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The vortex dynamics in $Bi_2Sr_2CaCu_2O_8$ single crystals unirradiated and with low-density columnar defect

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저밀도 원통형 결함이 $Bi_2Sr_2CaCu_2O_8$ 단결정의 볼텍스 동역학에 미치는 영향

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Abstract

We have studied vortex dynamics in $Bi_2Sr_2CaCu_2O_8$ single crystals of unirradiated and irradiated samples by using 100 × 100 μm^2 Hall sensor. Doses equivalent magnetic fields are 20 G, 100 G and 1 kG. In the magnetization measurement, a second magnetization peak (SMP) was observed in unirradiated, 20 G dose and 100 G dose samples in contrast to 1 kG dose sample. In the unirradiated sample, the SMP was observed in the range of 18 K ~ 35 K and the amplitude of the SMP decreased with increasing temperature. With increase of the irradiation dose, temperature region and sharpness of the SMP were reduced. In the magnetic relaxation measurement, we observed that the normalized relaxation rate S decreased with increasing the irradiation dose. Our results suggest that the vortex dynamics is not greatly affected by low-density columnar defects.

Keywords : Bi-2212, magnetization, relaxation, second magnetization peak (SMP)

I. Introduction

The many phenomena in the mixed state of high-temperature superconductors (HTSC) have been of considerable scientific and technological interest. One of the anomalous phenomena in the mixed state vortex phases of HTSC is the appearance of second maximum in the magnetization hysteresis loops in local and global M-H magnetization measurements with an applied field parallel to the single crystal c axis [1-11]. This so-called "second magnetization peak (SMP)" is located at field of a few hundred gauss and appears at temperature between ~ 20 K and 40 K. The origin of the SMP, H_{2p}, and the onset field, H_{on}, is the topic of extensive experimental and theoretical studies where much of the experimental work has been focused on the highly anisotropic $Bi_2Sr_2CaCu_2O_8$ (Bi-2212) single crystal. Despite

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remarkable experimental and theoretical efforts, the vortex phase diagram is still far from being completely elucidated. It has attracted much attention, in part because it may be a signature of a transition from three- to two-dimensional pinning behaviors of vortices in the superconductor [4]. At a low field, where the inhomogeneity of the magnetic field is large, vortices in neighboring layers are coupled strongly by magnetic or Josephson coupling. Above a characteristic field, H_{2p}, vortices in each layer are decoupled and each superconducting layer can be considered as a separate two-dimensional superconductor. Theoretical treatment of this dimensional transition in the pinning mechanism is given by Vinokur *et al.* [12].

However, there have been several explanations for the SMP that was attributed to surface barriers [13], sample inhomogeneities [14], a crossover from surface barriers to bulk pinning [15], dynamic effects [16], a weak first-order vortex-lattice melting [17], layer decoupling [18], or vortex stacking [19].

In this work, we address the dimensional transition in the pinning mechanism of the above issue through DC magnetization and magnetic relaxation measurement in Bi-2212 single crystals inclusive of the irradiation samples. We could observe that the SMP and the normalized relaxation rate S decreased with increasing the irradiation dose and temperature. In this work, we claim that the vortex dynamics is not greatly affected by low-density columnar defects.

II. Experiments

The Bi-2212 single crystals used in this work were grown by the standard flux method, and then irradiated by 1.3 GeV uranium ions at the Argonne Tandem Linear Accelerator System. We studied the magnetic properties of samples of unirradiated and various irradiation doses that correspond to a matching field of B_Φ = 20 G, 100 G and 1 kG. The defects are oriented parallel to the crystalline c axis. The crystals have dimensions of 840 × 950 μm^2 for unirradiated, 1300 × 1200 μm^2 for 20 G dose, 1080 × 1110 μm^2 for 100 G dose and 900 × 1120 μm^2 for 1 kG dose sample. The thickness of the samples is about 10 μm. The transition temperatures T_c was 82 K for unirradiated sample and the others were 81 K as determined from the zero-field-cooled and field-cooled magnetization measurement in a magnetic field of 10 Oe applied parallel to the c axis.

