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

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**Abstract**. 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. Especially, the multi-filamentary structure long REBCO with BHO coated conductors are effective for control of the shielding current of coated conductor excited by applied magnetic fields and alternating-current loss. We fabricated long $EuBa_2Cu_3O_X$ (EuBCO) with $BaHfO_3$ (BHO) coated conductors by the IBAD/PLD (conventional PLD) method, which showed the high in-field $I_c$ values. 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. We have tried to develop the long EuBCO with BHO coated conductors by the in-plume (plane-plume) PLD method with high deposition rate of about 24 nm/s to obtain high in-filed performance and low production cost. More recently, we fabricated the 105 m long EuBCO with BHO coated conductors with high uniformity of longitudinal $I_c$ distributions of 2.54 % (STDEV) by the in-plume (plane-plume) PLD method comparing with coated conductors by the conventional PLD method. We measured each $I_c$ value of 8 filaments of 581 μm in width and slot of 20 μm in width for 0.6 m long EuBCO with BHO coated conductors by in-plume (plane-plume) PLD method. $I_c$ distribution in a width direction of the EuBCO with BHO coated conductors by in-plume (plane-plume) PLD method is more uniform than that of the conventional PLD method.

## 1. Introduction

$REBa_2Cu_3O_{7-x}$ (REBCO, RE: rare earth element) with $BaMO_3$ (BMO, M: metal) coated conductors [1, 2] have been expected for the industrial and commercial applications at high temperatures in magnetic fields, such as magnetic resonance imaging (MRI) and heavy ion medical accelerator. Recently, we have found that $EuBa_2Cu_3O_{7-x}$ (EuBCO) with $BaHfO_3$ (BHO) coated conductors by IBAD (ion-beam assisted deposition) [3] and PLD (pulsed laser deposition) methods show higher critical current densities ($J_c$) and critical currents ($I_c$) at high temperatures in self and magnetic fields than those of other REBCO with BMO coated conductors. The obtained $I_c$(min) values in the all angles of applied magnetic field of 3 T at 77 K is 133.9 to 141.2 A/cm-w [4]. EuBCO with BHO layer were about 3.6 μm in thickness. As a result of 3D-SEM (Scanning Electron Microscope) images, the volume percentage

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of random oriented grains of EuBCO, CuO and voids etc. which prevent a superconducting current flow in the EuBCO layers were much lower than those in the $GdBa_2Cu_3O_{7-x}$ (GdBCO) layers [4]. Moreover, BHO nanorods in REBCO layers were formed short and thin with uniform distribution in the whole REBCO layers thickness in comparison with $BaZrO_3$ (BZO) and $BaSnO_3$ (BSO) nanorods in REBCO layers [5]. We successfully faricated a 93 m long EuBCO with BHO coated conductor which showed equivalent performance to that of short samples. However, the characteristics of uniformity of $I_c$ distributions and the $I_c$-B-$\theta$ profile of long length EuBCO with BHO coated conductors have not been yet achieved for the industrial and commercial applications.

The in-plume PLD method is performed shortening the target-substrate distance to increase the deposition rate [6, 7]. Moreover, we developed the plane-plume method, which could make the plane area for deposition by scanning the irradiation points of pulsed laser. This method is called as plane-plume PLD and can realize high uniformity of $I_c$ distributions in long REBCO coated conductors by in-plume PLD method can be expected, since it minimize the influence of 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 (plane-plume) PLD method. As a result, we fabricated the long EuBCO with BHO coated conductors with high uniformity of $I_c$ distributions comparing with those by the conventional PLD method.

