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Progress towards nanostructured SmBCO film for controlling pinning properties

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Abstract. We have studied the artificial pinning center (APC) techniques in Sm$_{1+xBa_{2-x}}$Cu$_3$O$_y$ (SmBCO) films deposited on single crystalline substrates. As a result, using the Low Temperature Growth (LTG)-PLD technique, $J_c$ of 0.28 MA/cm$^2$ at 77 K, $B=5$ T ($B \parallel c$) was obtained on 700 nm thick SmBCO films grown on 50 nm thick SmBCO-seed bufferd MgO substrate. Following the successful demonstration of the growth of SmBCO films on single crystalline substrate, the LTG technique was also extended to coated conductor on metal substrates. With the objectives of applying the superconducting magnetic application that operate at liquid nitrogen temperature, we report the $J_c$ in magnetic field and the microstructure of SmBCO coated conductor. PLD-SmBCO with a $J_c$ of over 0.1 MA/cm$^2$ at 5 T ($B \parallel c$, 77K) were grown on IBAD-YSZ/CeO$_2$ tape, which is higher than YBCO/IBAD. In addition, the $J_c$
1. INTRODUCTION

Recently many groups studied YBa$_2$:Cu$_3$:O$_y$ (YBCO) coated conductor and superconducting application that operate at liquid nitrogen temperature (77 K). We have studied the artificial pinning center (APC) techniques using the controlling microstructure for high superconducting properties in magnetic filed. Our groups classified 0, 1, 2 and 3 dimensional APC introduced into REBa$_2$:Cu$_3$:O$_y$ (REBCO) films. For example, The 0-dimensional APCs techniques are introduced with Co- and Zn-doped REBCO superconducting film [1]. The 1-dimensional APCs are dislocations and columnar defects [2]. The 2-dimensional APCs are grain boundaries and antiphase boundaries, and the 3-dimensional APC is impurity phase, respectively.

We have studied the growth mechanism and superconducting properties of SmBCO films. Table 1 shows the superconducting properties of the SmBCO films on deposited on single crystalline substrates by the conventional pulsed laser deposition (PLD) method and the novel PLD method from Ref. 3-6.

In particular, we have presented a low temperature method, the LTG technique, which is capable of fabricating SmBCO thin films at low temperature with high superconducting properties, comparable to those of YBCO thin films. The superconducting properties of the SmBCO thin film prepared using the LTG method were evaluated and its micro-structure was observed. The results confirm that $c$-axis oriented thin films with favorable properties can be obtained at a growth temperature of 100 °C lower than the temperature required for the fabrication of an SmBCO thin film using the ordinary PLD method [7], and that the $J_c$ property of the LTG-SmBCO thin film in the magnetic field is dramatically improved compared to the PLD-SmBCO thin film, exhibiting a high value of $J_c=0.28$ MA/cm$^2$ (77 K, $B//c$, 5 T)[4]. This value is comparable to that of NbTi, which is used for the fabrication of wires operating at 4.2 K. Based on the angle dependence of $J_c$ under the applied magnetic field, we also confirmed that the PC at the interior of the LTG-SmBCO thin film is isotropic. Also, based on observations of the microstructure by TEM analysis, we confirmed the existence of an Sm/Ba solid solution phase inside the LTG-SmBCO thin film, ranging in size from 50 to 100 nm. We speculate that the $J_c$ value for the LTG-SmBCO thin film in the magnetic field improves when the solid solution phase is a 3-dimensional APC [8].

Furthermore, nanoparticles and crystalline defects were created as the flux pinning in a high-$J_c$ SmBCO film during a film deposition process. We obtained extremely high $J_c$ values, $J_c=0.37$ MA/cm$^2$ (77 K, $B//c$, $B=5$ T) and $J_c=0.1$ MA/cm$^2$ (77 K, $B//c$, $B=8$ T) [5],[6]. From the elemental mapping by TEM-EDX, it appears that the regions of the high Sm composition, which is consistent with $0.08<x<0.16$, extends into SmBCO matrix phase, forming the network structure. We concluded the Sm-rich regions, formed nano-network and nano-particle, playing as the flux pinning in high $J_c$ SmBCO Films [6],[9].