We positioned an InP Hall sensor of sensing area 100 × 100 μm^2 at the center of the crystals. In this way we can avoid the edge effect where magnetization direction changes. We pass 10 mA current through Hall sensor from a Keithley 224 current source and the Hall voltage was measured using a Keithley 182 voltmeter. The magnetizations and the relaxations were recorded by using the Physical Property Measurement System (PPMS, Quantum Design) and the external magnetic field is always applied parallel to the c axis of the crystals. Magnetization loops were measured over a temperature range of 15 K < T < 50 K with the field-sweeping rate of 100 Oe/sec. The magnetic relaxation measurement was carried out in a period of 3600 sec at especial peak fields, H_{1p} (first magnetization peak), H_{on} (minimum absolute magnetization between H_{1p} and H_{2p}) and H_{2p} (second magnetization peak), in both process of increasing and decreasing field. In the analysis of the magnetic relaxation experiment, the data of t > 100 sec were used to avoid any transient effects.

III. Results and Discussions

Fig. 1 shows the magnetization loops for various temperatures in the unirradiated sample. The amplitude of the SMP decreased with increasing temperature, and the SMP could be clearly observed from 18 K up to 35 K. At temperatures below 18 K and above 35 K, the SMP was difficult to resolve. The SMP was located between 570 G at 35 K and 1100 G at 18 K. The onset field H_{on} could also be clearly identified between 450 G at 18 K and 380 G at 30 K. As shown the Figs. 1 and 2, the SMP smears out as temperature approaches either 18 K or 35 K.

Fig. 2 shows magnetization loops of the unirradiated and various irradiation dose samples at 25 K. The SMP was observed in the unirradiated, 20 G dose, and 100 G dose samples at around 600 G but it is clearly seen that the SMP is not observable in 1 kG dose sample. At low fields, before the SMP, the amplitude of magnetization was increased according to increase the irradiation dose, but at high fields, after the SMP, the amplitude of magnetization was nearly the same in all samples. In this result, it

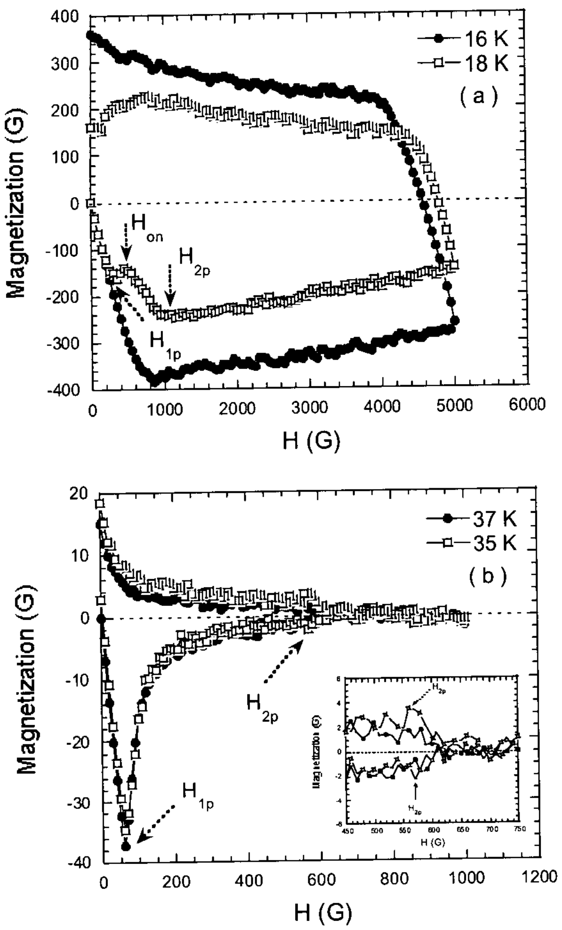

Fig. 1. The magnetization loops for variation of temperature in unirradiated sample. The SMP can be clearly observed from 18 K up to 35 K. The inset shows the magnetization loops near the SMP.

