Development of multi-filamentated long EuBCO coated conductors with BHO doping by plane-plume PLD method

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Abstract. Long REBa₂Cu₃Oₓ (REBCO, RE: rare earth element) coated conductors with BaMO₃ (BMO, M: metal) doping have been expected for the industrial and commercial applications. It is known that critical current (Ic) of REBCO coated conductors (with or without artificial pinning centers doping) in magnetic field at high temperature is superior to the other superconducting wires. Especially, we have found that EuBa₂Cu₃Oₓ (EuBCO) coated conductors with BaHfO₃ (BHO) doping show higher critical current density (Jc) and Ic at high temperature in self and magnetic fields than those of YBa₂Cu₃Oₓ and GdBa₂Cu₃Oₓ coated conductors with BHO doping. However, in order to realize EuBCO coated conductors with BHO doping for various applications such as an armature coil, the much higher uniformity of not only longitudinal but transversal Ic distributions of long REBCO coated conductors with high in-field performance for filamentary structure is required. The plane-plume PLD (pulsed laser deposition) method is performed by shortening the target-substrate distance and increasing the number of plumes with scan of X-Y axes directions to increase the deposition rate and averaging the deposition conditions which should relate to obtain the uniformity Ic distributions. We fabricated the EuBCO coated conductors with BHO doping (of 0.6 m length and 10 mm in width) by the combination of the ion-beam assisted deposition (IBAD) and the plane-plume PLD method and then we processed the multi-filamentary structure EuBCO coated conductors with BHO doping (of 8 filaments of 440 µm, 0.6 m in length and 5 mm in width) by using the excimer laser scribing to reduce the AC loss and to control the shielding current. Ic distributions in a width direction of this EuBCO coated conductor with BHO doping was improved as an uniformity of filament-Ic of 4.3 %.

Recently, we fabricated the 16 filamentary and 3 m long EuBCO coated conductor with BHO doping by IBAD / plane-plume PLD method. We confirmed that the hysteresis loss was reduce to 1/16 by a 16 filamentary EuBCO coated conductor with BHO doping comparing with EuBCO coated conductor with BHO doping without filamentation.
1. Introduction

We have been investigating the REBa$_2$Cu$_3$O$_y$ (REBCO, RE: rare earth element) coated conductors with BaMoO$_3$ (BMO, M: metal) doping [1-3]. In our previous work, we found that EuBa$_2$Cu$_3$O$_{7-\delta}$ (EuBCO) coated conductor with BaHfO$_3$ (BHO) doping by IBAD (ion-beam assisted deposition) [4] and PLD (pulsed laser deposition) methods show higher critical current ($I_c$) and critical currents density ($J_c$) at high temperatures in self and magnetic fields than those of other REBCO coated conductors with BMO doping, such as YBa$_2$Cu$_3$O$_{7-\delta}$ and GdBa$_2$Cu$_3$O$_{7-\delta}$ coated conductors with BHO doping. For example, the long EuBCO coated conductor with BHO doping showed high $I_c$ value of 141.2 A/cm-w in the all angles of applied magnetic field of 3 T at 77 K [5].

Recently, the REBCO coated conductors with BMO doping have been expected for the industrial and commercial applications at high temperatures in magnetic fields. However, the much higher uniformity of not only longitudinal and but transversal $I_c$ distributions of long REBCO coated conductors with BMO doping with high in-field performance is required for higher performance in these applications. On the other hand, the multi-filamentated long REBCO coated conductors with BMO doping are effective for the control of the shielding current of the coil and alternating-current loss (AC loss). However, the almost previous work of filamentation for coated conductors has been attempted to pure REBCO coated conductors. Therefore, the multi-filamentary structure was also required in the BHO doped EuBCO coated conductors for the wider industrial and commercial applications.

We have tried to develop the multi-filamentary structure in long EuBCO coated conductors with BHO doping by the plane-plume PLD method and the excimer laser scribing [6].

