Effects of c-axis correlated pinning in RE123 superconductors

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Abstract. We studied effects of the c-axis correlated disorder on the vortex liquid state in REBa$_2$Cu$_3$O$_7$ (RE123; RE = rare earth including Y) superconducting bulk samples. The dip structure for B//c-axis in the angular dependent resistivity appears for all samples used in this study. This means the reduction of the dissipation in the vortex liquid state by the c-axis correlated pinning. We analyzed the reduction of the dissipation by the c-axis correlated pinning by using the resistivity difference between on and off the dip, $\Delta \rho_{\text{max}}^n$. We found that $\Delta \rho_{\text{max}}^n$ shows the different field dependence for a part of the NEG123 bulk samples in comparison with those of the Y123 bulk samples. The different field dependence of $\Delta \rho_{\text{max}}^n$ is originated from the different type of the c-axis correlated defects such as twin boundary and probably nanolamella.

1. Introduction

Application-oriented research on c-axis correlated pinning is recently focused, in order to improve a critical current density $J_c$ of REBa$_2$Ca$_3$O$_y$ (RE123, RE = rare earth elements including Y) superconducting materials for B//c-axis. For instance, a BaZrO$_3$ addition in RE123 film fabrication process using a pulsed laser deposition is attempted to make columnar shaped precipitates, and those give rise to an enhancement of $J_c$ for B//c-axis [1]. In addition, the c-axis correlated disorders affect on the vortex state like a phase transformation from the vortex glass to the Bose glass state [2]. In the vortex liquid state, a certain pinned vortex liquid state appears, where the vortices are partially entangled due to the correlated disorders. From this reason, the irreversibility field, corresponding to the phase transition field between the vortex glass and liquid, can be enhanced by the introduction of the c-axis correlated disorders such as twin boundaries and columnar defects, although the random defects decrease irreversibility fields [3].

Whereas, a very high irreversibility field above 14 T at 77.3 K for B//c-axis was achieved in (Nd$_{0.33}$, Eu$_{0.38}$, Gd$_{0.28}$)Ba$_2$Cu$_3$O$_y$ (NEG123) bulk [4]. In this case, the c-axis correlated disorders also play an important role to push up the irreversibility field [5]. In order to improve the irreversibility field, it is important to study the effects of the c-axis correlated disorders in the vortex liquid state. In this article, we measured the high field transport property for various kind of RE123 bulk samples and discuss a role of the c-axis correlated disorders mainly in the vortex liquid state.
Table 1. specification of samples used in this study

| sample | preparation matrix | 211 addition |
|--------|--------------------|--------------|
| NEG-1  | OCMG* (Nd_{0.33}Eu_{0.38}Gd_{0.28})Ba_{2}Cu_{3}O_{y} | 3 mol % NEG211 |
| NEG-2  | OCMG* (Nd_{0.33}Eu_{0.38}Gd_{0.28})Ba_{2}Cu_{3}O_{y} | 40 mol % NEG211 |
| NEG-3  | OCMG* (Nd_{0.33}Eu_{0.38}Gd_{0.28})Ba_{2}Cu_{3}O_{y} | 5 mol % Gd211 |
| Y-1    | MG** YBa_{2}Cu_{3}O_{y} | 33 mol % Y211 |
| Y-2    | MG** YBa_{2}Cu_{3}O_{y} | 33 mol % Y211 |

sample | O₂ anneal
NEG-1  | 600°C 1 h+300°C 150 h
NEG-2  | 600°C 1 h+300°C 150 h
NEG-3  | 600°C 1 h+300°C 150 h
Y-1    | (600°C 2h+450°C 91h)+(600°C 2h+450°C 200h)
Y-2    | (600°C 2h+450°C 91h)+(600°C 2h+450°C 200h)+(300°C 720h)

*Oxygen controlled melt growth, **Melt growth in air

2. Experimental

We prepared five different samples in this study as listed in Table 1. NEG-1 to -3 are (Nd_{0.33}, Eu_{0.38}, Gd_{0.28})Ba_{2}Cu_{3}O_{y} bulk with 3 or 40 mol% NEG211 or 5 mol % Gd211. They include 10 wt% Ag and 0.5 mol% Pt and were fabricated by the oxygen controlled melt growth (OCMG) in 0.1 % O₂-Ar atmosphere [6]. Y-1 and -2 are YBa_{2}Ca_{3}O_{y} bulk with 33 mol% Y211, 10wt%Ag and 0.5 mol%Pt prepared by melt growth process in Air. Those were annealed under the condition indicated in Table 1. In particular, an extra long time O₂ annealing was performed only for Y-2 sample. Therefore, Y-2 sample is predicted to be under the slightly over-dope state. The sample was cut into a bar with dimensions of about 0.15 × 0.2 × 2mm³. This bar shape sample was mounted on a rotated sample holder with cernox and capacitance thermometers and a heater. The sample temperature was controlled by both the He gas flow in a temperature variable cryostat and the 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. Magnetic field angle was defined such that B//c-axis was θ = 0° and transport currents were always perpendicular to the field and c-axis. The transport current density was fixed to be about 10 A/cm² in the present study.