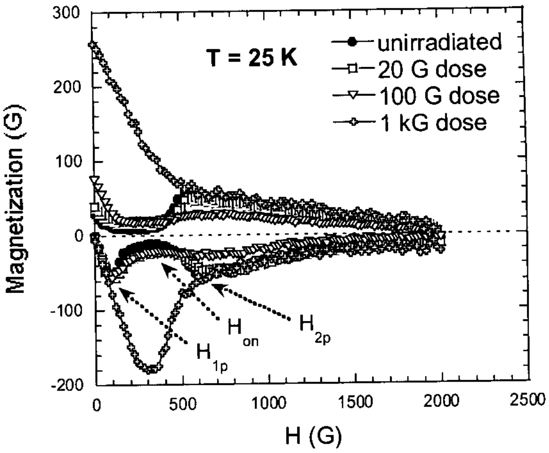

Fig. 2. The magnetization loops for various irradiation doses at 25 K. The SMP was not observed in 1 kG dose sample.

appears that the low dose of irradiation less than 100 G doesn't greatly affect the intrinsic properties of vortex pinning.

Fig. 3 shows the $H_{1p}(T)$, $H_{2p}(T)$, and $H_{on}(T)$ in the H-T phase diagram for Bi-2212 single crystals at the first magnetization peak $H_{1p}(T)$, the SMP field $H_{2p}(T)$, and onset field $H_{on}(T)$. We can see that H_{1p} and H_{2p} decreases with increasing temperature in all samples except the case of H_{on}. It has been suggested that either H_{2p} or H_{on} corresponds to a change of vortex structure from three- to two-dimensional transition [4]. On the other hand, three- dimensionally coupled pancake vortices are supposed to change into two-dimensional character at $H_{cr} = \Phi_0 / (\gamma s)^2$ as Josephson coupling between Cu-O layers is the dominant coupling mechanism. Here, Φ_0 is the flux quantum, γ is a anisotropic parameter and s for CuO$_2$ interlayer distance, resulting in a change of the pinning properties of vortices [4,20]. We obtained a value of H_{cr} ~ 350 G for Bi-2212. That value is temperature independent and much smaller than H_{2p}. Although H_{on} is scattered throughout temperature, it is more likely related to H_{cr} magnitude-wise.

As to H_{2p}, the narrow temperature window, 0.22 ~ 0.43 T_c, makes it difficult to analyze the nature of H_{2p}. It was reported that the peak effect only appears for $0.2 \leq T / T_c \leq 0.4$ for Bi-2212 crystals. In most cases, H_{2p} was found to be almost independent of temperature or slightly decreasing with lowering temperature [21-25]. On the other hand, Sun *et al.* [26] reported a different temperature dependence of $H_{2p}(T)$ for Pb and Pb/Cr-doped Bi-2212. There, the temperature dependence of $H_{2p}(T)$ similar to Fig. 3 was interpreted as decoupling field in the presence of the renormalization of the Josephson coupling by thermal fluctuation and static disorder. This may apply to our case since the irradiated samples certainly have the static disorder in the *ab* plane.

As shown in Fig. 3, the presence of the columnar defects doesn't affect $H_{2p}(T)$, which implies that even the unirradiated crystal contains appreciable amount of static disorder if we adapt the temperature dependence of H_{2p} is originated from the thermal-disorder-induced interlayer pancake vortex

