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Critical current properties in longitudinal magnetic field of YBCO superconductor with APC

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Abstract

The critical current density ($J_c$) properties of the Artificial Pinning Center (APC) introduced YBa$_2$Cu$_3$O$_7$ (YBCO) films in the longitudinal magnetic field were measured. Y$_2$O$_3$ or Y$_2$BaCuO$_5$ (Y211) was introduced as APCs to YBCO, and YBCO films with APC were fabricated on SrTiO$_3$ single crystal substrate. The sizes of Y$_2$O$_3$ and Y211 were 5—10 nm and 10—20 nm, respectively. As a result, $J_c$ enhancement in the longitudinal magnetic field was observed in Y$_2$O$_3$ introduced YBCO films. However, it was not observed in Y211 introduced YBCO films. Therefore, it was considered that $J_c$ properties in the longitudinal magnetic field were affected by introducing of small size APC, and it was necessary that APC does not disturb the current pathway in the superconductor.

Keywords: REBCO; longitudinal magnetic field; artificial pinning center; critical current density

1. Introduction

The REBa$_2$Cu$_3$O$_y$ (REBCO; RE = Rare Earth) coated superconductors have the large critical current density ($J_c$) up to the high magnetic fields, and also have the high critical temperature ($T_c$). Since REBCO coated superconductors have high $T_c$, applications using them can be operated in the liquid nitrogen. The running cost of the device which uses the liquid nitrogen is cheaper than that of the device which uses the liquid helium. Therefore, the REBCO...
coated superconductors are expected to be applied to the various superconducting applications such as the electric power transmission cable, the current limiting device, and so on [1, 2, 3].

In the longitudinal magnetic field in which the magnetic field is parallel to the current flow, Lorentz force does not work to the magnetic flux lines. Thus, \( J_c \) in the longitudinal magnetic field is larger than that in the perpendicular magnetic field [4]. There are some reports of \( J_c \) in the longitudinal magnetic field for the metallic superconductors [5, 6]. Cullen et al reported that \( J_c \) properties in the longitudinal magnetic field of \( \text{Nb}_3\text{Sn} \) superconductor film is 10 times larger than that in self-magnetic field, and the enhancement of \( J_c \) is largely depended on the pinning force by different kinds of dose of the neutron irradiation [6].

Recently, Tsuruta et al reported that \( J_c \) enhancement in the longitudinal magnetic field from \( J_c \) in the self-magnetic field in \( \text{SmBa}_2\text{Cu}_3\text{O}_y \) superconducting film with the Artificial Pinning Center (APC) below 0.6 T. The enhancement of \( J_c \) was observed only APC introduced specimen [7]. It is concluded that the introduction of APC is effective for the enhancement of \( J_c \) properties in the longitudinal magnetic field. Therefore, it is necessary to investigate the effect of the enhancement of \( J_c \) in the longitudinal magnetic field by the APCs properties such as the size, the shape and so on. In this paper, \( J_c \) properties of REBCO specimens with the different size and amount of APC are measured, and the relationship between the properties of APCs and \( J_c \) in the longitudinal magnetic field is discussed.

2. Experimental procedure

The \( \text{YBa}_2\text{Cu}_3\text{O}_7 \) (YBCO) films that used in the present work were fabricated on \( \text{SrTiO}_3 \) single crystal substrate by the pulsed laser deposition (PLD) method. \( \text{Y}_2\text{O}_3 \) or \( \text{Y}_3\text{BaCuO}_5 \) (Y211) was introduced as APCs to YBCO by the target-modified method [8]. In this method, the target with a small piece of APC seeds was used. The quantity of \( \text{Y}_2\text{O}_3 \) is 3 area% and 4 area%, respectively. And the quantity of Y211 is 2 area% and 4 area%, respectively. The shape of \( \text{Y}_2\text{O}_3 \) and Y211 were the particle, and the size were 5—10 nm and 10—20 nm, respectively. Hence the size of \( \text{Y}_2\text{O}_3 \) is smaller than that of Y211. The ratio of pinning center in the superconducting layer of Y211 is larger than that of \( \text{Y}_2\text{O}_3 \), since the size of Y211 is larger than that of \( \text{Y}_2\text{O}_3 \) as shown in Table 1. The thicknesses of the APC doped YBCO layer of \( \text{Y}_2\text{O}_3 \) and Y211 were 170 nm and 300 nm, respectively. Since it is difficult to control the thickness, samples thickness varies. Micro bridge of 80 μm width and 1 mm length was fabricated in the YBCO layer with the APC of each specimen. \( E-J \) properties of each specimen were measured by the four-probe method. The value of \( J_c \) of each specimen was evaluated by using the electric field criteria: \( E_c = 1.0 \times 10^4 \text{ V/m} \). \( J_c \) properties were measured under the longitudinal or the perpendicular magnetic field, in the range from 0 T (self-field: s. f.) to 0.5 T. The arrangement of current \( J \) and external magnetic field \( B \) is shown in Fig. 1. All experiments were performed in liquid nitrogen. Specifications of specimens are listed in Table 1.

