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Vortex dynamics in $Bi_2(Sr,La)_2CuO_{6+\delta}$ and $Bi_2Sr_2CaCu_2O_{8+\delta}$ single crystals with columnar defects

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Abstract

Vortex dynamics is studied in La-substituted $Bi_2Sr_2CuO_{6+\delta}$ (Bi-2201) and $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi-2212) single crystals irradiated with 3.8 GeV $^{181}Ta^{37+}$ ions through the relation between the frequency and the loss peak temperature in the temperature dependence of the imaginary part of AC magnetic susceptibility χ''. In unirradiated Bi-2201 and Bi-2212, the behavior of thermally activated flux flow or creep is observed. The Bose-glass behavior is observed at fields below the matching field B_Φ in irradiated Bi-2212. On the other hand, the Bose-glass behavior is not observed in irradiated Bi-2201. This difference is due to the extremely weak coupling between pancake vortices along the *c*-axis in Bi-2201 even under the presence of columnar defects. The vortices in Bi-2201 irradiated with heavy ions are almost decoupled, resulting in the occurrence of thermally activated vortex creep.

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Keywords: AC susceptibility; Heavy-ion irradiation; Vortex dynamics; Bi-2201 single crystal; Bi-2212 single crystal

1. Introduction

The vortex state and dynamics of high-T_c superconductors with columnar defects (CDs) have attracted considerable attention due to their physical interest and the impact of the strongly enhanced pinning on the technological application. For a system of vortex *lines* in the presence of CDs, a theory developed by Nelson and Vinokur [1] predicts the existence of a Bose-glass phase at temperature $T < T_{BG}$, where vortex lines are localized on or between CDs. For three-dimensional (3D) material of $YBa_2Cu_3O_{7-\delta}$ (YBCO), an experimental evidence of the second-order Bose-glass transition was provided by Jiang et al. [2] through the critical scaling of the frequency-dependent AC resistivity. It is known that the glass transition does not occur at $T > 0$ in a

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purely two-dimensional (2D) vortex system [3,4]. The fact that the Bose-glass behavior is observed in highly anisotropic $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi-2212) with CDs [5–7] indicates that the vortices are correlated enough along the *c*-axis direction to encounter the Bose-glass transition in Bi-2212 with CDs. The 3D coupling of vortices by CDs is demonstrated by the transport measurements in flux transformer geometry [7,8] and Josephson plasma resonance in Bi-2212 with CDs [9].

In order to study the influence of dimensionality of vortices on the Bose-glass behavior, we have investigated the vortex dynamics in the presence of CDs in a Bi-2212 single crystal and a $Bi_2(Sr,La)_2CuO_{6+\delta}$ (Bi-2201) single crystal. The anisotropy of Bi-2201 is much higher than that of Bi-2212. To the best of our knowledge, the effect of CDs on the vortex dynamics in Bi-2201 has not been reported. In the case of extreme anisotropy represented by the Bi- and Tl-based high-T_c superconductors, 2D ''pancake'' vortices are weakly coupled between layers by Josephson and by magnetic interactions. According to the Josephson plasma resonance experiments [10], the anisotropy factor $\gamma \equiv (m_c/m_{ab})^{1/2}$ of Bi-2201 is about 750 and much higher than that of Bi-2212 ($\gamma \sim 100$) when both have the optimum T_c. Therefore, the Josephson interaction between two pancake vortices $E_J \propto \varepsilon_0 s/\gamma^2$ [4] in Bi-2201 is much weaker than that in Bi-2212, where $\varepsilon_0 = (\Phi_0^2/4\pi\mu_0\lambda_{ab}^2)$ and s is the interlayer spacing (λ_{ab} is the penetration depth in the *ab*-plane). Moreover, the magnetic interaction between two pancake vortices along the field direction $E_m \propto \varepsilon_0 d^2/\lambda_{ab}$ [4] (d is the thickness of superconducting plane) is also smaller in Bi-2201, provided that d is the thickness of CuO_2 layers. It is natural to regard CuO_2 layers as a superconducting plane because they sustain superconductivity. The thickness of a CuO_2 plane is about 1 Å in Bi-2201. For Bi-2212, d corresponds to the double CuO_2 layers and is about 3 Å. The thinner CuO_2 plane results in the weaker magnetic coupling in Bi-2201.

