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Vortex dynamics in $Bi_{2+x}Sr_{2-(x+y)}La_yCuO_{6+\delta}$ and $Bi_2Sr_2CaCu_2O_y$ irradiated with heavy-ions: correlation between the Bose-glass behavior and the coupling of pancake vortices

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Abstract

Vortex dynamics is investigated in $Bi_{2+x}Sr_{2-(x+y)}La_yCuO_{6+\delta}$ (Bi-2201) and $Bi_2Sr_2CaCu_2O_y$ (Bi-2212) irradiated with 3.5 GeV $^{136}Xe^{31+}$ ions through the relation between the frequency and the loss peak temperature in ac susceptibility in order to seek the Bose-glass transition. The Bose-glass behavior is observed at fields below about half of matching filed, $B_\Phi/2$ in irradiated Bi-2212. On the contrary to irradiated Bi-2212, the Bose-glass behavior is not observed in irradiated Bi-2201. This is due to the extremely weak coupling of pancake vortices along the *c* axis in Bi-2201 in spite of the presence of columnar defects. The pancake vortices in Bi-2201 irradiated with heavy-ions are almost decoupled, resulting in the occurrence of thermally activated flux flow or creep.

Keywords: AC susceptibility; Loss peak; Bose-glass; Coupling of pancake vortices; Bi-2201 single crystal; Bi-2212 single crystal

1. Introduction

It is now well accepted that the introduction of columnar defects by swift heavy-ion irradiation can considerably enhance the pinning properties of high-temperature superconductors [1,2].

For a system of vortex *lines* in the presence of columnar defects, the theory developed by Nelson and Vinokur [3] predicts the existence of a Bose-glass phase at temperature $T < T_{BG}$ where vortex lines are localized on or between the columnar defects. For "3D" material of $YBa_2Cu_3O_{7-\delta}$, an experimental evidence of a second-order Bose-glass transition was provided by Jiang et al. [4] through the critical scaling of the frequency-dependent ac resistivity. In contrast to a 3D vortex

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system, a glass transition is difficult in a 2D vortex system, due to the occurrence of a plastic creep [5]. The existence of the Bose-glass transition in a 2D vortex system requires the effective "3D" coupling among pancake vortices through the columnar defects. For "2D" material of $Bi_2Sr_2CaCu_2O_y$, the Bose-glass transition is complicated [6]. Nonlinear onset of ac response does not correspond to the phase boundary of the Bose-glass phase [7]. On the contrary, the power-law-like behavior, observed in *ab*-plane and *c* axis resistivity indicates the existence of the Bose-glass transition in Bi-2212 defected by columnar pins [8,9].

In the present paper, we investigate the vortex dynamics in Bi-2201 and Bi-2212 in the presence of columnar defects through the frequency dependence of the loss peak temperature in the imaginary part of susceptibility (χ'') in order to evaluate the Bose-glass transition.

2. Experimental

$Bi_{2+x}Sr_{2-(x+y)}La_yCuO_{6+\delta}$ (Bi-2201) ($T_c \approx 20$ K) and $Bi_2Sr_2CaCu_2O_y$ (Bi-2212) ($T_c \approx 90$ K) single crystals were grown by the traveling solvent floating zone (TSFZ) method. The characteristics of these single crystals are described in Refs. [10–12]. The Bi-2201 crystal with dimensions of $2.9(l) \times 1.4(w) \times 0.096(t)$ mm^3 and the Bi-2212 crystal with dimensions of $2.0(l) \times 2.0(w) \times 0.082(t)$ mm^3 were irradiated with 3.5 GeV $^{136}Xe^{31+}$ions at RIKEN Ring Cyclotron Facility to introduce columnar defects along the sample *c*-axis. This type of irradiation has previously been shown to produce continuous amorphous tracks of diameter ≈6 nm in Bi-2212 [13]. In all cases, the total pin density was 1.2×10^{11}/cm^2, which corresponds to a dose-equivalent matching field $B_\Phi = 2.4$ T. The irradiation reduced T_c by 5 K for Bi-2201, and 3 K for Bi-2212.

The temperature dependence of susceptibility was measured under the ac field (the amplitude $H_{ac} = 0.5$ Oe) and dc field ($0\ \mathrm{T} \leqslant B_{ex} \leqslant 5$ T) applied parallel to the *c*-axis. The dc irreversibility temperature was determined by resolving the collapse of zero-field-cooled (ZFC) and field-cooled (FC) magnetization using a commercial SQUID magnetometer.

