Vortex pinning phase diagram for various kinds of c-axis correlated disorders in RE123 films

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Abstract. The critical current density $J_c$ and resistivity $\rho$ of REBa$_2$Cu$_3$O$_x$ (RE123) films were evaluated in high magnetic field and wide temperature regions. We use three different samples such as a heavy ion irradiated Y123 film, a BaZrO$_3$ (BZO) added Y123 film and a low temperature growth Sm$_{1-x}$Ba$_{2+x}$Cu$_3$O$_y$ (LTG-Sm123) film. In these films, there exist the different c-axis correlated disorders like columnar shaped fission tracks for the heavy ion irradiated Y123 film, columnar shaped BZO precipitates for the BZO added Y123 film and edge dislocations at grain boundaries for the LTG-Sm123 films. The large peak of the angular dependence of $J_c$ for $B//c$ direction was observed for all samples measured in this study in a low field region, suggesting that the c-axis correlated pinning works well for these samples. However, we found that the behavior of the $J_c$ peak for $B//c$ strongly depends on a sort of c-axis correlated pinning centers. In the case of the columnar shaped fission tracks in the Y123 film, the $J_c$ peak for $B//c$ increases monotonically with increasing a magnetic field and seems to be connected with the dip structure in the angular dependence of $\rho$. In the case of the columnar shaped BZO precipitates, however, the $J_c$ peak for $B//c$ vanishes in a high field region above a few tesla and no dip behavior of $\rho$ was observed. On the contrary, in the case of the edge dislocations for LTG-Sm123 films, the $J_c$ peak for $B//c$ shrinks with increasing field and almost vanishes. But it grows again with further increasing a magnetic field and the dip of the angular dependence of $\rho$ is also observed. Hence the vortex pinning phase diagram strongly depends on a sort of c-axis correlated pinning centers. It is considered that these different behaviors of the $J_c$ peak for $B//c$ are related to the competition of the random and c-axis correlated pinnings.

1. Introduction

Large anisotropy of the superconducting properties is one of the serious problems on the application of the high-$T_c$ oxide superconductors. It was found that the nano-rods consisting of the BaZrO$_3$ precipitates enhanced the critical current density $J_c$ for $B//c$-axis [1]. In that case, the large peak at $B//c$ on the angular dependence of $J_c$ is observed and the anisotropy of $J_c$ was reduced as well. It is expected that the c-axis correlated pinning is a key technology to overcome the large anisotropy. Therefore, it is necessary to understand a mechanism of the c-axis
correlated pinning from basic and practical research points of view. In the vortex physics, it is known that the c-axis correlated pinning changes the dimensionality of the vortex system from three dimensional vortex glass to two dimensional Bose glass below the matching field $B_\phi$, where the number of vortices is the same as that of the c-axis correlated pinning centers \[2\]. However the high field properties in much larger fields than the matching field is still unknown. In addition, the competition of the random pinning and the c-axis correlated one should be taken into account for the practical materials because of the existence of many strong pinning centers. Recently we have found the complex vortex pinning states for the Sm$_{1-x}$Ba$_{2+x}$Cu$_3$O$_y$ film fabricated by the low-temperature-growth (LTG) technique \[3\]. Therefore, the vortex pinning behavior based on the vortex states should be investigated, in order to understand high field properties of the critical current density and the irreversibility field of the high-$T_c$ oxide superconducting materials such as coated conductors with the c-axis correlated disorders. In this paper, we compare the c-axis correlated pinning behaviors for three film samples with different c-axis correlated pinning centers.

2. Experimental

We use three different samples such as a heavy-ion irradiated YBa$_2$Cu$_3$O$_x$(Y123) film, a 1.5wt\% BaZrO$_3$ (BZO) added YBa$_2$Cu$_3$O$_x$(Y123) film and a low temperature grown Sm$_{1+x}$Ba$_{2-x}$Cu$_3$O$_y$ (LTG-Sm123) film \[4, 5, 6\]. Table 1 shows the specification of the samples used in this study. In these films, there exist the different c-axis correlated disorders like columnar shaped fission tracks for the heavy ion irradiated Y123 film, columnar shaped BZO precipitates (nano-rods) for the BZO added Y123 film and edge dislocations at grain boundaries for the LTG- Sm123 films. The sample was mounted on a rotating sample holder with cernox and capacitance thermometers and a heater. The sample temperature was controlled by both He gas flow in a temperature variable cryostat and a heater placed on the sample holder. Magnetic fields were applied using a 20 T superconducting magnet at the High Field Laboratory for Superconducting Materials (HFLSM), Institute for Materials Research (IMR), Tohoku University. High field data above 20 T were measured in a 33 T resistive magnet at the High Field Magnet Lab., IMM, Radboud University Nijmegen. The direction of the magnetic field angle was defined such that $B//c$-axis was $\theta = 0^\circ$ and transport currents were always perpendicular to the field and c-axis. Resistivities and critical currents were measured by a four-probe method. $J_c$ was determined by a 1 $\mu$V/cm criterion. The irreversibility field was determined by the $10^{-7}\Omega \cdot cm$ criterion. It corresponds to $J_c = 10$ A/cm$^2$.