It has confirmed that the SmBCO system offers great potential as a coated conductor in high temperature superconducting magnets. With the objectives of applying the SmBCO coating, the objectives of applying the SmBCO coated conductor on metal substrate is comparable to the best results of SmBCO films on MgO single crystalline substrates.

| TABLE 1 | PLD | LTG |
| --- | --- | --- |
| on MgO | $B_{c1} \sim 7.7$T, $J_c=0.5$ MA/cm$^2$ @77K, $J_c=0.87$MA/cm$^2$ @77K, 5T | $B_{c1} \sim 10.5$T @77K, $J_c=0.37$ MA/cm$^2$ @77K, 5T |
| LTG | $B_{c1} \sim 10.8$T @77K, $J_c=0.23$ MA/cm$^2$ @77K, 5T |

It has confirmed that the SmBCO coated conductor on metal substrate is comparable to the best results of SmBCO films on MgO single crystalline substrates.
coated conductor, we report the critical current ($I_c$) of thick SmBCO film and the $J_c$ in magnetic field of SmBCO film on the metal substrates.

2. Experimental

We fabricated an SmBCO film on a MgO (100) substrate and IBAD tape by the PLD method using an ArF ($\lambda=193$ nm) excimer laser. The substrate was placed opposite the SmBCO target at a distance of 50 mm. The repeating frequency of the excimer laser employed was 10 Hz with an approximate energy density of 1.0 J/cm$^2$. The partial pressure of oxygen during the growth process was fixed at 0.4 Torr. After thin film deposition, oxygen gas was introduced up to 20 Torr and the film was cooled rapidly. The laser target was prepared using the solid-phase reaction method with a loading of 50 mm. The repeating frequency of the excimer laser employed was 10 Hz with an approximate energy density of 1.0 J/cm$^2$. The partial pressure of oxygen during the growth process was fixed at 0.4 Torr. After thin film deposition, oxygen gas was introduced up to 20 Torr and the film was cooled rapidly. The laser target was prepared using the solid-phase reaction method with a loading composition of Sm$_{1+\delta}$Ba$_{2-x}$Cu$_3$O$_y$ ($x=0$ to 0.18).

The superconducting properties and the electric resistivity $\rho$ of the SmBCO film were measured using the 4-probe method. Magnetic fields at 77 K ranging from 0 to 9 T were applied parallel to the c-axis of the REBCO film. To evaluate the angle-dependency of $J_c$, the magnetic field, measurements were taken with the angle of the applied magnetic field varied from $0^\circ$ to $135^\circ$ at temperatures $\leq$77 K for applied magnetic fields from 0 to 9 T. For $J_c$ measurements, samples were patterned into micro-bridges approximately 100 µm wide and 200 µm long. The $I_c$ criterion for the determination of $J_c$ during $I$-$V$ measurement was defined as a voltage of 1 µV/cm. Before $J_c$ and $T_c$ values were determined, the REBCO film was annealed at 350°C in an oxygen stream for 1 hour.

The micro-structure of the REBCO film was observed and its Sm/Ba composition $x$ was measured using a transmission electron microscope (TEM) equipped with an energy dispersive X-ray spectroscope (EDX). The orientation of the REBCO film was analyzed using $\theta$-2$\theta$ X-ray diffraction and $\Phi$ scanning with a Cu-K$_\alpha$.

3. Results and discussion

3.1 SmBCO thick films on MgO for high $I_c$

From the surface morphology of the SmBCO film, the terrace of the steps on the film surface were smooth, which was changed growth mode shifts from 3D island growth to atomically flat 2D layer-by-layer growth as the Sm-Ba substitution [10]. To circumvent the problem of deteriorating microstructure in films above 1 µm thickness, we have introduced an approach in which 50 nm thick layers of Sm-rich SmBCO (Sm$_{1.01}$Ba$_{1.99}$Cu$_3$O$_y$) layers are intercalated between 0.25 µm thick stoichiometric SmBCO layers. Figure 1 shows the dependence of the ratio of $a$-axis oriented on film thickness in the SmBCO single-layer films and multi-layer films. In the figure, the vertical axis indicates values calculated from diffraction peak intensities of the (200) and (007) planes. The SmBCO single-layer film, deposited by the conventional PLD method using the stoichiometric SmBCO targets, exhibits

![Fig. 1](image-url)
c-axis orientation in the 0.5 μm thick, but above the 1.0 μm thick a-axis orientation grains increases as the thickness increases. A similar trend has also been reported in the YBCO case [11]. On the other hand, in the SmBCO multi-layer film on MgO deposited using the Sm$_{1.08}$Ba$_{1.92}$Cu$_3$O$_y$ and the stoichiometric SmBCO targets, a-axis oriented grains did not occur even when the thickness was increased above the 1.5 μm thick. Thus the novel multi-layer technique is capable of fabricating SmBCO thick films with mainly c-axis orientation at the thickness above 1.5 μm. Furthermore from the surface morphologies measured by AFM images, the resulting films show a much better surface than standard SmBCO single-layer film of comparable thickness.