3. Results and discussion

Fig. 1(a) and (b) illustrate the temperature dependence of susceptibility before and after the irradiation for Bi-2201 and Bi-2212, respectively. The loss peak in χ'' shifts to higher temperature with the irradiation, as shown by the arrows. The shift is small for Bi-2201, due to the large reduction of T_c of 5 K by the irradiation which corresponds 25% of T_c before irradiation.

Within a linear response, the loss peak of χ'' appears at T_p, satisfying a condition that the resistivity becomes $\rho_{ab} = 0.225\pi w t \mu_0 f$ [14]. Here w is the width of the sample, t the thickness, and f the frequency of the ac field. This condition is repre-

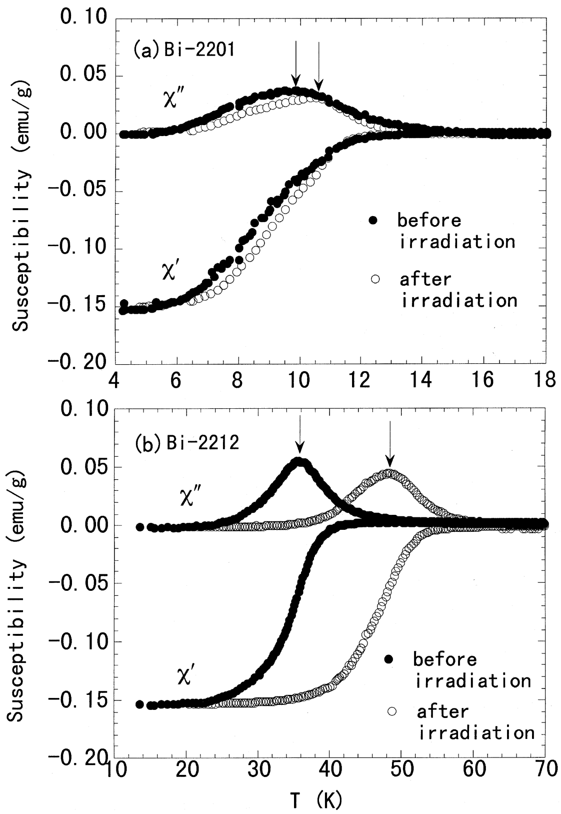

Fig. 1. The temperature dependence of the susceptibility (a) for Bi-2201 ($B_{ex} = 0.02$ T, $H_{ac} = 0.5$ Oe, $f = 5$ kHz) and (b) for Bi-2212 ($B_{ex} = 4.0$ T, $H_{ac} = 0.5$ Oe, $f = 5$ kHz) before and after the 3.5 GeV $^{136}Xe^{31+}$ ion irradiation. Arrows show the loss peak in the temperature dependence of the imaginary part of the susceptibility (χ'').

sented as $\omega\tau \approx 1$, if the characteristic relaxation time of the sample τ is taken as $wt/\pi^2(\rho_{ab}/\mu_0)$. Because the amplitude of ac field of 0.5 Oe used in the experiments was sufficiently low, the ac response was almost linear at T_p with a noise-level third-harmonic response. Therefore, $\omega\tau \approx 1$ holds at T_p. For a Bose-glass transition, the relaxation time of the sample τ diverges as $(T - T_{BG})^{-n}$ toward a Bose-glass temperature T_{BG}. The relation between f and T_p is, then, $f \sim (T_p - T_{BG})^n$ in the same way as the temperature dependence of resistivity $\rho \sim (T - T_{BG})^n$ which vanishes at T_{BG}. For a Bose-glass transition, Monte Carlo simulations of a vortex loop model yield estimates of 3.5–4.5 for the n $[= \nu'(z' - 2)]$ value [15]. On the other hand, when the thermally-assisted flux flow or creep prevails in the vortex motion, $\tau \sim \exp(U/T)$ and, therefore, an Arrhenius-like behavior $f \sim \exp(-U/T_p)$ appears with an activation energy U. In unirradiated Bi-2201 and Bi-2212, an Arrehenius-like behavior is usually observed.