The results for Ta-ion irradiated Bi-2212 and Bi-2201 were compared to each other. The Bose-glass behavior was observed in irradiated Bi-2212, while it was not observed in irradiated Bi-2201. The experimental result implies that vortices in Bi-2201 are almost decoupled in spite of the introduction of CDs.

2. Experimental procedure

Bi-2201 ($T_c \approx 27$ K) and Bi-2212 ($T_c \approx 90$ K) single crystals with the optimum T_c were grown by the travelling solvent floating zone (TSFZ) method. The characteristics of these single crystals are described in Refs. [11–13]. The reference (unirradiated) sample and the sample for irradiation were cut from one large crystal. The Bi-2201 crystal with dimensions of $1.6(l) \times 1.2(w) \times 0.06(t)$ mm^3 and the Bi-2212 crystal with dimensions of $2.6(l) \times 1.6(w) \times 0.04(t)$ mm^3 were irradiated with 3.8 GeV $^{181}Ta^{37+}$ ions at RIKEN Ring Cyclotron Facility to introduce CDs along the sample *c*-axis. As the projected range of 3.8 GeV $^{181}Ta^{37+}$ ion is about 0.1 mm in both Bi-2201 and Bi-2212, the irradiating ions pass through the specimen completely. The irradiation dose or the density of CDs was $4 \times 10^{10}/cm^2$ which corresponds to a dose-equivalent matching field B_Φ of 0.8 T. The irradiation reduced T_c by 2 K for Bi-2201, and 1 K for Bi-2212. Several single crystals of Bi-2201 and Bi-2212 were also irradiated with the dose of $2 \times 10^{10}/cm^2$ for transmission electron microscopy (TEM) observation. The TEM images have confirmed that the defect density is almost equal to the irradiation dose deduced from the beam currents and the irradiation time. The average radius of the ion track was 5 nm in Bi-2201 and 4 nm in Bi-2212.

The temperature dependence of the AC magnetic susceptibility $\chi \equiv \chi' - i\chi''$ was measured under the AC magnetic field $H_{AC}\ \sin(2\pi ft)$ with a low amplitude $H_{AC} = 0.5$ Oe in a frequency range of 100 Hz $\leq f \leq$ 35 kHz and the external DC magnetic field B_{ex}. The relation between the frequency and the loss peak temperature (T_p) at which χ'' became maximum was investigated. The AC and the external DC magnetic fields were applied in the direction parallel to the *c*-axis. The two components χ' and χ'' of the AC susceptibility were determined by using the signal from a susceptometer which consisted of a pair of balanced secondary coils and primary coil. To avoid the surface or geometrical barrier effects at low fields and high temperatures [14,15], the experiments were performed under the DC field above 0.1 T.

There are two kinds of losses in the AC loss: the eddy current loss and hysteresis loss. In most AC experiments in a small AC field and a large DC field, the amplitude of vortex oscillation is much smaller than the vortex spacing so that the critical state with hysteresis loss is not relevant. The AC response is in the linear regime well above the glass temperature and there, the eddy current loss is relevant. Figs. 1 and 2 show a temperature dependence of AC susceptibility of irradiated Bi-2201 and Bi-2212 at various frequencies, respectively. The temperature dependence of χ'' strongly depends on the frequency, while the value of χ'' at a given temperature does not depend strongly on the magnitude of H_{AC} as shown in the inset of Figs. 1 and 2. The experimental results show that the AC loss is attributed to the eddy current loss at T_p, and not the hysteresis loss in the nonlinear critical state. For the latter case, AC susceptibility would depend on the amplitude of AC field, but would not depend on the frequency [16–18]. Moreover, the value of T_p is independent of the amplitude of AC field from 0.1 to 2.0 Oe and the third-harmonic response signal is below noise-level at T_p for $H_{AC} = 0.5$ Oe. The linearity at T_p was confirmed in the measuring frequency range of 100 Hz $\leq f \leq$ 35 kHz.