## 2. Experimental procedure

The EuBCO with BHO layer were deposited by in-plume (plane-plume) PLD method with vapor-liquid-solid (VLS) [8] mode on 10 mm wide $CeO_2$ / $LaMnO_3$ / IBAD-MgO / $Y_2O_3$ / $Gd_2Zr_2O_7$ / Hatelloy C-276 substrates. The value of in-plane and out-of-plane texturing degrees ($\Delta\phi$ and $\Delta\omega$) 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 with BHO layer. Commercially available targets of sintered off-stoichiometric $EuBa_{1.8}Cu_{3.0\ \mathrm{or}\ 3.2}O_x$ containing 3.5 mol% doped BHO with a diameter of 6 inch were used for deposition of the EuBCO with BHO layer. The deposition temperature was about 930 ° C for a substrate tape with a transferring speed of 60 m/h. The oxygen pressure was maintain 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. The thickness of EuBCO layer with BHO nanorods was about 800 nm for one time deposition with the substrate tape transferring speed of 60 m/h as a typical value. $I_c$ values was measured by using the conventional four-terminal method with the criterion of 1 μV/cm. The multi-filamentary structure long EuBCO with BHO coated conductors was fabricated by using the KrF excimer laser with the wavelength of 248 nm irradiation with Reel-to-Reel system [9]. To examine the angular dependence of $I_c$ values on applied magnetic field angle, which was changed from 0 to 180 degrees to *c*-axis (180 degree corresponds to a magnetic field paralleled to the *c*-axis direction).

## 3. Results and discussions

Figure 1 shows (a) the schematic diagrams of our conventional (out-of-plume) and (b) in-plume (plane-plume) PLD system. The in-plume PLD is performed shortening the target-substrate distance to increase the deposition rate. However, the in-plume PLD is difficult to control the deposited REBCO layer composition and the increased supersaturation. 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 (plane-plume PLD).

Figure 2 indicates the longitudinal $I_c$ distributions at 77 K and self-field of (a) a 93 m long EuBCO with BHO coated conductor by conventional PLD method with deposition rate of 4.2 nm/s and (b) a 105 m long EuBCO with BHO coated conductor by the in-plume (plane-plume) PLD method with deposition rate of 24 nm/s. The EuBCO with BHO layer were about (a) 3.6 μm and (b) 0.8 μm in thickness, respectively. The $I_c$ was measured every 0.6 m. The STDEV (standard deviation) of

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longitudinal $I_c$ distributions is improved to 2.54 from 4.02 % by using the in-plume PLD method. The transferring substrate through the inside of multi-plume with scan of X-Y axes directions (plane-plume) is less affected by change of plume conditions such as tilt and swing of 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 etc. Figure 3 shows the longitudinal *n*-values at 77 K and self-field of (a) a 93 m long EuBCO with BHO coated conductor by the conventional PLD method and (b) a 105 m long EuBCO with BHO coated conductor by the in-plume (plane-plume) PLD method. The *n*-value was measured every 0.6 m. The STDEV of longitudinal *n*-values distributions is also improved to 2.49 from 8.42 % by using the in-plume PLD method.

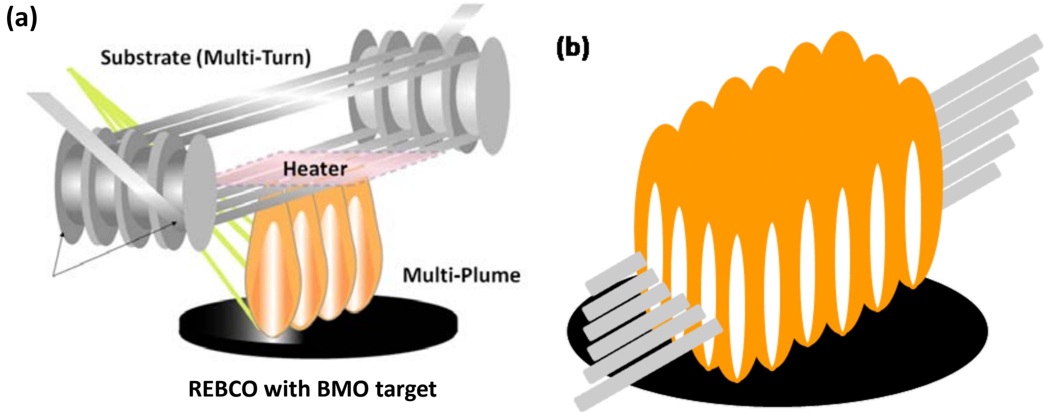


Fig. 1 (a) schematic diagrams of our conventional (out-of-plume) and (b) in-plume (plane-plume) PLD system.