Fig. 2 shows Arrhenius plots for the frequency and T_p for Bi-2212 after the Xe irradiation. For $B_{ex} \leqslant 1.5$ T, Arrhenius-like behavior $f \sim \exp(-U/T_p)$ is observed with the activation energy U of 5173 K at 1.5 T, and 3698 K at 2.0 T. For $B_{ex} \leqslant 1.25$ T, the deviation from Arrhenius-like behavior is, however, apparent. The Bose-glass behavior $f \sim (T_p - T_{BG})^n$ is obvious instead, as shown in the inset of Fig. 3. The existence of the Bose-glass behavior indicates that the pancake vortices are well coupled in Bi-2212 irradiated with heavy ions. The value of n extracted from the fit is in the range of from 2.4 to 4.3 and very close to the estimates of the simulation for a Bose-glass transition [15]. In Fig. 3, the Bose-glass temperature T_{BG} is plotted in B_{ex}–T plane, together with the dc irreversibility line (DC IL). There is a clear crossover in DC IL characterized by the appearance of a kink at about $B_\Phi/2$ which separates low and high-field regimes of DC IL, as previously reported [6,16]. Another slight kink is observed near B_Φ. The Bose-glass transition is observed only below the crossover field, $B_{ex} \leqslant 1.25$ T ($\approx B_\Phi/2$), and the DC IL almost corresponds to the Bose-glass transition line.

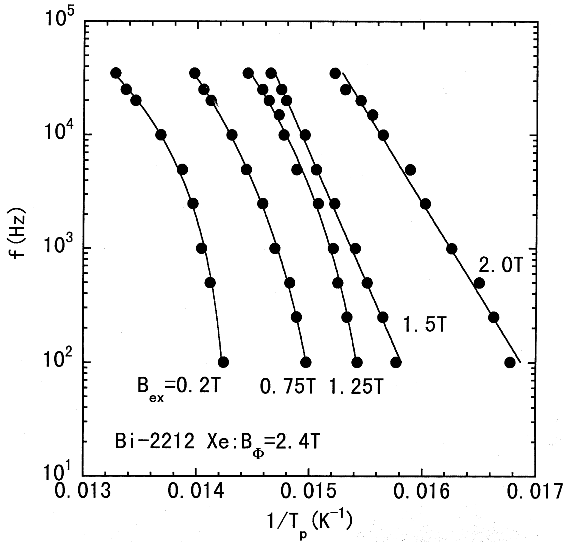

Fig. 2. Arrhenius plots for the frequency and T_p for Bi-2212 after the Xe irradiation ($B_\Phi = 2.4$ T) at several dc external fields B_{ex}.

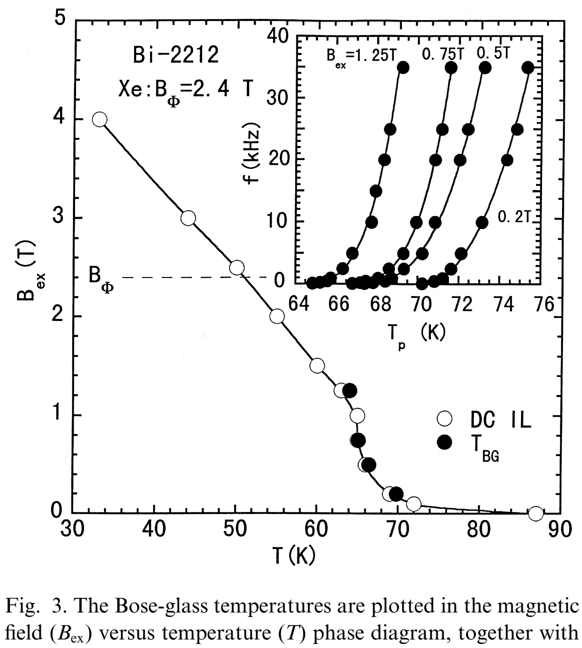

Fig. 3. The Bose-glass temperatures are plotted in the magnetic field (B_{ex}) versus temperature (T) phase diagram, together with the dc irreversibility line (DC IL). The inset shows the relation between the frequency and T_p at dc fields $B_{ex} = 0.2$, 0.5, 0.75 and 1.25 T for Bi-2212 after the Xe irradiation ($B_\Phi = 2.4$ T). The lines are fits to the data using the relation of $f \sim (T_p - T_{BG})^n$. The values of the exponent n are 2.4, 3.3, 4.3 and 3.3 for $B_{ex} = 0.2$, 0.5, 0.75 and 1.25 T, respectively.