2. Experimental procedure

The plane-plume PLD method is performed shortening the target-substrate distance (about 70 mm) to increasing the number of plumes (18 plumes) by scan in X-Y axes directions to increase the deposition rate and averaging the deposition conditions which should relate to obtain the uniformity $I_c$ distributions [7-9]. The EuBCO layer with BHO doping were deposited by the plane-plume PLD method with vapor-liquid-solid (VLS) mode on 10 mm wide CeO$_2$ / LaMnO$_3$ / IBAD-MgO / Y$_2$O$_3$ / Gd$_2$Zr$_2$O$_7$ / Hatelloy C-276 substrate [10]. The value of in-plane and out-of-plane texturing degrees ($\Delta\phi$ and $\Delta\alpha$) of CeO$_2$ cap layer were about 2 to 3 and 1 to 2 degrees, respectively. A 200 W industrial XeCl excimer laser with a wavelength of 308 nm was used at a pulse repetition rate of 300 Hz and a pulse energy of 600 to 700 mJ. The optical system is synchronized to the laser pulse and scanning of the laser beam to on a bulk EuBCO target containing BHO was controlled as well. The laser repetition rate at 300 Hz is divided into 18 plumes which are almost the same in size and shape. Typically, the pulse repetition rate of 300 Hz and a pulse energy of 600 to 700 mJ lead the deposition rate of about 24 nm/s for a EuBCO layer with BHO doping. Commercially available targets of sintered off-stoichiometric EuBa$_{1.8}$Cu$_{1.3}$O$_y$ containing 3.5 mol% doped BHO with a diameter of 6-inch were used for deposition of the EuBCO layer with BHO doping. The deposition temperature was about 930 °C for a substrate tape with a transferring speed of 60 m/h. The oxygen pressure was maintained to be at about 800 mTorr with a flow of 10 sccm oxygen. The T-S distance (distance between the target and the substrate) was set about 70 mm although the distance in the conventional PLD method is about 100 mm. The thickness of EuBCO layer with BHO nanorods was about 700 nm for one time deposition with the substrate tape transferring speed of 60 m/h as a typical value. $I_c$ value was measured by the conventional four-terminal method with the criterion of 1 $\mu$V/cm. The multi-filamentary structure was fabricated by using the KrF excimer laser with the wavelength of 248 nm irradiation with Reel-to-Reel system.

3. Results and discussions

In our previous work, figure 1 shows the longitudinal $I_c$ distributions at 77 K and self-field of (a) a 93 m long EuBCO coated conductor with BHO doping by the conventional PLD method with deposition rate of 4.2 nm/s and (b) a 105 m long EuBCO coated conductor with BHO doping by the in-plume (plane-plume) PLD method with deposition rate of 24 nm/s [9]. The EuBCO layers with BHO doping
were about (a) 3.6 \mu m and (b) 0.7 \mu m in thickness, respectively. The transferring substrate through the inside of multi-plume with scan of X-Y (6-3) axes directions (plane-plume) is less affected by the change of plume conditions such as tilt and swing of the plume. Therefore, we thought that the longitudinal $I_c$ distributions shows uniform since few changes in compositional shift of EuBCO layer from target, deposition rate of EuBCO layer (with change optimized deposition temperature), and EuBCO layer thickness.

![Fig. 1 Longitudinal $I_c$ distributions at 77 K and self-field of (a) a 93 m long EuBCO coated conductor with BHO doping by conventional PLD method and (b) a 105 m long EuBCO coated conductor with BHO doping by plane-plume PLD method.](image)

Figure 2 indicates two dimensional $J_c$ distributions of the (a) 93.7 m long EuBCO coated conductor with BHO doping in 10 mm width by conventional PLD method and (b) 20.1 m long EuBCO coated conductor with BHO doping in 10 mm width by plane-plume PLD method by SHPM (Scanning Hall Probe Microscopy) with Reel-to-Reel system. The amplitude of the sheet current density corresponded to that of critical current density almost in all area of the coated conductor except for the region where current direction changed. The uniformity of in-plane $J_c$ distribution of 20 m long EuBCO coated conductor with BHO doping was improved by the plane-plume PLD method.

