Remarkable progress in fabricating RE123 coated conductors by IBAD/PLD technique at Fujikura

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Abstract. Increase of production rate and improvement of quality for RE123 coated conductors have been tried. In-plane texturing of MgO was attempted by the IBAD system with the world largest ion source. As a result of optimizing condition in large deposition area, the dramatically high throughput of 1000 m / h was realized to obtain the IBAD-MgO with Δφ < 10°. Furthermore, simple buffer structure was demonstrated. Well textured CeO2 layer with Δφ of around 4° was obtained by directly deposited on IBAD-MgO layer in spite of large lattice mismatch of 28% between CeO2 and MgO. Several over 100 m buffer substrates with the architecture of / PLD-CeO2 (60 m / h) / IBAD-MgO (333~1000 m / h) / Y2O3 (500 m / h) / Al2O3 (150 m / h) / Hastelloy / were already prepared. On these production substrates, GdBCO layer was deposited by the large PLD system at high throughput. The 260 m long GdBCO tape with Ic > 600 A except some locations was obtained at the throughput of 15 m / h. In addition to the speed-up, the very high Ic of 1040 A was also achieved by the hot-wall heating PLD system.

1. Introduction
REBa2Cu3Oy (RE : rare earth elements, RE123) coated conductors are well known to have the potential of low cost and high performance as a superconducting wire. Fujikura has been applying IBAD/PLD technique and recently succeeded in fabrication of 500 m-length GdBa2Cu3Oy (GdBCO) coated conductor with critical current (Ic) of over 300 A / cm [1-3]. The critical current performance reached practical level. However, the limitation of the process speed was still large: Ion-Beam-Assisted-Deposition (IBAD) process speed was 5 ~ 7 m / h and Pulsed-Laser-Deposition (PLD) process speed was 5 ~ 15 m / h at best. In the IBAD process, it was reported that MgO exhibited sharp in-plane texture at only several tens nm, though our conventional Gd2Zr2O7 (GZO) needs great thickness of about 1 μm [4-6]. Hence, the change of the IBAD materials from GZO to MgO will make dramatically high throughput possible. In the PLD process, on the other hand, the slow rate mentioned above was caused mainly by the deposition at low laser power which was 40 ~ 50% of maximum power (180 W). This was because the deposition at high laser power, especially high laser pulse frequency, possibly degrade crystallinity and in-plane texture of the layer and made the stable deposition for the long time difficult. This is the reason why the possibility of the speed-up of PLD process at high laser power was examined.
2. Experimental
On polycrystalline Hastelloy tape (0.1 mm x 10 mm$^2$), Al$_2$O$_3$ layer and Y$_2$O$_3$ layer were deposited by ion beam sputtering technique. The thicknesses of Al$_2$O$_3$ and Y$_2$O$_3$ layer were 150 nm and 20 nm respectively. In-plane texturing of MgO was performed on this substrate by the large IBAD system with the world largest ion source (110 x 15 cm) at the tape speed of 1000 m / h. The assisting ion was Ar$^+$ with the energy of 1200 eV and irradiating direction was 45° from the substrate normal. In plane texture of MgO was evaluated by full width at half maximum of X-ray phi-scan ($\Delta \phi$) of MgO (220) peaks after epitaxially growing another several hundreds nm thick MgO. In the next process, about 500 nm thick CeO$_2$ layer was deposited directly on IBAD-MgO layer by PLD technique. In-plane texture of CeO$_2$ was evaluated by $\Delta \phi$ of CeO$_2$ (220) peaks and atomic structure of CeO$_2$/MgO interface was observed by transmission electron microscopy (TEM). GdBCO superconducting layers were deposited on these substrates by using 2 types of large reel-to-reel PLD systems with different heating system; contact heating system (type 1) and hot-wall heating system (type 2) as shown in Figure 1 and Figure 2.

![Figure 1. Schematic illustration of reel-to-reel PLD system with contact heating (the type 1).](image1)

![Figure 2. Schematic illustration of reel-to-reel PLD system with hot-wall heating (the type 2).](image2)

They have multi lanes and function of scanning laser beam. Laser source is KrF excimer and its maximum power is 180 W and all GdBCO films in this paper were deposited at the laser power of maximum 180 W. The tape speed was 40 ~ 80 m / h and the deposition was repeated to thicken GdBCO layer. A critical current ($I_c$) was measured by a 4-probe method at 77K in a self-field or 3 T. The criterion of $I_c$ was 1 $\mu$V/cm.

3. Results and discussion
3.1. Preparation of long in-plane textured buffer tape based on IBAD-MgO
IBAD-MgO layer fabricated by the large IBAD system exhibited sharp in-plane texture of $\Delta \phi < 10^\circ$ as shown in Figure 3. Furthermore, CeO$_2$ layer directly deposited on IBAD-MgO layer also exhibited sharp in-plane texture of $\Delta \phi = 4^\circ$ as shown in Figure 4. Figure 5 shows the cross sectional TEM image at the interface between IBAD-MgO and PLD-CeO$_2$. From this figure, it is revealed that MgO and CeO$_2$ layer aligned on Y$_2$O$_3$. MgO<001> and CeO$_2$<001> are parallel to the substrate normal, and MgO<100> and CeO$_2$<100> are horizontal to the substrate normal. Lattice mismatch between MgO and CeO$_2$ is 28.5% in this orientation relationship. But there are no secondary phase and amorphous layer at the interface.
Then, we fabricated a 1 km long IBAD-MgO film at the throughput of 1000 m / h. To evaluate in-plane texture of IBAD-MgO, PLD-CeO$_2$ layers were fabricated on short samples cut from each 20 m of 1 km long IBAD-MgO tape. Figure 6 shows in-plane textures of CeO$_2$ films and tape positions. It indicates that IBAD-MgO film at the throughput of 1000 m / h had stable property. An average of in-plane textures were 4.1° and a standard deviation was 0.1°.