When the AC response is in the linear regime, the maximum AC loss occurs when $\omega\tau = 1.11$ ($\tau = wt\mu_0/4\pi\rho$) in a superconductor with a shape of long strip and when $\omega\tau = 0.97$ in a square thin superconductor under a perpendicular AC field [19]. Here, $\omega = 2\pi f$ is the angular frequency, w the width of the sample, t the thickness, and ρ the resistivity of the sample. In the measuring frequency range, the eddy current loss at the loss peak temperature corresponds to the resistivity $5 \times 10^{-4} \leq \rho \leq 0.2$ μΩ cm for typical sample dimension of $w = 1.5$ mm and $t = 0.05$ mm. In a glass transition, the resistivity vanishes at T_g as $\rho \sim (T - T_g)^n$. The relation between frequency f and T_p is, then, $f \sim (T_p -$

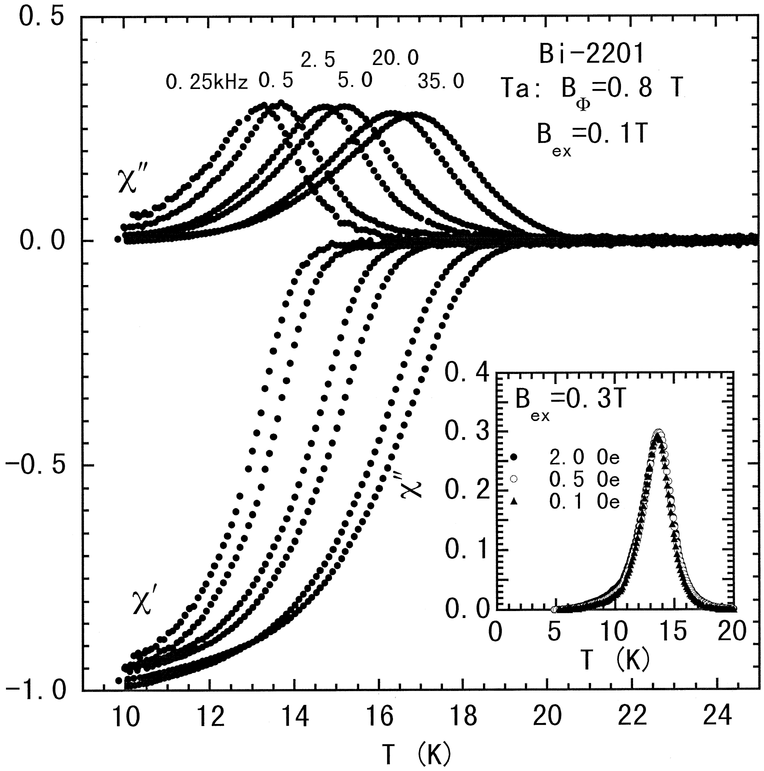

Fig. 1. The temperature dependence of the real part (χ') and the imaginary part (χ'') of the AC susceptibility in Bi-2201 irradiated with 3.8 GeV Ta ions at different frequencies ($B_{ex} = 0.1$ T, $H_{AC} = 0.5$ Oe). The inset shows the temperature dependence of χ'' at different H_{AC} ($B_{ex} = 0.3$ T, $f = 5$ kHz).