| Table 1: Specifications of specimens | shape of | size of | thickness | \( J_c \) (s.f.) |
|-------------------------------------|----------|---------|-----------|---------------|
|                                     | APCs     | APCs[nm]| [nm]      | [GA/m²]       |
| YBCO +4 area% \( \text{Y}_2\text{O}_3 \) | particle | 5—10    | 170       | 49.0          |
| YBCO +3 area% \( \text{Y}_2\text{O}_3 \) | particle | 5—10    | 170       | 40.1          |
| YBCO +4 area% Y211                  | particle | 10—20   | 300       | 19.9          |
| YBCO +2 area% Y211                  | particle | 10—20   | 300       | 16.2          |

3. Results and discussion

Fig. 2 shows the magnetic field dependence of \( J_c \) properties of each specimen in the longitudinal magnetic field and the perpendicular magnetic field. The enhancement of \( J_c \) in the longitudinal magnetic field from that in self-
magnetic field was observed for the specimens with Y$_2$O$_3$. The maximum $J_c$ in the longitudinal magnetic field was observed below $B = 0.3$ T and about 20% larger than that in self-magnetic field of the specimen. On the other hands, the enhancement of $J_c$ in the longitudinal magnetic field was not observed in the specimens with Y211. In addition, $J_c$ in the longitudinal magnetic field of the specimen which contains larger amounts of APCs was higher for each APC. Fig. 3 shows the magnetic field dependence of $J_c$ normalized by $J_c$ in self-magnetic field ($J_c$(s.f.)). The enhancement of $J_c$ ($J_c/J_c$(s.f.)) in the longitudinal magnetic field was more remarkable in the specimen which contains large amount of APCs. From these results, it is found that introducing APCs to superconducting layer is effective to increase $J_c$ in longitudinal magnetic field, and the enhancement of $J_c$ from self-magnetic field in longitudinal magnetic field was observed in the specimen with small APCs (Y$_2$O$_3$). Although, it is effective to introduce APCs to superconductor to improve $J_c$ in longitudinal magnetic field, it is also necessary that the current should be parallel to the external magnetic field. The large APCs may obstruct the current flow. As a result, it seems that external magnetic field and current flow deviates from parallel, and the enhancement of $J_c$ in the longitudinal magnetic field is not observed in the large APCs (Y211). In addition, the thickness of the specimens with Y211 was larger than that of specimens with Y$_2$O$_3$. If the thickness of superconducting layer increases, the homogeneous of specimen seems to decrease. However, it is reported that decrease of $J_c$ is only 15% as increasing thickness of superconducting layer from 170 nm to 300 nm in YBCO+Y211 [9]. Hence, the reason for decrease of $J_c$ in Y211 is ascribed to the larger size of APC.

Fig. 4 shows the magnetic field dependence of $n$-value of each specimen in the longitudinal magnetic field, where $n$-value is determined from $E$-$J$ characteristics from the electric filed region of $10^4$-$10^6$ V/m. The $n$-values of specimen with Y$_2$O$_3$ tend to increase as increasing $J_c$, and take the maximum value at the maximum value of $J_c$. Although the $n$-values increases with increasing $J_c$ in the perpendicular magnetic field, similar results are observed in the longitudinal magnetic field. On the other hands, the $n$-values of the specimen with Y211 tend to decrease in the longitudinal magnetic field. Since the $n$-values tend to increase only for the case of $J_c$ enhancement, it is considered that the $n$-value relates with enhancement of $J_c$ in the longitudinal magnetic field. If the superconductor is highly homogeneous, distribution of $J_c$ is small in the superconductor, and the $n$-value is high. The homogeneousness of superconductor is important for the higher $J_c$ in the longitudinal magnetic field as discussed above. Therefore, it is considered that the current flow and the external magnetic field becomes parallel in the superconductor which has high $n$-value, and the enhancement of $J_c$ in longitudinal magnetic field was observed.

From these results, we should discuss the possibility to have higher $J_c$ in the longitudinal magnetic field. Since the enhancement of $J_c$ was observed in the specimen with 4 area% Y$_2$O$_3$, more enhancement of $J_c$ might be observed in the specimen with 5 area% Y$_2$O$_3$ or 6 area% Y$_2$O$_3$ which size is smaller than 10 nm. In addition, since it is considered that the thickness of specimen affects $J_c$ of specimen with Y211 in the longitudinal magnetic field, the enhancement of $J_c$ might be observed in the thinner specimen with high homogeneous superconducting layer.
4. Conclusion

The \(J_c\) properties of the APC introduced YBCO films were measured. The enhancement of \(J_c\) in the longitudinal magnetic field from that in the self-magnetic field was observed in the specimen with smaller APCs (\(Y_2O_3\)), and not observed in the specimen with larger APCs (\(Y_{211}\)). The maximum \(J_c\) of the specimen with \(Y_2O_3\) in the longitudinal magnetic field was observed below \(B=0.3\) T and is about 20% larger than that in self-magnetic field of the specimen. The \(n\)-values in the longitudinal magnetic field tended to increase when the \(J_c\) increases in the longitudinal magnetic field. It is considered that the size of the APC or the thickness of the specimen affected \(J_c\) in the longitudinal magnetic field, and it is expected that more enhancement of \(J_c\) was observed in the specimen with more amount of \(Y_2O_3\) or the thinner specimen with \(Y_{211}\).

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