WBP1-1

Improvement of uniformity of I_c distributions in long REBCO with BMO coated conductors by in-plume PLD method

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Long $REBa_2Cu_3O_X$ (REBCO, RE: rare earth element) with $BaMO_3$ (BMO, M: metal) coated conductors have been expected for the industrial and commercial applications at high temperatures in magnetic fields. More recently, we fabricated long $EuBa_2Cu_3O_X$ (EuBCO) with $BaHfO_3$ (BHO) coated conductors by the PLD method, which showed the high in-field I_c values of about 120 -140 A/cm-w at 77 K and 3 T [1]. However, in order to realize REBCO with BMO coated conductors for industrial and commercial applications, the much higher uniformity of not only longitudinal and but transversal I_c distributions of long coated conductors with high in-field performance is required.

The in-plume PLD method is performed shortening the target-substrate distance to increase the deposition rate. However, it is difficult to control the deposited REBCO layer composition and the increased supersaturation for in-plume PLD method. To solve these problems, we used the Ba-deficient off-stoichiometric REBCO target and increase the number of multi-plume with scan of X-Y axes directions. Moreover, high uniformity of I_c distributions in long coated conductors by in-plume PLD method can be expected, since the deposition through the inside of multi-plume is less affected by change of plume conditions such as tilt and swing of plume.

We have tried to develop the long EuBCO with BHO coated conductors by the in-plume PLD method with vapor-liquid-solid (VLS) mode [2] and high deposition rate of about 24 nm/s to obtain high in-filed performance and low production cost. As a result, we fabricated the long EuBCO with BHO coated conductors with high uniformity of I_c distributions by the in-plume PLD method comparing with coated conductors by the conventional PLD method. The detail of uniformity of I_c distributions and in-filed performance of long EuBCO with BHO coated conductors fabricated by in-plume PLD method will be discussed.

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Keywords: PLD, long REBCO with BMO coated conductors, uniformity of Ic distributions

WBP1-2

Evaluation of Laser Irradiated $YBa_2Cu_3O_{7-x}$ Film with $BaHfO_3$

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There are many processes available to fabricate $YBa_2Cu_3O_{7-x}$ (YBCO) high temperature superconductor, such as metal organic deposition (MOD) and pulse laser deposition (PLD) [1] .Spin-coating and dip-coating techniques have commonly been applied to coat substrates with the solution in the case of MOD. $BaHfO_3$ (BHO) pinning centers have been introduced to improve superconducting properties of YBCO [2][3]. Laser irradiation is known to be effective for fabrication YBCO, due to braking chemical bond and well mixing the metal components [4]. So it could probably contribute for introduction of BHO pinning centers, so that we applied laser irradiation for MOD of YBCO-BHO system. In this paper, the influence of the laser irradiation was evaluated.

A solution with salts of Y, Ba, Cu, and Hf was prepared to introduce BHO pinning centers, then the solution was coated on a substrate. The substrate was heated to 573 K in a dry oxygen atmosphere and heated to 703 K in a moist oxygen atmosphere for the calcination, then the film was irradiated by laser (The wave length: 532 nm; frequency: 200 kHz) in whole area of the film, homogeneously. After the irradiation, the sample was crystallized at 1073 K for 150 min. In this work, two YBCO films, non laser irradiated sample (sample1) and laser irradiated sample (sample2), were prepared for the comparison of laser irradiation effects. Critical temperature (T_c) was measured by four terminal method, and the microstructures were analyzed by X-ray diffraction (XRD).

T_c of sample1 and sample2 were similar, 90.2 K and 90.5 K. Fig.1 shows XRD-θ/2θ scan results of the two samples after the crystallization. Formation of YBCO with BHO was confirmed for both films, but the intensities of YBCO 00*l* peaks of sample2 were decreased about 50% in comparison to sample1. It was indicating that the quantity of YBCO of laser irradiated film was less than that of non laser irradiated film. No other phases were presented for laser irradiated film. It was considered that laser irradiated YBCO or amorphization might have taken place during the laser irradiation process.