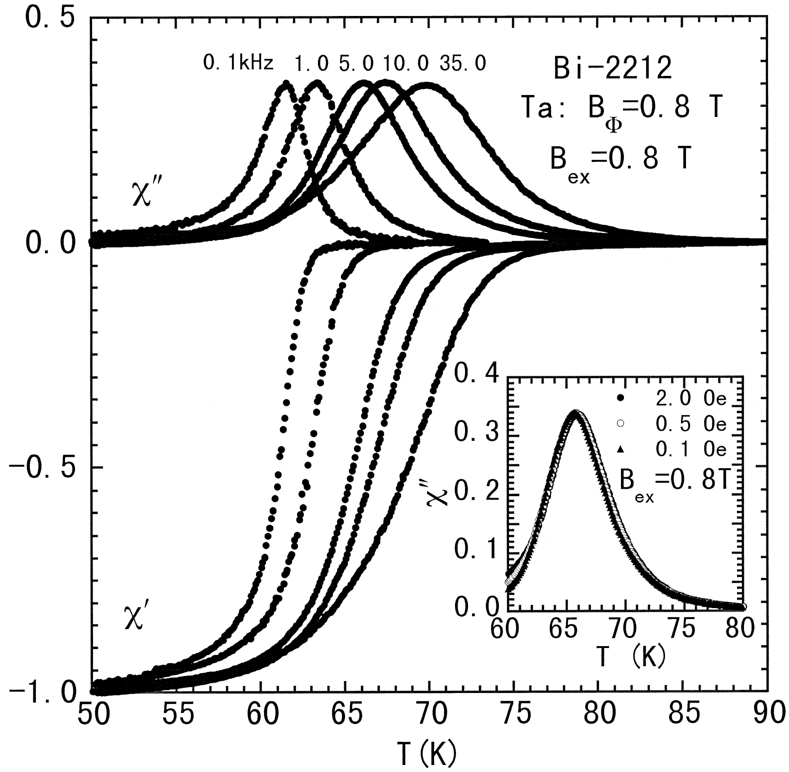

Fig. 2. The temperature dependence of χ' and χ'' in Bi-2212 irradiated with 3.8 GeV Ta ions at different frequencies ($B_{ex} = 0.8$ T, $H_{AC} = 0.5$ Oe). The inset shows the temperature dependence of χ'' at different H_{AC} ($B_{ex} = 0.8$ T, $f = 5$ kHz).

$T_g)^n$, similarly to the temperature dependence of resistivity. On the other hand, when the thermally assisted flux flow (TAFF) or creep dominates the vortex motion, the resistivity behaves according to $\rho \sim \exp(-U/T)$ and, therefore, the Arrhenius-like behavior $f \sim \exp(-U/T_p)$ appears with an activation energy U.

3. Results and discussion

We first discuss the results for Bi-2212. Fig. 3(a) shows the Arrhenius plot for the frequency and T_p for unirradiated Bi-2212. The Arrhenius-like behavior is observed in the unirradiated Bi-2212. The behavior is usually taken to be indicative of TAFF or creep. Fig. 3(b) shows Arrhenius plots for the frequency and T_p for irradiated Bi-2212. The deviation from the Arrhenius-like behavior is apparent. The glass behavior $f \sim (T_p - T_g)^n$ is observed instead, as shown in Fig. 3(c). Fig. 4(a) shows the relation between the glass temperature deduced from the fit to the relation of $f \sim (T_p - T_g)^n$ and the external magnetic field B_{ex}. Above about the matching field B_Φ, the glass temperature decreases rapidly with increasing B_{ex} because the interstitial vortices that are not trapped by CDs exist above B_Φ and they move easily.

Fig. 4(b) shows the exponents n in the glassy behavior. At fields below B_Φ, the value of n is almost constant about 4 and is close to the Bose-glass exponent $\upsilon'(z'-2) = 3.5$–4.5 obtained from the numerical simulations [20,21] and the I–V scaling analysis for a heavy-ion irradiated Tl-2212 ($z' = 4.9$ and $\upsilon' = 1.1$) [22]. Thus, the present glass temperature T_g is identified with the Bose-glass temperature T_{BG} for $B_{ex} < B_\Phi$. The existence of the Bose-glass behavior indicates that the pancake vortices are well correlated along the c-axis in Bi-2212 irradiated with heavy ions. At fields above B_Φ, the value of n