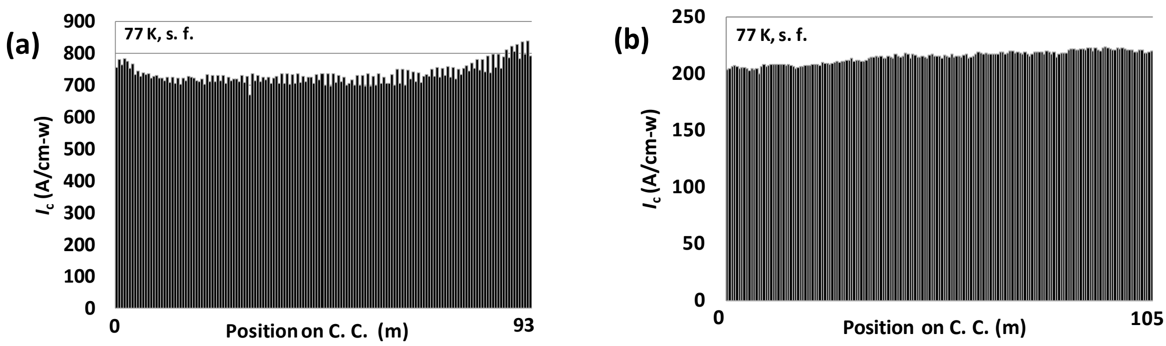


Fig. 2 Longitudinal $I_c$ distributions at 77 K and self-field of (a) a 93 m long EuBCO with BHO coated conductor by conventional PLD method and (b) a 105 m long EuBCO with BHO coated conductor by in-plume (plane-plume) PLD method.

Figure 4 indicates the $I_c$ distributions of (a) 0.6 m long EuBCO with BHO coated conductor of 8 filaments of 440 μm in width by the conventional (out-of-plume) PLD method and (b) 0.6 m long EuBCO with BHO coated conductor of 8 filaments of 581 μm in width by the in-plume (plane-plume) PLD method. We measured each $I_c$ value of 8 filaments of 440 or 581 μm in width and slot of 20 μm in width for 0.6 m long EuBCO with BHO coated conductors. The variation of each $I_c$ value were (a) 10.4 and (b) 4.3 %, respectively ($\{(I_{c\ ave.}) / (I_{c\ min.})\} / I_{c\ ave.} \times 100$ (%)). $I_c$ distribution in a width direction of the EuBCO with BHO coated conductors by in-plume (plane-plume) PLD method is more uniform than that of the conventional PLD method.

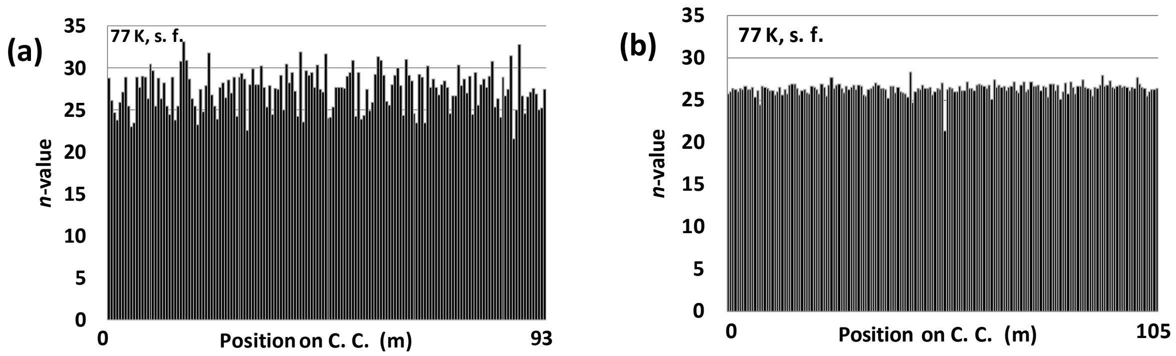


Fig. 3 Longitudinal *n*-values at 77 K and self-field of (a) a 93 m long EuBCO with BHO coated conductor by conventional PLD method and (b) a 105 m long EuBCO with BHO coated conductor by in-plume (plane-plume) PLD method.