Fig.2 shows the thickness in the SmBCO thick film dependence on the critical current density at 77K, self field. The $J_c$ values for the SmBCO thin films with a thickness below 0.5μm using the conventional PLD and multilayer-PLD method are nearly the same, namely, about 5-6 MA/cm$^2$. The behaviors of these thickness-dependent $J_c$ values, however, are completely different. $J_c$ of SmBCO single-layer films decreases as the thickness increases. Nevertheless, $J_c$ of SmBCO multi-layer film remains unchanged in the entire thickness range. The $J_c$ value reaches 5 MA/cm$^2$ ($I_c=800$A/cm-W) with the thickness of 1.7μm at 77 K, which is two times higher than that of the conventional PLD films.

3.2 SmBCO coated conductor on IBAD tape for high J$_c$ in high magnetic field

From our results about SmBCO films on single crystalline substrate, we will discuss the SmBCO coated conductor on metal substrates with the objectives of applying the superconducting magnet. The PLD-SmBCO coated conductors were deposited at 830°C on PLD-CeO$_2$ / IBAD-YSZ / Hastelloy (IBAD-tape). Furthermore, we have developed LTG-coated conductor, which is a seed layer technique, thin Sm-riched SmBCO (Sm$_{1.08}$Ba$_{1.92}$Cu$_3$O$_y$) layer with a thickness of 100 nm are deposited at $T_s=860$°C on IBAD-tape prior to the deposition of thicker SmBCO layer at $T_s=780$°C.

Fig.3 shows the magnetic field dependence of $J_c$ in LTG-SmBCO and PLD-SmBCO on IBAD-tape at 77 K. Magnetic fields were applied
perpendicular to the film surface. For comparison, the figure also gives literature values to NbTi (4.2 K) [12] and YBCO on IBAD (75.5 K) [13]. The LTG-SmBCO coated conductor /IBAD was confirmed to provide an improved \( J_c \) in magnetic field as compared with the conventional PLD-SmBCO/IBAD and YBCO/IBAD coated conductor. The PLD-SmBCO coated conductor had \( J_c = 0.11 \text{ MA/cm}^2 \) (77 K, \( B//c, B=5 \text{ T} \)). In addition, the LTG-SmBCO coated conductor achieved the highest value of \( J_c = 0.24 \text{ MA/cm}^2 \) (77 K, \( B//c, B=5 \text{ T} \)), these \( J_c \) values are equal to that of NbTi wire measured at 4.2K.

Fig. 4 shows the \( J_c-B-\theta \) curves for LTG-SmBCO, PLD-SmBCO and YBCO coated conductors measured at 77K, 3T. The LTG-SmBCO coated conductor exhibits less variation in \( J_c \) with PLD-SmBCO and YBCO coated conductor. It can be inferred that LTG-SmBCO coated conductor contains as isotropic PC, which is similar to the SmBCO films on single crystalline substrate [8].

From the pinning force calculated by \( F_p = J_c B \), the maximum \( F_p \) value of LTG-SmBCO coated conductor and PLD-SmBCO coated conductor reached about 15 and 7 GN/m³ at 77 K, respectively. On the other hand, the \( F_{p,max} \) value of the LTG-SmBCO film on the MgO is 18 GN/m³ at 77 K.

High \( J_c \) and pinning force values in magnetic field demonstrate the potential of the SmBCO film on the metal substrate, which is similar to the results on the film on the single crystalline substrate.

4. Conclusion

We have demonstrated the successful fabrication of a high performance SmBCO thick film on MgO and coated conductor on metal substrate, shown as Table 2. An \( I_c \) of 800 A/cm-w was obtained on SmBCO film grown by the novel multi-layer technique with the 1.7μm thick. Further, the \( J_c \) of SmBCO coated conductor grown with the LTG technique achieved 0.24 MA/cm² (77K, 5T), which values are equal to that of NbTi (4.2K, 5T). This performance is comparable to the best SmBCO results on MgO single crystalline substrate.

Table 2

| SmBCO  | PLD     | LTG    |
|--------|---------|--------|
|        | on YSZ-IBAD | LTG LTG-nano |
|        |          |        |    |
|        | \( B_{u}=9.2 \text{ T} \) @77K | \( B_{u}=10.3 \text{ T} \) @77K |
|        | \( J_c=3.0 \text{ M A/cm}^2 \) @77K,5T | \( J_c=0.24 \text{ M A/cm}^2 \) @77K,5T |

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