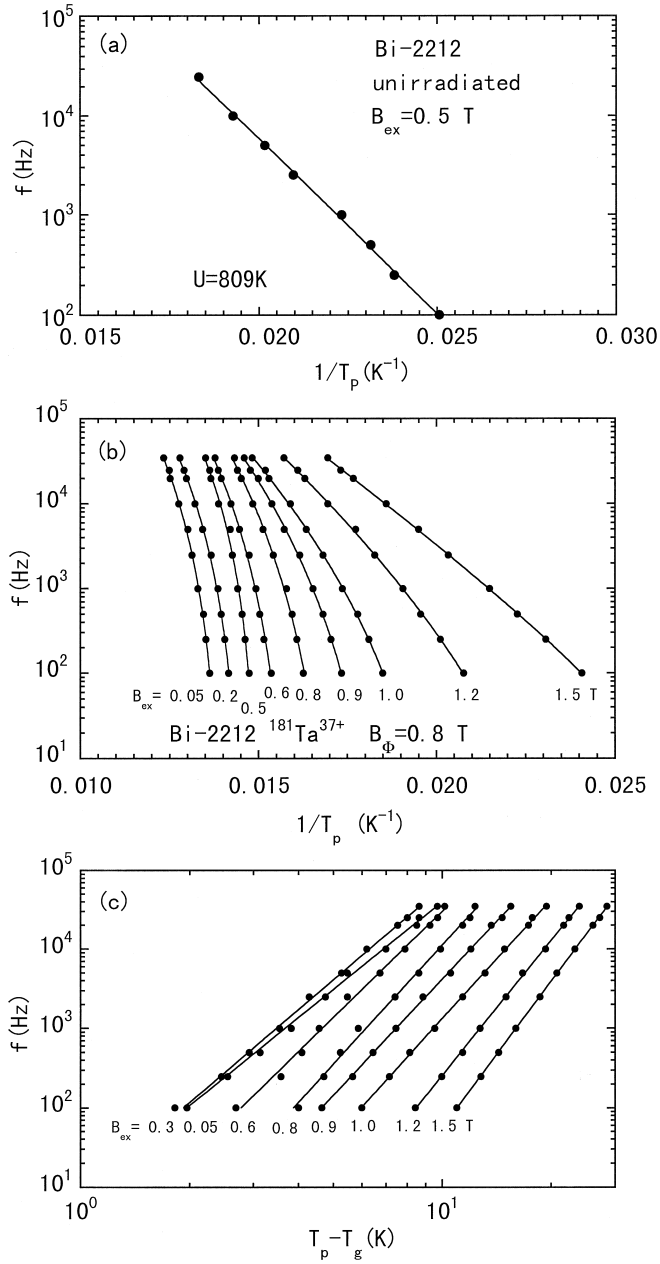

Fig. 3. (a) Arrhenius plot for the frequency and T_p for unirradiated Bi-2212. (b) Arrhenius plots for the frequency and T_p for Bi-2212 irradiated with Ta ions at several DC external fields B_{ex}. (c) f vs. T_p–T_g on a log–log plot.

increases with B_{ex}, indicating that the vortex dynamics deviates from that of Bose-glass. This is due to the creep of the vortices which are not trapped by CDs at $B_{ex} > B_{\Phi}$. The crossover in the vortex dynamics at B_{Φ} in heavy-ion irradiated Bi-2212 was also reported and discussed previously in Ref. [23]. The recently found anomaly which is associated with the recoupling of vortices at $B_{\Phi}/3$ [24,25] is also