| sample | Heavy-ion irradiated Y123 | BZO added Y123 | LTG-Sm123 |
|--------|--------------------------|----------------|------------|
| material | YBa$_2$Cu$_3$O$_x$ | YBa$_2$Cu$_3$O$_x$ | Sm$_{1+x}$Ba$_{2-x}$Cu$_3$O$_y$ |
| preparation | sputtering | PLD* | LTG** with NPs*** |
| substrate | SrTiO$_3$ | SrTiO$_3$ | MgO |
| c-axis correlated pin | columnar defects | BaZrO$_3$ nano rods | edge dislocations |
| matching field | 3 T | 2-3 T | 1-3 T |
| $T_c$ | 80.7 K | 86.6 K | 93.3 K |
| ref. | \[4\] | \[5\] | \[6\] |

* pulsed laser deposition, ** low temperature growth by PLD, *** nano-particles
3. Results and discussion

Figure 1 shows the angular dependence of $J_c$ at 70 K and resistivity at 77.3K for three different films. We confirmed that these behaviors are independent qualitatively of temperatures from 50 to 77.3 K. In a low field region, the two peaks on the angular dependence of $J_c$ appear at $\theta=0$ and 90°, respectively. The peak at $\theta=90^\circ$ originates from the effective mass anisotropy and/or the intrinsic pinning based on the layer structure as reported previously [7, 8]. The peak at $\theta=0^\circ$ comes from the c-axis correlated pinning. We focus on the $J_c(\theta)$ peak at $\theta=0^\circ$ (B//c) here. In the heavy-ion irradiated Y123, the $J_c$ peak for B//c as well as the dip structure on the angular dependence of resistivity in the vortex liquid state above irreversibility field (fig. 1 (d)) remains even in high fields. And the dip structure on the angular dependence of resistivity in the vortex liquid state above irreversibility field appears as shown in Fig. 1(d). It indicates the existence of the partially entangled vortex liquid (PEL) above the irreversibility line [9]. Therefore, the $J_c(\theta)$ peak at B//c is connected to the PEL state and closely related to the enhancement of $B_i$ by the c-axis correlated pinning [10, 11]. The matching field, where the number of vortices becomes the same as that of the columnar defects, is about 3 T for the heavy-ion irradiated sample used in this study. It is suggested that the strong c-axis correlated pinning is effective even in high fields above the matching field.

In contrast, the $J_c(\theta)$ peak at B//c disappears in high field region above 7 T and no dip structure on the angular dependence of resistivity is observed in the BZO added Y123 film. At high temperatures, however, we observed the small and broad dip behavior on the angular dependence of resistivity at 2 T. The matching field of this sample is about 2-3 T from the microstructure measurement. It is suggested that the BZO nano-rods hardly work as a c-axis correlated pinning in a high field region above the matching field.

LTG-Sm123 film shows a complex behavior as reported before [3]. When the magnetic field increases, the $J_c(\theta)$ peak at B//c shrinks gradually and almost vanishes around 1-3 T. However, it grows again with further increasing a magnetic field. The dip of the angular dependence of resistivity is also observed at B//c for the same sample in the high field region above the irreversibility field.

From the obtained results at various temperatures, we propose the schematic vortex pinning diagrams for the different c-axis correlated pinnings as shown in Fig. 2. The c-axis correlated pinning behavior can be observed in the wide temperature-field plane in the case of columnar...
Figure 2. Schematic vortex pinning phase diagram for different samples. (a) heavy-ion irradiated Y123, (b) BZO added Y123 and (c) LTG-Sm123 films.

defects by the fission track (Fig. 2(a)), but shrinks immediately above the matching field for the BZO nano-rods (Fig. 2(b)). In the case of the edge dislocations for the LTG-Sm123 as the c-axis correlated pinning center, the reentrant behavior of the c-axis correlated pinning behavior appears as shown in Fig. 2(c).