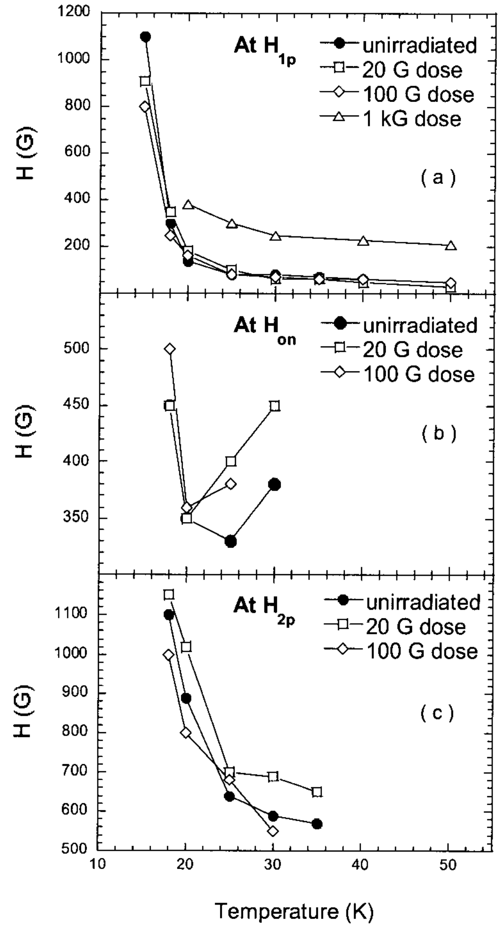

Fig. 3. The superconducting H-T phase diagram for Bi-2212 single crystals with initial field penetration first peak $H_{1p}(T)$, onset field $H_{on}(T)$ and SMP $H_{2p}(T)$.

decoupling, and this can be one reason why the low-density columnar defect is not much effective to vortex pinning in our case. Another reason for weak dependence on the presence of columnar defects is that the physically meaningful field values are higher than the effective pinning field of irradiated samples. It has been observed that vortex pinning is most effective around fields of 0.3 B_Φ when almost all the vortices can find the columnar defects individually. Then this field in the case of 100 G dose is ~ 30 G, even smaller than H_{1p}. In the case of 1 kG dose, the effective field is ~ 300 G, thus any intrinsic or weak disorder effect around this field is dominated by the pinning by columnar defects.

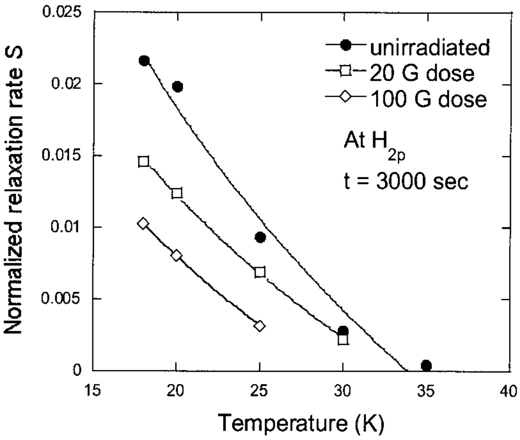

Fig. 4. Temperature dependence of the normalized relaxation rate S at H_{2p} for each sample in the increasing the field at 3000 sec. The solid lines are logarithmic fitting lines.

The normalized relaxation rate S was known as

$$S = -d(\ln M)/d(\ln t) \propto kT/U \qquad (1)$$

where M is magnetization, k is the Boltzmann constant, and U is an activation energy. Fig. 4 shows the normalized relaxation rate S calculating by Eq. (1) at H_{2p} for each sample in the increasing the field at 3000 sec. We could observe that the normalized relaxation rate S decreases with increasing the irradiation dose and temperature. The decreasing of the S at H_{2p} with increasing the irradiation dose and temperature explains that the vortex pinning is stronger than before irradiation. The dotted lines are experimental data and the solid lines are logarithmic fitting curves. This implies $U \sim T/(a - b\ln T)$ where a and b are positive constants

IV. Conclusion

We have measured the magnetic properties of unirradiated and various irradiation dose Bi-2212 single crystals in the mixed state using a 100 × 100 μm^2 Hall sensor. In the magnetization measurement, the second magnetization peak was observed from 18 K to 35 K in unirradiated sample. The temperature region and the sharpness of the SMP were reduced with the increase of the irradiation dose. In the magnetic relaxation, we could observe the temperature and the irradiation-dose dependence of the normalized relaxation rate S. In this work, we suggest that the vortex dynamics is not greatly affected by low-density columnar defects and the dimensional crossover in the pinning mechanism from three-dimensional pinning to two- dimensional pinning is likely due to the thermal-disorder-induced interlayer pancake vortex decoupling.

Acknowledgments

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