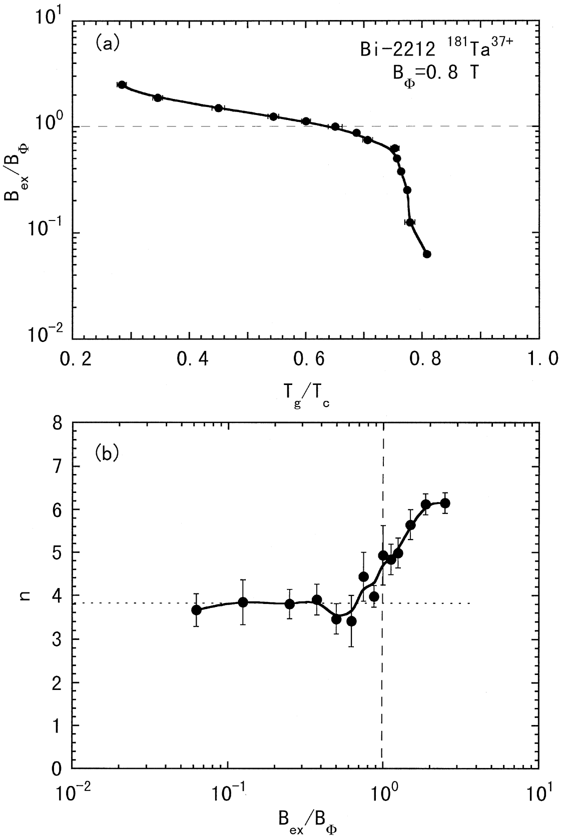

Fig. 4. (a) The glass transition line in the B_{ex}/B_{Φ}–T_g/T_c plane for Bi-2212 irradiated with Ta ions. (b) The exponent n in the glassy power law $f \sim (T_p - T_g)^n$ as a function of B_{ex}/B_{Φ}. The dotted line indicates the average value of n ($=3.8$) at fields $B_{ex} < B_{\Phi}$. The solid line is a guide for the eye.

expected to influence the glassy exponent n. A slight decrease in n at $B_{ex}/B_{\Phi} > 1/3$ may be due to this recoupling of vortices. A further precise investigation is, however, needed to clarify the influence of the recoupling of vortices at $B_{\Phi}/3$ on the glassy behavior.

We turn next to the results for Bi-2201. Fig. 5(a) and (b) show Arrhenius plots for the frequency and T_p in unirradiated Bi-2201 and irradiated Bi-2201, respectively. On the contrary to the Bose-glass behavior $f \sim (T_p - T_{BG})^n$ in irradiated Bi-2212, the Arrhenius-like behavior $f \sim \exp(-U/T_p)$ is observed in irradiated Bi-2201 (Fig. 5(b)) as well as in the unirradiated one (Fig. 5(a)). A glass analysis is not successful anymore in irradiated Bi-2201 in contrast to the case of Bi-2212, indicating that the vortices are not coupled enough to encounter the Bose-glass transition. We have also confirmed the absence of the Bose-glass behavior in irradiated Bi-2201 for 3.5 GeV $^{136}Xe^{31+}$ irradiation [26].

In Fig. 6, the activation energy U is plotted as a function of B_{ex} for Bi-2201 irradiated with Ta ions. The activation energy U in the irradiated Bi-2201 is only about twice of that in the unirradiated one at $B_{ex} = 0.1$ T. The heavy-ion irradiation appears not to enhance the pinning strongly in Bi-2201. When the vortices are not coupled well, the advantages of the linear geometry of CDs are lost, resulting in the small enhancement of U.

We now estimate the correlation length along c-axis of a vortex line in a vortex line motion from the effective depinning length U/U_p [1,27] in the irradiated Bi-2201. Here, $U_p \equiv (\Phi_0^2/4\pi\mu_0\lambda_{ab}^2)$ $[0.5 + \ln(R/\xi_{ab})]$ is the pinning potential per unit length of a CD, where ξ_{ab} is the coherence length and R

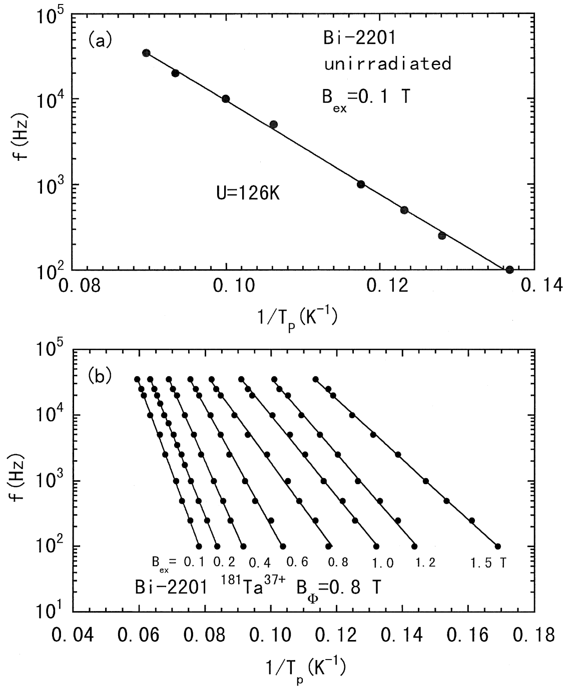

Fig. 5. (a) Arrhenius plot for the frequency and T_p for unirradiated Bi-2201 at $B_{ex} = 0.1$ T. (b) Arrhenius plots for the frequency and T_p for Bi-2201 irradiated with Ta ions ($B_{\Phi} = 0.8$ T) at several DC fields B_{ex}.