Fig. 4 illustrates Arrhenius plots for the frequency and T_p for Bi-2201 after the Xe irradiation. On the contrary to the results for Bi-2212, the Arrehenius-like behavior $f \sim \exp(-U/T_p)$ is observed for 0.2 T $\leqslant B_{ex} \leqslant$ 1.5 T without the Bose-glass behavior. In the inset of Fig. 4, the activation energy U is plotted as a function of B_{ex} for Bi-2201 after the Xe irradiation. The activation energy is much lower than that observed in irradiated Bi-2212 about 5000 K at 1.5 T. The value of U depends on B_{ex} below 1.0 T, while, above 1.0 T, it is almost constant about 100 K. There is a crossover at 1.0 T about $B_\Phi/2$ (the arrow in the inset of Fig. 4) as observed in Bi-2212. The value of U of 100 K is comparable to the pinning energy of a pancake vortex by a columnar defect, $U_{2D} = (\Phi_0^2 d/4\pi\mu_0\lambda_{ab}^2)\ln(R/\xi_{ab})$ ($\approx$44 K). Here $R = 3.0$ nm is the radius of the columnar defect, $\xi_{ab} = 1.5$ nm the coherence length, $\lambda_{ab} = 200$ nm the penetration depth and $d = 0.13$ nm the thickness of superconducting plane for Bi-2201. The absence of the strong field dependence U indicates that the single vortex creep or plastic creep takes place above 1.0 T, that is, $R_\perp < d_r$ above 1.0 T, where $R_\perp$ is the dimension of the vortex bundle transverse to the direction of the vortex creep and d_r is the mean spacing between columns. Therefore, the activation energy comes from the depinning of single-vortex line for 1.0 T $\leqslant B_{ex} \leqslant B_\Phi$. Above 1.0 T, the effective depinning length defined as U/U_p [17] is about 0.3 nm, comparable to the layer spacing, where $U_p = (\Phi_0^2/4\pi\mu_0\lambda_{ab}^2)\ln(R/\xi_{ab})$. This indicates that pancake vortices in Bi-2201 irradiated with heavy-ions are almost decoupled. Thus, columnar defects are not effective for coupling pancake vortices in Bi-2201, as opposed to the case in Bi-2212. As a result, the Bose-glass phase does not exist in the irradiated Bi-2201 in spite of the lower thermal energy (lower T_c) which suppresses thermal fluctuations and assists the appearance of the Bose-glass phase.

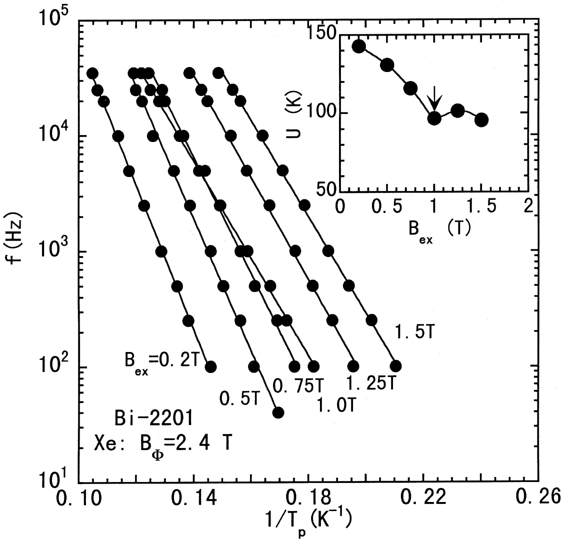

Fig. 4. Arrhenius plots for the frequency and T_p for Bi-2201 after the Xe irradiation ($B_\Phi = 2.4$ T) at several dc fields B_{ex}. The inset shows the dc magnetic field dependence of the activation energy U.

Why is the coupling between pancake vortices in Bi-2201 weaker than that in Bi-2212? A pair of pancake vortices interact with each other via the magnetic coupling and the Josephson coupling between successive layers. The number of CuO_2 planes in a half unit cell is different between Bi-2201 and Bi-2212. So, the thickness of superconducting plane of Bi-2201 about Cu ion radius ($\approx$1 Å) is shorter than that of Bi-2212 ($\approx$3 Å). Pancake vortices in Bi-2201 is, therefore, expected to have weaker coupling along the c axis than those in Bi-2212, taking into account the magnetic coupling between two pancake vortices $E_m \sim (\Phi_0^2/4\pi\mu_0\lambda_{ab}^2)d^2/\lambda_{ab}^2$, where d is the thickness of superconducting plane. The difference in Josephson coupling between these materials is believed to be small when the samples have a value of T_c close to the optimal one because, at that case, the values of electronic anisotropy ρ_{ab}/ρ_c of these materials are the same order of about 10^{-5} at the onset of the superconductivity [10,11].

4. Conclusion

The relation between the frequency and the loss peak temperature shows the Bose-glass behavior at the dc fields below about half of the matching field in Bi-2212 irradiated with 3.5 GeV Xe ions. The absence of the Bose-glass behavior and the observed low activation energy in Bi-2201 in spite of the introduction of columnar defects are ascribed to the extremely weak coupling of pancake vortices in this system. The difference between Bi-2201 and Bi-2212 in the existence of the Bose-glass behavior seems to come from the difference in the strength of the magnetic coupling between pancake vortices.

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