B = 0.015$ T ($B \ll B_\phi/3$) at $T = 4.5$ K, (c) for $B = 0.25$ T ($B < B_\phi/3$) at $T = 63$ K and (d) for $B = 0.34$ T ($> B_\phi/3$) at $T = 63$ K. In Fig. 6(a), p_{trap} is close to 1 at lower temperatures and lower magnetic field. In this case, the vortex configuration corresponds to Fig. 6(b), which shows that the vortices are pinned in each single column, almost independently. As the temperature or the magnetic field increases, p_{trap} decreases because the vortex–vortex interactions and the thermal fluctuations are influenced. It seems that the vortices tend to become decoupled pancakes. Nevertheless, at the characteristic magnetic field of $B_\phi/3$, the trapping rate jumps almost discontinuously. Although the

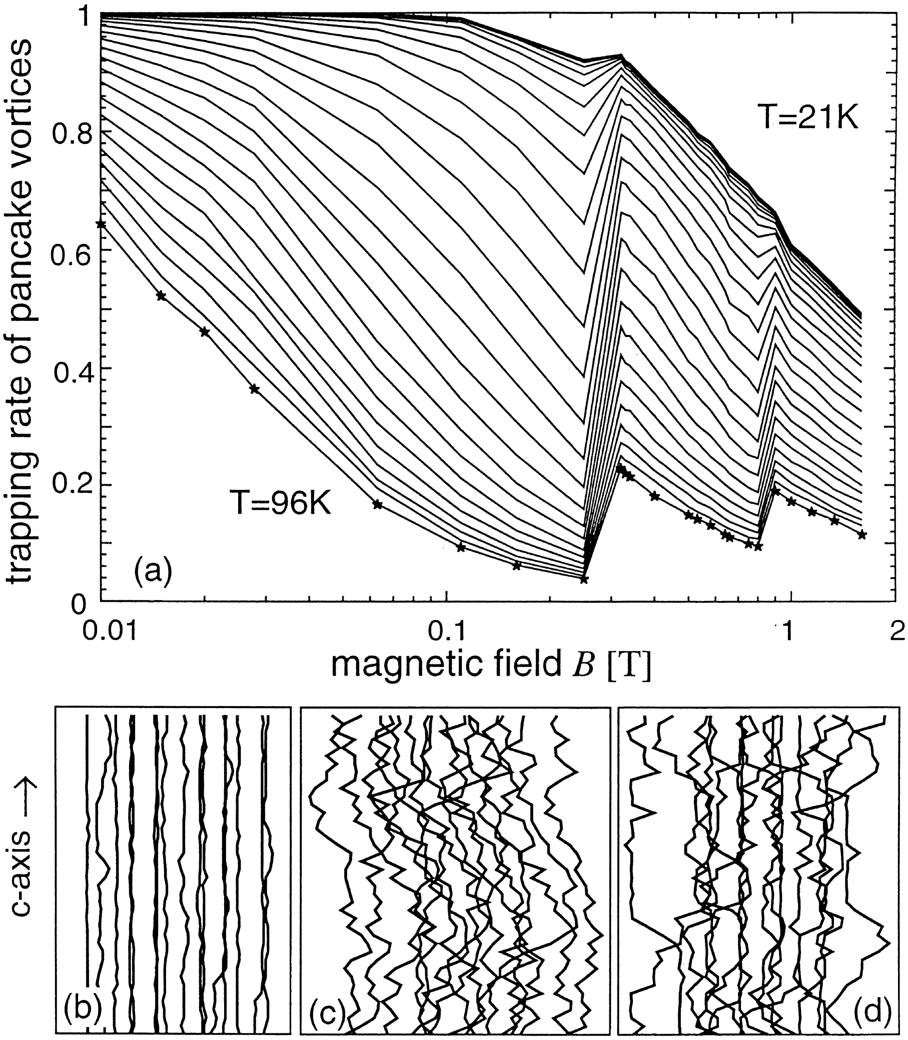


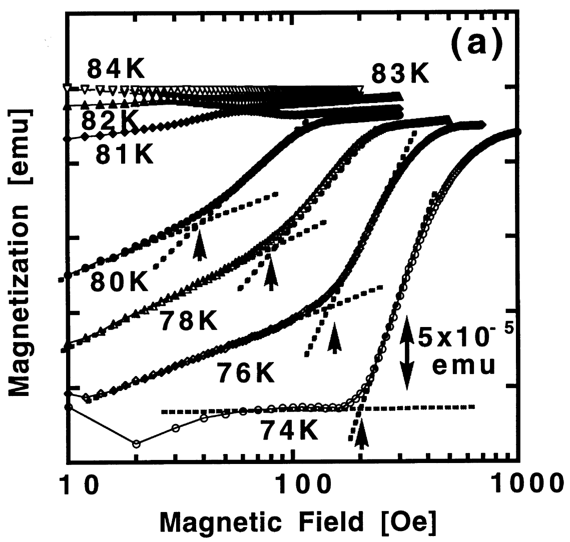
Fig. 6. Upper panel: (a) Trapping rate p_{trap} of pancake vortices within the columnar defects as a function B at the temperature from 21 to 96 K. The curves differ by temperature intervals of 3 K. Lower panel: indicate vortex configurations along the c-axis; (b) for $B = 0.015$ T at $T = 4.5$ K, (c) for $B = 0.25$ T ($B \ll B_{\phi}/3$) at $T = 63$ K and (d) for $B = 0.34$ T ($>B_{\phi}/3$) at $T = 63$ K.

configuration looks like a liquid (Fig. 6(c)) just below the $B_{\phi}/3$ at 63 K, it becomes line-like vortices (Fig. 6(d)). As the jump happens with increasing a magnetic field at a fixed temperature and its width becomes larger with increasing a temperature, this discontinuity is a field-driven transition and is relevant to the competition between the vortex–vortex interaction and the pinning potential. In contrast with the