3. Results and discussion

Figure 1 shows the angular dependence of resistivity at 77.3 K for NEG-3 and Y-2 samples. Generally, the angular dependence of a flux flow resistivity in high-$T_c$ oxide superconductors reveals the behavior of the effective mass anisotropy. However, one should notice that the dip structure on the angular dependence of the resistivity appears for both samples. A shape and a width of the dips for both samples seem to be similar each other. Although the depth of the dip strongly depends on the magnetic field and temperature, the width was almost constant. Since a dissipation in the vortex liquid phase was reduced by the c-axis correlation, this dip structure suggests the existence of the pinned vortex liquid state [7]. The reduction of the dissipation in the vortex liquid phase due to the c-axis correlated pinning can be characterized by the difference of the resistivity between on and off the dip. Based on the result in Fig. 1, we selected 0° and 12° as angles on and off the dip, respectively. A comparison of the resistivity normalized by that at 100 K, $\rho_n$, for the Y-2 sample is shown in Fig. 2. The kink on the temperature
dependence of \( \rho \) can be observed only for \( B//c \). The resistivity rapidly decreases with lowering temperature below the characteristic temperature of the kink, \( T_k \) for \( B//c \). On the contrary, the resistivity at \( \theta=12^\circ \) monotonically decreases with decreasing temperature without a kink, and is almost the same as that at \( \theta = 0^\circ \) above \( T_k \). The difference of the normalized resistivity for between \( 0^\circ \) and \( 12^\circ \), \( \Delta \rho_n \), is plotted as a function of temperature in Fig. 3. \( \Delta \rho_n \) decreases to a negative value at first but increases to positive one below \( T_k \) and then has a peak with decreasing temperature. The decrease of the \( \Delta \rho_n \) at higher temperatures comes from the usual effective mass model. Similar behaviors in terms of the resistivity can be found for all samples already mentioned in Table 1 [8]. The increase of the \( \Delta \rho_n \) with decreasing temperature is due to the enlargement of the correlation length of the vortices along c-axis [2]. The correlation length along c-axis diverges at the vortex melting temperature and the vortices go into the Bose glass state, when the c-axis correlated disorder is effective. Here, we define the maximum values of the resistivity difference normalized by the normal resistivity, \( \Delta \rho_n^{\text{max}} \), as characteristic parameters of the dissipation reduction by the c-axis correlated disorders in the pinned liquid state. We depict \( \Delta \rho_n^{\text{max}} \) of various bulk samples as a function of the magnetic field in Fig 4. \( \Delta \rho_n^{\text{max}} \) are monotonically decreases with increasing magnetic field for Y-1, Y-2 and NEG-2 but increases for the NEG-1 and NEG-3. Hence, the field dependence of \( \Delta \rho_n^{\text{max}} \) can be divided into two groups. The c-axis correlated disorder for Y123 is considerably twin boundaries. Whereas, it was pointed out that the array along c-axis of the RE-rich clusters like nanolamella may also work as the c-axis correlated pinning in NEG123 bulk [9]. The nanolamella structure is usually observed only for the narrow range of the RE211 addition from 3 to 10%. Therefore, the effective c-axis correlated disorder is the twin boundary for Y-1, Y-2 and NEG-2 but is probably the nanolamella for NEG-1 and -3. The RE-rich clusters, which are constituents of the nanolamella, have a lower critical temperature than the matrix and hence causes the field induced pinning behavior. The slight increase of the \( \Delta \rho_n^{\text{max}} \) with magnetic field for NEG-1 and 3 as shown in Fig. 4 may be understood by the field-induced pinning behavior as well, because the field induced pinning becomes stronger for higher field up to the certain magnetic field.

4. Conclusions
We measured resistivity in high magnetic fields for various kind of RE123 bulk samples. The reduction of the dissipation due to the c-axis correlated pinning in the vortex liquid state was
observe for all samples used in this study. The dissipation reduction by the c-axis correlated pinning decreases for Y123 and 40 mol% NEG211 added NEG123, but increases slightly for a small amount of RE211 added NEG123 with increasing a magnetic field. These differences can be originated by the different type of c-axis correlated defects such as twin boundary and nanolamella.

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