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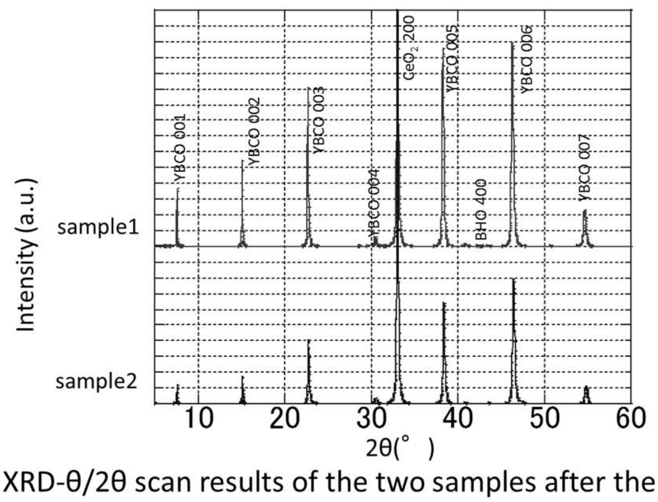

Fig.1 XRD-θ/2θ scan results of the two samples after the crystallization.

Keywords: REBCO, Laser irradiation, MOD, Artificial pinning centers

WBP1-3

3D Study of $EuBa_2Cu_3O_y$ and $GdBa_2Cu_3O_y$ Coated Conductors Using Focused Ion Beam-Scanning Electron Microscopy System

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$EuBa_2Cu_3O_y$ (EuBCO) or $GdBa_2Cu_3O_y$ (GdBCO) layers containing $BaHfO_3$ (BHO) nanorods were deposited on Hastelloy™ tapes with textured CeO_2/$LaMnO_3$/MgO/Y_2O_3/Gd-Zr-O buffer layers by PLD [1]. Nanostructures of these layers were characterized by scanning electron microscopy (SEM) and transmission electron microscopy. In addition, 3D reconstruction of the both EuBCO and GdBCO layers were performed using a focused ion beam-SEM system [2]. Both the EuBCO and the GdBCO layers were mainly composed of *c*-axis oriented EuBCO and GdBCO grains. The average diameter of the BHO nanorods was almost the same value in the both layers, which is 4.5 nm. In addition, outer growth EuBCO or GdBCO grains having different orientations compared with those of a matrix of *c*-axis oriented grains were formed. They were nucleated on CuO grains in the matrix and obstructed supercurrent. In the case of GdBCO layer, the outer growth grains were only seen near the GdBCO surface. On the other hand, Ba-Cu-oxides were found on the surface of *c*-axis oriented EuBCO grains. The Ba-Cu-oxides were considered to be a liquid phase during the PLD process, because those formed large droplet shape. In general, $REBa_2Cu_3O_y$ (RE: rare earth) layers grow in a vapor-solid growth mode in the PLD process. However, the growth mode of the EuBCO layer would be changed from a vapor-solid to a vapor-liquid-solid mode at least within the PLD conditions (temperature, P_{O2} etc.) in this study, which was proved to some extent by existence of Ba-Cu-oxides on the surface [1,2]. The results of 3D reconstruction of the both layers indicated that the volume fraction of the outer growth grains in the matrix of the *c*-axis oriented EuBCO grains were much lower than that in the matrix of the GdBCO. In addition, the voids, which were found between the outer growth grains and the matrix of the GdBCO, were not confirmed in the EuBCO layer, and large Ba-Cu-oxides of a droplet morphology were distributed on the surface of the EuBCO layer [2].
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[1] A. Ibi et al., *Physics Procedia*, **81**, 97-100 (2016).
[2] D. Yokoe et al., *AMTC Letters*, **5**, 154-155 (2016).