Below the matching field, the vortices can be trapped by the c-axis correlated defects, because the number of the vortices is smaller than that of the c-axis correlated disorders. In this case, the Bose glass (BG) state should exist as reported before [2]. However, some vortices cannot be trapped by the c-axis correlated disorders directly in the high field region above the matching field. Those vortices locate in between the c-axis correlated pinning and interact with random pinning or the c-axis correlated pinning through the vortex interaction, competitively. Therefore, we can consider two collective vortex pinning states appears in a collective random pinning state and a collective correlated pinning one [3]. In the collective correlated pinning state, the interstitial vortices in between the c-axis correlated disorders interact with other vortices pinned by the c-axis correlated disorders through the elastic constant of the vortices and then

Figure 3. Irreversibility field of different samples.
the correlated pinning behavior such as the $J_c(\theta)$ peak for $B//c$ and the dip of the angular dependent resistivity. In the collective random pinning state, the interstitial vortices are pinned by the random pinning centers and the random pinning behavior without the peak is shown in the angular dependence of $J_c$ for $B//c$. The fission track is well known as the strong c-axis correlated pinning centers and those directions are completely aligned. But the direction of the BZO nano-rods fluctuates. In higher fields, the distance in between vortices is shorter, as a result fluctuation of the c-axis correlated disorders becomes relatively larger. Hence, the correlation of the nano-rods along c-axis may be weak in high fields.

On the other hand, the edge dislocation works as the $\delta\kappa$ pinning and therefore depends on the mean-free path. In this case, the elementary pinning force is not so strong in comparison with the fission tracks. In addition, there are strong random pinning centers of RE-rich nanoparticles in the LTG-Sm123 films [6]. Due to the competition of the random pinning and the c-axis correlated one, it is considered that the complex vortex pinning phase diagram appears in the LTG-Sm123 system.

The irreversibility fields $B_i$ for $B//c$ are represented in Fig. 3. The $B_i$ values for $B//c$ at high temperatures are affected by the reduction of those critical temperatures $T_c$s due to an introduction of the c-axis correlated pinning. Since the deterioration of $T_c$ for LTG-Sm123 with naturally produced edge dislocations at the grain boundaries is smallest in this study, the $B_i$ value at high temperature is largest and it reaches about 10.3 T at 77.3 T for instance.

Let us now focus on the vortex pinning properties of the heavy-ion irradiated Y123 with typical strong c-axis correlated pinning centers, in order to discuss the effects of the matching field on the vortex pinning properties. The $J_c$ properties of the heavy-ion irradiated Y123 at various temperatures are plotted as a function of external magnetic field in Fig. 4. From the $J_c$ data in Fig. 4, the global pinning force densities $F_p$ were estimated. Figure 5 shows a scaling plot of $F_p$. The high field part of the $F_p$ curve gradually shrinks with decreasing temperature from 77.3 K to 66.6 K but seems to be scaled in the low temperature region. It is considered that this change of $F_p$ in the high temperature region is related with the normalized matching field. When temperature decreases, the normalized matching field decreases relatively because of the

**Figure 4.** $J_c-B$ properties of the heavy-ion irradiated Y123 at various temperatures.

**Figure 5.** Scaling plot of global pinning force densities $F_p$ of the heavy-ion irradiated Y123 at various temperatures. Arrows show the normalized matching field at various temperatures.
increasing $B_i$ as shown by the arrows in Fig. 5. The $F_p$ is enhanced below the matching field. At high temperatures, the matching field decreases across the peak field of $F_p$ with decreasing temperature. When the matching field becomes smaller than the peak field of the $F_p$ curve at low temperatures below 70 K, the $F_p$ curves trend to be scaled in the high field region above the peak field of $F_p$. All vortices below the matching field can be pinned by the c-axis correlated pinning but the number of the interstitial vortices pinned by the vortex interaction through those elastic constant increases with increasing a magnetic field above the matching field. Therefore, the vortex pinning behavior changes across the matching field as shown in Fig. 2 (a). In fact, it is reported that the anomaly in the derivative of the $J_c - B$ curve also observed at the matching field [12]. The different pinning states affects the $F_p$ curve scaling in high temperatures. However, when the normalized matching field becomes small enough at low temperature, we can see the scaling behavior of the $F_p$ curves as shown in Fig. 5. Therefore, the results of the Fig. 5 indicate the effects of the matching field on the $F_p$ scaling properties.

4. Summary
The vortex pinning properties in the different c-axis correlated pinning centers such as columnar shaped fission tracks, columnar shaped BZO nano-rods and edge dislocations at grain boundaries are discussed on the basis of the angular dependence of the critical current density and resistivity in high field. We found that the vortex pinning properties for different c-axis correlated pinning is almost the same in a low field region but can much differ considerably in the high field region above the matching field. From the obtained data, the vortex pinning phase diagrams depending on a sort of c-axis pinning centers were proposed. It is considered that those different behaviors in the high field region are related to the interstitial vortices in between the vortices pinned by the c-axis correlated disorders. In addition, we also found that the matching field affects to the scaling properties of the global pinning force density.

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