VL phase, at the temperatures below T_{BG}, the vortices tend to become the decoupled Bose-glass state. This predicts a peak effect in the magnetization curves, because the decoupled panckes can easily move to be pinned. On the characteristic magnetic field $B_{\phi}/3$, one possibility is the matching effect. It is easily understood when the defects are distributed regularly, but, in the random distribution, it is still unclear why the matching effect occurs.

3.3. DC magnetization

From the prediction of the Monte Carlo simulations, DC magnetization measurements have been performed. Fig. 7 shows the DC magnetization curves at various temperatures as a function of magnetic fields in a logarithmic scale. The magnetic field was applied parallel to the c-axis. In Fig. 7(a), a dip structure (here, the dip is called as a second peak) appears from 80 K and is clearly seen at 74 K, which is indicated by arrows. At lower temperatures, the second peak becomes more pronounced at around 400 Oe (not shown in the figure). Increasing the magnetic field further, the third peak is observed from 72 K, which is shown in Fig. 7(b). The peak exists almost independent to temperature at a constant magnetic field around 2.2 kOe.

Fig. 8 shows a magnetic phase diagram of the Bi(2 2 1 2) with columnar defects, obtained from the DC magnetization measurements. In the figure, irreversibility lines obtained from the M–H curves are drawn for the sample with columnar defects (after irradiation), and also for the pristine one (before irradiation). Due to the columnar defects, the irreversibility line is enhanced enormously in the magnetic fields below B_ϕ (0.62 T).