Keywords: 3D, FIB-SEM, PLD, Growth mode

WBP1-4

Apparent pinning potential of SmBCO superconducting thin film with BHO artificial pins

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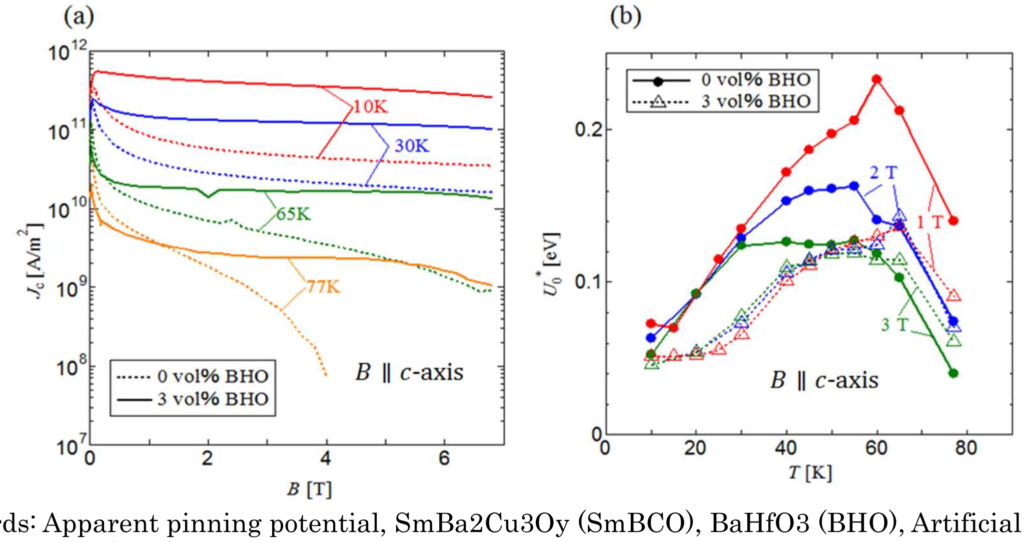
Introduction of artificial pins such as **$BaHfO_3$ (BHO)** is effective for improving the high magnetic field characteristics of the critical current density J_c of oxide superconductors [1]. In particular, excellent J_c characteristics can be obtained when **BHO** is added. Therefore, **$SmBa_2Cu_3O_y$ (SmBCO)** wire with **BHO** added as artificial pins is expected to be introduced into high magnetic field application such as MRI. Since this device will be commonly operated in the high uniformity magnetic field, a decay of superconducting current is required to be suppressed severely. Therefore, it is necessary to clarify the relaxation characteristics of J_c. In this study, in order to investigate the flux pinning characteristics of $SmBa_2Cu_3O_y$ with **BHO** at high concentration, the relaxation characteristics of J_c were measured and the effect of artificial pin addition was investigated. The superconducting sample used in this study is a **SmBCO** thin film on which a superconducting layer was fabricated on the IBAD - MgO substrate by the PLD method. The artificial pin was added at 3 volume% **BHO** and 0 volume% without addition was also prepared. The thickness of the superconductor is d = 250 nm for both samples. J_c was evaluated from the magnitude of the magnetic moment and, U_0^* was evaluated from the time logarithmic relaxation rate of magnetization using a SQUID magnetometer. Figure 1(a) shows the magnetic field dependence of J_c. In the case of 3 volume% BHO showed a constant value in the measurement magnetic field range above 2 T with almost no degradation of J_c value. Figure 1(b) shows the temperature dependence of U_0^*. U_0^* of both sample increases with increasing temperature and shows a peak in the medium temperature region. On the other hand, the U_0^* value is smaller for 3 volume% BHO with higher J_c. It is known that U_0^* has a relationship between the critical current density absence of flux creep J_{c0} and $U_0^* J_{c0}^{2/3}$ in the case of three-dimensional pinning. The reason for low U_0^* of 3 volume% BHO with high J_{c0} is that the pinning correlation distance L in the length direction of the magnetic flux lines is shorter than d. Hence, U_0^* of 3 volume% BHO becomes smaller. This work was partly supported by NU-AIST alliance project. IBAD-MgO substrates were provided by AIST.