In our previous work, figure 3 shows the $I_c$ distributions of (a) 0.6 m long EuBCO coated conductor with BHO doping of 8 filaments of 440 \mu m in width by the conventional (out-of-plume) PLD method and (b) 0.6 m long EuBCO coated conductor with BHO doping of 8 filaments of 581 \mu m in width by the plane-plume PLD method. We measured each $I_c$ value of 8 filaments of 440 or 581 \mu m in width and slot of 20 \mu m in width for 0.6 m long EuBCO coated conductor with BHO doping. The variation of each $I_c$ value were (a) 10.4 and (b) 4.3 %, respectively ($\{I_{c \text{ ave.}} / I_{c \text{ min.}}\} / I_{c \text{ ave.}} \times 100 \%$). $I_c$ distribution in a width direction of the EuBCO coated conductor with BHO doping by the plane-plume PLD method was much improved from that of the conventional PLD method.

We fabricated a 100 m long EuBCO coated conductor with BHO doping by plane-plume PLD method and then a 3 m long sample was cut out from this 100 m long EuBCO coated conductor with BHO doping. Furthermore, we processed 16 filamentary structures to this 3 m long EuBCO coated conductor with BHO doping by excimer laser scribing method. Figure 4 (a) indicates photograph of the EuBCO coated conductor with BHO doping of 16 filaments in 10 mm width. We confirmed that the hysteresis loss was reduced to 1/16 by a 16 filamentary and 3 m long EuBCO coated conductor with BHO doping comparing with EuBCO coated conductor with BHO doping without filamentation (figure 4 (b)). From these results, $J_c$ distribution in a width direction of these EuBCO coated conductors with BHO doping by the plane-plume PLD method is also reasonably uniform even in the long coated conductors.
Fig. 2 Two dimensional $J_c$ distributions of the (a) 93.7 m long EuBCO coated conductor with BHO doping in 10 mm width by conventional PLD method and (b) 20.1 m long EuBCO coated conductor with BHO doping in 10 mm width by plane-plume PLD method by SHPM with Reel-to-Reel system.

Fig. 3 Normalized $I_c$ distributions of (a) 0.6 m long EuBCO coated conductor with BHO doping of 8 filaments of 440 $\mu$m in width by conventional PLD method and (b) 0.6 m long EuBCO coated conductor with BHO doping of 8 filaments of 581 $\mu$m in width by plane-plume PLD method.
Fig. 4 A photograph of the EuBCO coated conductor with BHO doping of 16 filaments in 10 mm width and (b) hysteresis loss was reduced to 1/16 by a 16 filamentary and 3 m long EuBCO coated conductor with BHO doping comparing with EuBCO coated conductor with BHO doping without filamentation.

4. Conclusion
We have been investigating the long REBCO coated conductors with BMO doping by IBAD / conventional (out-of-plume) PLD and plane-plume PLD method. The plane-plume PLD is effective to obtain high uniformity of longitudinal and transversal $J_c$ in long EuBCO coated conductor with BHO doping with high deposition rate and high in-field performance because of the transferring substrate through the inside of multi-plume with scan of X-Y axes direction (plane-plume) which less affected by change of plume condition such as tilt and swing of plume.

We evaluated two dimensional $J_c$ distributions of the 20 m long and 10 mm wide EuBCO coated conductor with BHO doping by SHPM with Reel-to-Reel system. As a result, the uniformity of in-plane $J_c$ distribution of 20 m long EuBCO coated conductor with BHO doping was improved by the plane-plume PLD method.

Moreover, we fabricated 16 filamentary and 3 m long EuBCO coated conductors with BHO doping in 10 mm width by IBAD / plane-plume PLD and excimer laser scribing method. We confirmed that the hysteresis loss was reduced to 1/16 by a 16 filamentary and 3 m long EuBCO coated conductor with BHO doping comparing with EuBCO coated conductor with BHO doping without filamentation.

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