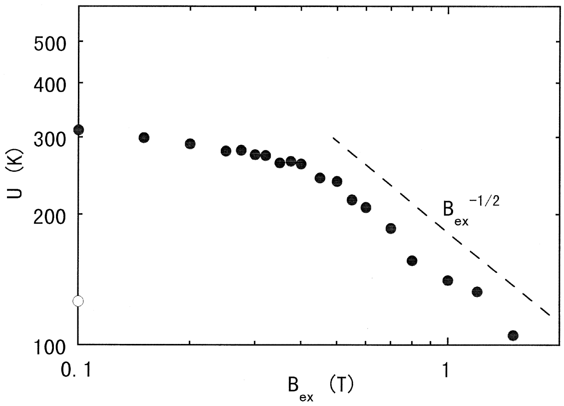

Fig. 6. The DC external magnetic field dependence of the activation energy U for irradiated Bi-2201 (solid circles) and for unirradiated one (open circle).

the radius of a CD. The activation energy U is 312 K at 0.1 T. As the vortex–vortex interaction is negligible, U comes from the energy of single-vortex line depinning at 0.1 T. The effective depinning length $U(B_{ex} = 0.1\ \mathrm{T})/U_p$ is about 3 nm, comparable to the layer spacing s of 1.2 nm, where $U_p \approx 1 \times 10^{11}$ K/m, taking into account $R = 5.0$ nm, $\xi_{ab} = 4$ nm, and $\lambda_{ab} = 400$ nm [28]. This short depinning length indicates that pancake vortices in Bi-2201 are almost decoupled even in the presence of CDs. When the effective depinning length is shorter than $2s = 2.4$ nm, pancake vortices can depin individually, resulting in nonglassy creep [1,27]. Thus, the Bose-glass behavior is not observed in the irradiated Bi-2201. Instead, the Arrhenius-like behavior $f \sim \exp(-U/T_p)$ appears, indicating the occurrence of thermally activated vortex creep.

Finally, we discuss the magnetic field dependence of the activation energy for irradiated Bi-2201. As shown in Fig. 6, the value of the activation energy U strongly depends on B_{ex} at high fields, while U depends on B_{ex} weakly at low fields. At high fields above 0.5 T, the field dependence of U approaches $B_{ex}^{-1/2}$. The field dependence of $B_{ex}^{-1/2}$ indicates that the plastic motion of vortex over the vortex spacing $a_0 \propto B_{ex}^{-1/2}$ becomes dominant at high fields. In the 2D vortex system, the vortex–vortex interaction leads to the plastic motion of vortices rather than the elastic one [4,29–31]. According to Ref. [31], the activation energy U for the plastic creep is given by $\varepsilon_0 a_0/\gamma$. On the other hand, at low fields, the vortex–defect interaction is more important than the vortex–vortex interaction so that the activation energy is almost governed by a single-vortex depinning process, resulting in the weak field dependence of U. The activation energy U is ideally independent of the magnetic field in the low field regime where the vortex–vortex interaction is negligible. The crossover from a weak field dependence of U below B_Φ to $B_{ex}^{-1/2}$ dependence at high fields was also observed in transport measurement for heavy-ion irradiated Bi-2212 [32].

4. Conclusion

The relation between the frequency and the loss peak temperature shows the Bose-glass behavior at the DC fields below the matching field B_Φ in Bi-2212 irradiated with 3.8 GeV Ta ions. On the other hand, the Arrhenius-like behavior appears in Bi-2201 irradiated with Ta ions. The absence of the Bose-glass behavior and the low activation energy in Bi-2201 in spite of the introduction of CDs are ascribed to the intrinsically weak coupling between pancake vortices. The difference between Bi-2201 and Bi-2212 in vortex dynamics comes from the difference in the strength of the coupling between pancake vortices.

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