[1] Y. Yoshida et al, J. Japan Inst. Met. Mater, 74, (2010), 416 – 421



Keywords: Apparent pinning potential, SmBa2Cu3Oy (SmBCO), BaHfO3 (BHO), Artificial Pinning Center (APC)

WBP1-5

Transport properties of grain boundaries in $SmBa_2Cu_3O_y$ films with $BaHfO_3$ nanorod pinning centers on bicrystal and IBAD substrates over a wide temperature and field range

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Critical current densities (J_c) in $REBa_2Cu_3O_y$ (REBCO) films are significantly suppressed at grain boundaries (GBs) with large tilt angle [1]. Recently, we reported that $BaHfO_3$ (BHO) nanorods improve in-field J_c at GBs in $SmBa_2Cu_3O_y$ (SmBCO) films at 77 K [2]. For further development of the coated conductors (CCs), GB transport in REBCO films with nanorod pinning centers at lower temperature should be investigated. In this work, therefore, we have studied the J_c properties at GBs in BHO-doped SmBCO films at various temperatures (T) and magnetic fields (B) to reveal the effect of nanorod pinning centers on in-field GB transport in REBCO films.
We have fabricated pure and BHO-doped SmBCO films on (001) single-crystal and [001]-tilt bicrystal $(LaAlO_3)_{0.3}$-$(SrAl_{0.5}Ta_{0.5}O_3)_{0.7}$ substrates with misorientation angle (θ) of 5°, 10°, and 15°, and have measured their J_c properties at T from 4.2 to 77 K and in B from self field to 9 T. We defined critical misorientation angle (θ_c) where extrapolation of exponential fitting for J_c at θ = 5°-15° reaches that for the films on single-crystal. Figure (a) and (b) show the mapping images of θ_c as a function of T and B for the pure and BHO-doped films, respectively.
We found that θ_c for the pure films was large at low T and high B (~4.0° at 9 T, 4.2 K), while it was small at high T and high B (~1° at 7 T, 77 K). On the other hand, for the BHO-doped films, θ_c does not depend on T, but on B (3.2 - 6.2° at 0 – 9 T). In comparison, θ_c for BHO-doped films is larger than that for pure films over a wide range of T and B.
These results indicate that, for the application of CCs, modest orientation of REBCO film is required for pure films at low T and high B, and that a wider range of orientation is acceptable for BHO-doped films than for pure films.
We will also report J_c properties of SmBCO films on IBAD-MgO substrates with various orientation to compare it with the study on the bicrystal substrates.
This work was partly supported by JSPS (15H04252, 15K14301, 15K14302, 16H04512, 16H20898), JST-ALCA, and NU-AIST alliance project. The IBAD-MgO substrates we used were manufactured and provided by AIST.

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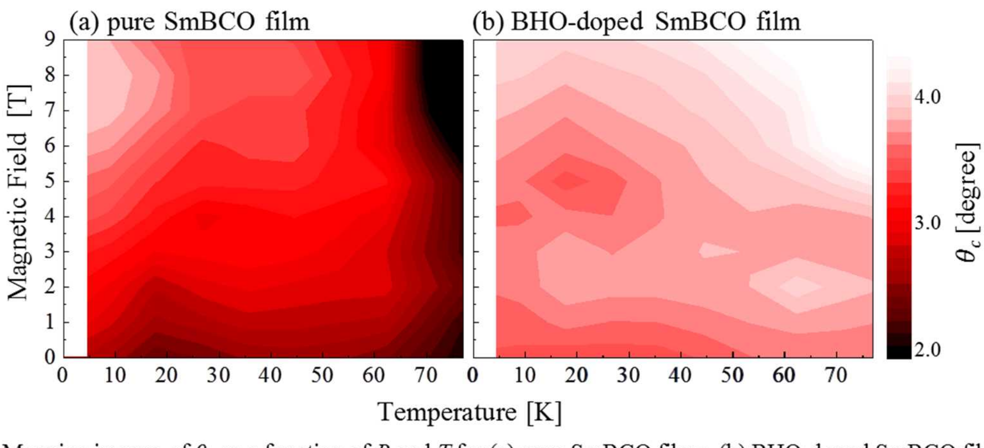