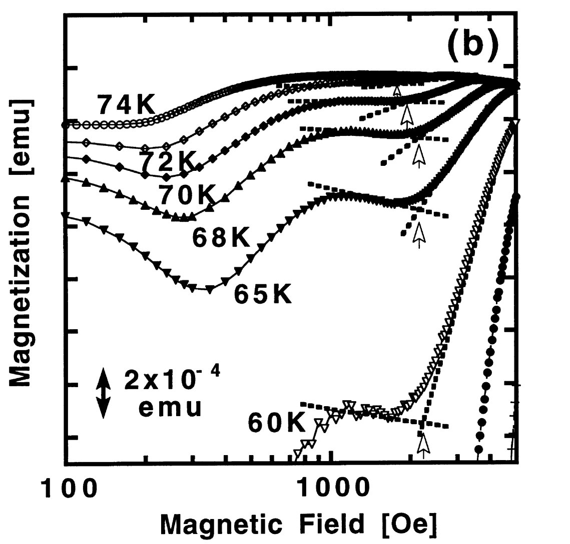


Fig. 7. DC magnetization curves of $Bi_2Sr_2CaCu_2O_{8+\delta}$ single crystal with columnar defects as a function of temperature; (a) from 84 to 74 K and (b) from 74 to 50 K in a logarithmic scale of magnetic fields. In the figures, only the results are shown for the increment of magnetic fields parallel to the c-axis to be seen clearly. Arrows indicate the development of the second peak (a) and the third peak (b).

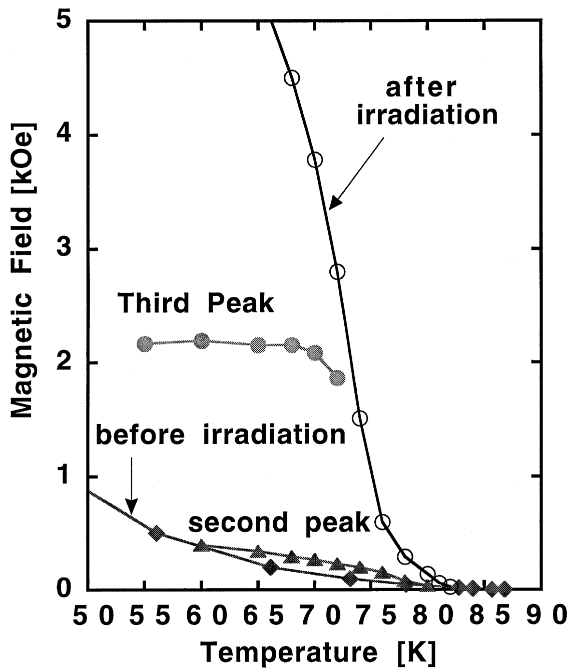


Fig. 8. Magnetic phase diagram of single crystal $Bi_2Sr_2CaCu_2O_{8+\delta}$ with and without the columnar defects in the vicinity of the characteristic magnetic field $B_\phi/3$.

The line rises at 75 K, which is a relatively higher temperature compared to that caused by Pb-irradiation. The difference between them is the radius of the columnar defects. This may suggest that thermal fluctuation is reduced by the deep potential well of the columnar defects produced by Bi-ion.

The second peak exists just above the irreversibility line of the pristine sample. The peak coincides well to the first-order melting line of the flux-line lattice at least above 55 K. In the presence of the columnar defects, the melting line exists as a peak effect line. At lower fields, vortices form a line-like structure pinned in the columnar defects, but with increasing magnetic field, the line decouples into pancake vortices because two dimensionality of the pristine sample still remains.

The third peak in the irreversibility region has been found for the first time in this measurement. This peak is almost constant at 2.2 kOe, independent of temperature. The magnetic field is close to the value of $B_\phi/3$, which was predicted by the Monte Carlo simulations. So, at the third peak line, vortices become a decoupled state. As some part of the vortices exist between the defects below the line, the pancake vortices can easily move and can be pinned at the defects, which is considered to cause the third peak.

In the reversibility region, although the JPR measurements and the simulations imply the sharp transition at $B_\phi/3$, a clear jump could not be observed in the DC magnetization. The magnetization measurements using a SQUID detect a macroscopic signal, which sometimes includes non-uniformity of the magnetic field. Microscopic measurements will be needed to confirm the clear jump by using a micro-Hall probe.

