Vortex dynamics in Bi$_{2+x}$Sr$_{2-(x+y)}$La$_y$CuO$_6$+$\delta$ and Bi$_2$Sr$_2$CaCu$_2$O$_y$ 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$_y$CuO$_6$+$\delta$ (Bi-2201) and Bi$_2$Sr$_2$CaCu$_2$O$_y$ (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, $B_{U}/2$ 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. © 1998 Published by Elsevier Science B.V. All rights reserved.

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].

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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$_2$Sr$_2$CaCu$_2$O$_y$, 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 doped 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 ($\chi''$) in order to evaluate the Bose-glass transition.

2. Experimental

Bi$_{2+x}$Sr$_{2-2x}$La$_{y}$CuO$_{6+y}$ (Bi-2201) ($T_c$ = 20 K) and Bi$_2$Sr$_2$CaCu$_2$O$_y$ (Bi-2212) ($T_c$ = 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 $\approx$6 nm in Bi-2212 [13]. In all cases, the total pin density was $1.2 \times 10^{11}$/cm$^2$, which corresponds to a dose-equivalent matching field $B_d$ = 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 T $\leq B_{ex} \leq 5$ 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 $\chi''$ 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 $\chi''$ appears at $T_p$, satisfying a condition that the resistivity becomes $\rho_{ab} = 0.225\pi w t f$ [14]. Here $w$ is the width of the sample, $t$ the thickness, and $f$ the frequency of the ac field. This condition is repre-
sented as $\omega\tau \approx 1$, if the characteristic relaxation time of the sample $\tau$ is taken as $\omega\tau \approx 1$. 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 $\tau$ 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 $n$ value [15]. On the other hand, when the thermally-assisted flux flow or creep prevails in the vortex motion, $\tau \sim \exp(U/\kappa T)$ and, therefore, an Arrhenius-like behavior $f \sim \exp(-U/\kappa T_p)$ appears with an activation energy $U$. In unirradiated Bi-2201 and Bi-2212, an Arrhenius-like behavior is usually observed.

Fig. 2 shows Arrhenius plots for the frequency and $T_p$ for Bi-2212 after the Xe irradiation. For $B_{ex} \leq 1.5$ T, Arrhenius-like behavior $f \sim \exp(-U/\kappa T_p)$ is observed with the activation energy $U$ of 5173 K at 1.5 T, and 3698 K at 2.0 T. For $B_{ex} \leq 1.25$ 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 $B_{ex}/2$ which separates low and high-field regimes of DC IL, as previously reported [6,16]. Another slight kink is observed near $B_{c2}$. The Bose-glass transition is observed only below the crossover field, $B_{ex} \leq 1.25$ T ($\approx B_{c2}/2$), 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 ($B_{ex} = 2.4$ T) at several dc external fields $B_{ex}$.](image)

![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 ($B_{ex} = 2.4$ 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.](image)
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 Arrhenius-like behavior $f \sim \exp(-U/T_p)$ is observed for $0.2 \, T \leq B_{cx} \leq 1.5 \, T$ 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 at 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 $B_{ex}$/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, $U_{2D} = (\Phi_0^2/4\pi\mu_0\lambda_{ab}^2)\ln(R/\xi_{ab})$ ($\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 the 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, $R < d$ above 1.0 T, where $R_c$ is the dimension of the vortex bundle transverse to the direction of the vortex creep and $d_c$ is the mean spacing between columns. Therefore, the activation energy comes from the depinning of single-vortex line for 1.0 T $\leq B_{ex} \leq B_B$. Above 1.0 T, the effective depinning length defined as $U' = (\Phi_0^2/4\pi\mu_0\lambda_{ab}^2)\ln(R/\xi_{ab})$. 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.

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 \, $A) is shorter than that of Bi-2212 ($\approx 3 \, $A). 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 $E_m \approx (\Phi_0^2/4\pi\mu_0\lambda_{ab}^2)d^2/\lambda_{ab}^2$, 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 $\rho_{ab}/\rho_c$ 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.

References