Fig. Mapping images of θ_c as a function of B and T for (a) pure SmBCO films, (b) BHO-doped SmBCO films

Keywords: REBCO, grain boundary, critical current, bicrystal

WBP1-6

The effect of deposition rate of SmBCO thin films on the pinning center formation in the process of reactive co-evaporation

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We investigated the effect of deposition rate of SmBCO thin films fabricated by reactive co-evaporation on the superconducting properties using gradient technique in EDDC (Evaporation using Drum in Dual Chamber) system. The EDDC system is composed of two chambers; reaction chamber and evaporation chamber. A drum is exposed to both reaction and evaporation chamber. Below the drum, a shutter with triangle open area was inserted, and particles only passed through the open area of shutter. By means of this configuration of EDDS system, we could obtain 30 cm long tape sample with deposition rate gradient. We prepared two SmBCO coated tape samples with different drum rotation speed of 50 RPM and 100 RPM. The deposition rate changes continuously from 0 (one end of the tape) to 25 nm/sec (the other end) for both drum rotation speed. But the deposition thickness per one rotation of the drum at 50 rpm drum rotational speed is twice that at 100 rpm. Critical current of the sample at 100 RPM was measured by non-contact Hall Probe method. We found out that as deposition rate increased, the critical current density decreased and saturated in the deposition rate range of more than 15 nm/sec. The critical current density corresponding to the deposition rate of 25 nm/sec was 3MA/cm2. The maximum critical current density was 5 MA/cm2. The critical current of the sample at 50 RPM was lower than that at 100 RPM. Micro structure was analyzed by TEM and XRD. The superconducting properties were measured by PPMS. By virtue of the gradient method, we could obtain optimal deposition conditions of deposition rate and rotation speed.

WBP1-7

Effect of flux pinning force on in-field current carrying capabilities in the force-free state of $REBa_2Cu_3O_y$ films with particulate artificial pinning centers

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Some researchers have reported the longitudinal magnetic field (LMF) effect which includes various peculiar electromagnetic phenomena in the force-free state. Especially, critical current density (J_c) enhancement by the LMF effect in a certain magnetic field compared with those in self-field have been reported, which is called as "J_c gain".

So far, we have reported the J_c gain via the LMF effect in $REBa_2Cu_3O_y$ (RE123) films with multilayered-artificial pinning centers (APCs) at liquid nitrogen temperature. While, some researchers also have showed the J_c gain or its enhancement by doping the particulate APCs. However, we cannot explain the complete flux pinning mechanism and the relationship between the flux motion and its pinning in the force-free state. For power cable application, we need not only to clarify the LMF effect mechanism, but also to suggest the suitable film structure showing high current carrying capability.

In this study, we investigate the LMF effect in RE123 films with particulate APCs such as RE_2BaCuO_5 (RE211) in order to reveal the flux pinning contribution to in-field J_c enhancement in the force-free state. In particular, we focus on the flux pinning force (F_p) in the maximum force state such as *B*//*c* and *B*//*ab* because flux motion in the force-free state includes several directions of the Lorentz force. We fabricated RE123 films with RE211 nanoparticles by pulsed laser deposition method and alternating target technique. These films have periodic multilayered film structure with non-doped RE123 and RE211 doped RE123 layers. We changed the density of RE211 and film thickness of each layer.

As a result, we observed the J_c enhancement, but no J_c gain, in RE211-doped RE123 films in the force-free state compared with a non-doped RE123 film. In addition, we observed the tendency that the higher F_p in *B*//*ab*, in which the Lorentz force acts along *c*-axis of the RE123, may cause the higher J_c in the force-free state. We speculate that the APCs along the *ab*-plane which can pin the flux motion along the *c*-axis contribute the J_c enhancement in the force-free state. We will discuss results of in-field J_c in the force-free state for F_p, the film structures in detail and compare to the other film structures such as multilayered-APCs.

Keywords: flux pinning, force-free state, artificial pinning center