4. Conclusion

In summary, we have found a new phase transition in the VL phase by the JPR measurements on Bi(2 2 1 2) single crystal with columnar defects irradiated by heavy-ions. The transition is also confirmed by the Monte Carlo simulations, not only in the VL phase, but also in the Bose-glass phase at the characteristic magnetic field of $B_\phi/3$. In the Bose-glass phase, the transition appears as a peak effect, which was confirmed by the DC magnetization measurements. It should be noted that the transition has been confirmd in two kinds of samples produced at different Laboratories. Therefore, it is suggested that this new transition is a universal property, which means that, by the introduction of the columnar defects into Bi(2 2 1 2) single crystal, new phenomena could be observed in the physics of vortex matter.

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References

[1] G. Blatter, M.V. Feigel'man, V.B. Geshkenbein, A.I. Larkin, V.M. Vinokur, Rev. Mod. Phys. 66 (1994) 1125.
[2] L. Civale, A.D. Marwick, T.K. Worthington, M.A. Kirk, J.R. Thompson, L. Krusin-Elbaum, Y. Sun, J.R. Clem, F. Holtzberg, Phys. Rev. Lett. 67 (1991) 648.
[3] M. Konczykowski, F. Rullier-Albenque, E.R. Yacoby, A. Shaulov, Y. Yeshurun, P. Lejay, Phys. Rev. B 44 (1991) 7167.
[4] D.R. Nelson, V.M. Vinokur, Phys. Rev. Lett. 68 (1992) 2398.
[5] Q. Li, Y. Fukumoto, Y. Zhu, M. Suenaga, T. Kaneko, K. Sato, C. Simon, Phys. Rev. B 54 (1996) R788.
[6] C.J. van der Beek, M. Konczykowski, T.W. Li, P.H. Kes, W. Benoit, Phys. Rev. B 54 (1996) R792.
[7] L.N. Bulaevskii, V.M. Vinokur, P. Maley, Phys. Rev. Lett. 77 (1996) 936.
[8] M. Kosugi, Y. Matsuda, M.B. Gaifullin, L.N. Bulaevskii, N. Chikumoto, M. Konczykowski, J. Shimoyama, K. Kishio, K. Hirata, K. Kumagai, Phys. Rev. Lett. 79 (1998) 3984.

[9] M. Kosugi, Y. Matsuda, M.B. Gaifullin, L.N. Bulaevskii, N. Chikumoto, M. Konczykowski, J. Shimoyama, K. Kishio, K. Hirata, K. Kumagai, Phys. Rev. B., submitted.
[10] R. Sugano, T. Onogi, K. Hirata, M. Tachiki, Phys. Rev. Lett. 80 (1998) 2925.
[11] K. Hirata, T. Mochiku, K. Kadowaki, in: T. Matsushita, K. Yamafuji (Eds.), Proceedings of the eighth International Workshop on Critical Currents in Superconductors, Kitakyushu, Japan, 27–29 May, 1996, World Scientific, Singapore, 1996, p.145.
[12] N. Chikumoto, M. Kosugi, Y. Matsuda, M. Konczykowski, K. Kishio, Phys. Rev. B 57 (1998) 14 507.
[13] K. Kadowaki, T. Mochiku, in: Proceedings of International Workshop on Superconductivity, Honolulu, Hawaii, June 23–26, 1992, p. 112.
[14] N. Motohira, K. Kuwahara, T. Hasegawa, K. Kishio, K. Kitazawa, J. Ceram. Soc. Jpn. 97 (1989) 994.
[15] Y. Matsuda, M.B. Gaifullin, K. Kumagai, M. Kosugi, K. Hirata, Phys. Rev. Lett. 78 (1997) 1972.
[16] A.E. Koshelev, Phys. Rev. Lett. 77 (1996) 3901.
[17] Y. Matsuda, M.B. Gaifullin, K. Kumagai, K. Kadowaki, T. Mochiku, K. Hirata, Phys. Rev. B 55 (1997) R8685.
[18] W.E. Lawrence, S. Doniach, in: E. Kanda (Ed.), Proceedings of LT12, Kyoto, 1970, Keigaku, Tokyo, 1971, p. 361.