Next, GdBCO superconducting layer was formed on such substrates in order to verify the actual critical current performance. High critical current density ($J_c$) of over 3MA / cm$^2$ was obtained at 1.0 µm thick GdBCO film. It was confirmed that the substrates with the architecture of / PLD-CeO$_2$ (60 m / h) / IBAD-MgO (333~1000 m / h) / Y$_2$O$_3$ (500 m / h) / Al$_2$O$_3$ (150 m / h) / Hastelloy / could produce high quality GdBCO coated conductors and we already prepared several over 100 m substrates with such architecture.
3.2. High critical current and high throughput in PLD-GdBaCO process

GdBaCO films with high $I_c$ were fabricated at the high throughput by the type 1 PLD system. Figure 7 shows the GdBaCO thickness dependence of $I_c$ and its throughput.

$I_c > 300$ A and $J_c > 3$ MA/cm$^2$ was achieved at the GdBaCO throughput of 45 m/h. Several over 100 m long tapes with $I_c$ of completely over 300 A were already obtained at the GdBaCO throughput of 40 m/h. Furthermore, Figure 7 indicates that $I_c$ increased along with the GdBaCO thickness up to about 3.5 μm. Then we attempted the fabrication of the over 200 m long tape with high $I_c$ at the GdBaCO throughput of 15 m/h. The longitudinal $I_c$ distribution of this long tape is shown in Figure 8.
$I_c > 600$ A except for several locations was achieved. These several low $I_c$ points were possibly caused by defects of substrate and removable by enhancement of polishing and cleaning substrate. Since this long tape showed great self-field $I_c$, in-field $I_c$ was also measured. This GdBCO sample with self-field $I_c = 610$ A exhibited high $I_c$ of 42 A at 77 K and 3 T (B // c-axis). Long tapes with high $I_c$ like this expected to enable the power electric application small.

On the other hand, the type 2 PLD system produced higher $I_c$ than the type 1. Figure 9 shows the thickness dependence of $I_c$ for short GdBCO samples fabricated by the type 2 PLD. $I_c$ increased along with the GdBCO thickness up to 6 μm and reached the great high value of 1040 A. It was confirmed that high crystallinity was kept up to 6 μm thick from the cross-sectional TEM image as shown in Figure 10.
4. Summary
Increase of production rate and improvement of quality for RE123 coated conductors were performed. In IBAD process, Bi-axially textured MgO layer was successfully obtained by the IBAD system with the world largest ion source. As a result of further optimization of condition in large deposition area, the dramatically high throughput of 1000 m/h was realized to obtain the IBAD-MgO with $\Delta \phi < 10^\circ$. In addition, simple buffer structure was demonstrated. Well textured CeO$_2$ layer with $\Delta \phi$ of around $4^\circ$ was obtained by directly deposited on IBAD-MgO layer in spite of large lattice mismatch of 28% between CeO$_2$ and MgO. Several over 100 m buffer substrates with the architecture of / PLD-CeO$_2$ (60 m/h) / IBAD-MgO (333~1000 m/h) / Y$_2$O$_3$ (500 m/h) / Al$_2$O$_3$ (150 m/h) / Hastelloy / were already prepared. On these production substrates, GdBCO layer was deposited by the large PLD system. The GdBCO layers with high $J_c$ was successfully obtained at even the high laser power of 180 W. At the short sample experiment, GdBCO throughput reached 45 m/h for $I_c > 300$ A and 15 m/h for $I_c > 600$ A. Finally, the 260 m long GdBCO tape with $I_c > 600$ A except some locations was obtained at the throughput of 15 m/h. In addition to the speed-up, the very high $I_c$ of 1040 A was also achieved by the hot-wall heating PLD system. Fujikura are now ready for fabricating several tens km GdBCO coated conductors with high critical current performance.

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References
[1] Y. Iijima, N. Tanabe, O. Kohno, Y. Ikeno, 1992  *Appl. Phys. Lett.* 60 769.
[2] H. Fuji, M. Igarashi, Y. Hanada, T. Miura, S. Hanyu, K. Kakimoto, Y. Iijima, T. Saitoh, 2008  *Physica C* 468 1510.
[3] M. Igarashi, H. Fuji, K. Kakimoto, S. Hanyu, T. Miura, Y. Hanada, T. Hayashida, Y. Iijima, T. Saitoh, 2008  *Abstracts of CSJ Conference* 78 113.
[4] C. P. Wang, K. B. Do, M. R. Beasley, T. H. Geballe and R. H. Hammond, 1997  *Appl. Phys. Lett.* 71 2955.
[5] P. N. Arendt, S. R. Foltyn, 2004  *MRS Bull.* 29 543.
[6] V. Selvamanickam, Y. Chen, X. Xiong, Y. Y. Xie, J. L. Reeves, X. Zhang, Y. Qiao, K. P. Lenseth, R. M. Schmidt, A. Rand, D. W. Hazelton, K. Tekletsadik, 2007  *IEEE Trans. Appl. Supercond.* 17 No.2, 3231.