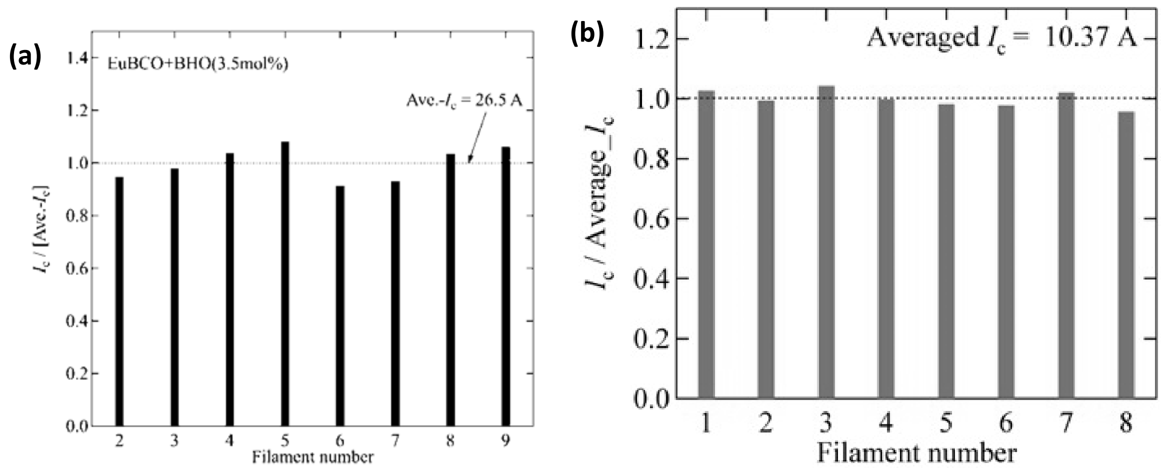


Fig. 4 Normalized $I_c$ distributions of (a) 0.6 m long EuBCO with BHO coated conductor of 8 filaments of 440 μm in width by conventional PLD method and (b) 0.6 m long EuBCO with BHO coated conductor of 8 filaments of 581 μm in width by in-plume (plane-plume) PLD method.

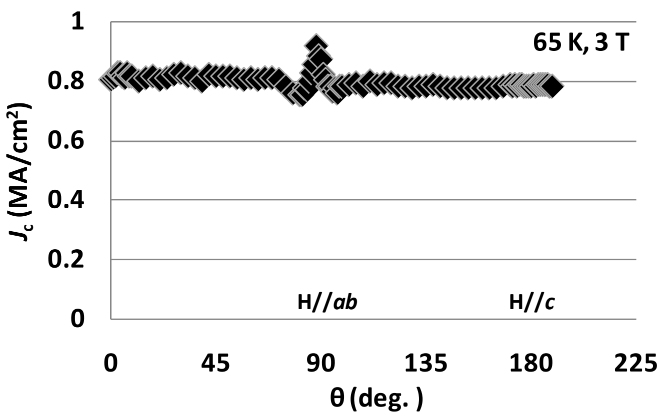


Fig. 5 Angular dependence of applied magnetic field of 3 T on $I_c$ values for EuBCO with BHO coated conductor at 65 K by in-plume (plane-plume) PLD method.

Figure 5 shows the angular dependence of the applied magnetic field of 3 T on the $J_c$ values at 65 K for EuBCO with BHO coated conductor by in-plume (plane-plume) PLD. The EuBCO with BHO layer was about 1.6 μm in thickness. The in-plume (plane-plume) PLD is effective to improve $J_c$ anisotropies in magnetic field at high temperature. It is supposed that the BHO becomes much shorter and random direction in EuBCO layer by the in-plume (plane-plume) PLD method comparing with the conventional PLD method because of supersaturation should increase with increasing deposition rate. In addition, the in-plume PLD method also is considered naturally to introduce lots of stacking faults by the result of TEM images.

## 4. Conclusion

We have been investigating the long REBCO with BMO coated conductors by IBAD / conventional (out-of-plume) PLD and in-plume PLD method. The in-plume PLD is effective to increase the deposition rate with high superconducting characteristics. Moreover, the in-plume (plane-plume) PLD method is also effective to obtain high uniformity of longitudinal and transversal $I_c$ and longitudinal *n*-values distributions in long EuBCO with BHO coated conductors 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 the $J_c$-B-$\theta$ profile at 65 K and 3 T of EuBCO with BHO coated conductor by in-plume PLD method. The in-plume PLD method is also effective to improve $J_c$ anisotropies in magnetic field at high temperature.

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