Evaluation of superconducting properties for YBa$_2$Cu$_3$O$_y$ coated conductors fabricated by self-heating technique in Pulsed Laser Deposition method

W. Sato, Y. Tsuchiya, Y. Ichino and Y. Yoshida
Department of Electrical Engineering, Nagoya University, Furo-cho, Chikusa-ku, Nagoya 464-8601 Japan
E-mail: sato.wataru@e.mbox.nagoya-u.ac.jp

Abstract. We fabricated YBa$_2$Cu$_3$O$_y$ coated conductors with 0.4 - 4.0 μm in the thickness on IBAD-MgO template deposited on Hastelloy metal substrates which were heated by a self-heating (S-H) technique in pulsed laser deposition method. The self-heating (S-H) technique is a method to heat a metal substrate by the Joule heat. In addition, preset substrate temperature ($T_s$) was gradually changed during the film deposition. It is possible to suppress a-axis grains even in a thick film by the S-H technique. Critical current density ($J_c$) and critical current ($I_c$) reached 2.0 MA/cm$^2$ and 800 A/cm-width in a film with the thickness of 4.0 μm at 77 K and self-field.

1. Introduction
REBa$_2$Cu$_3$O$_y$, (REBCO) coated conductors (CCs) are used for superconducting magnetic energy storage (SMES), magnetic resonance imaging (MRI), high temperature superconducting cables and generators. They would greatly benefit from further increase of critical currents ($I_c$). In order to improve the $I_c$, it is essential to increase the film thickness while maintaining the high critical current density ($J_c$). However, it has been reported that a-axis oriented grains are generated as the film thickness increases and $J_c$ decreases [1]. The occurrence of a-axis grains is due to decrease of substrate surface temperature during the deposition. Thus, many research groups have studied the method of heating substrate. Some typical heating methods are a cold wall and a hot wall technique. Figure 1 shows the cold wall technique. A substrate is heated by using a heater [2]. It is difficult to keep the surface temperature constant during the deposition because of the indirect heating from the underside of the tape. Although this technique has such characteristics, we could fabricate Sm$_{1+δ}$Ba$_2$Cu$_3$O$_y$ multilayer thick films with insertion of Sm-Rich Phase [3]. The hot wall technique can easily keep the surface temperature constant due to the direct radiant heating of the surface and thermal insulation effectiveness of the closed box structure.
Fujikura Ltd. reported that GdB$_2$Cu$_3$O$_{6+x}$, CCs with the thickness of about 6 μm could be fabricated using the hot wall technique [4]. On the other hand, in Figure 2, a self-heating (S-H) technique is a technique to heat the substrate by the Joule heat after applying a heating current through the Hastelloy metal substrates [5]. This technique provides rapid thermal response compared with the conventional heating technique that heats the substrate with a heater [6]. Ruipeng et al. and Selvamanickam et al. reported that successful fabrication of multilayer Gd$_{0.5}$Y$_{0.5}$Ba$_2$Cu$_3$O$_7$ thick CCs and Zr-doped (Gd,Y)Ba$_2$Cu$_3$O$_7$ thick film using this technique [7, 8]. Furthermore, when the substrate surface temperature decreases, the substrate surface temperature can be kept constant by momentarily raising the preset substrate temperature. Therefore, it is expected to suppress a-axis grains even in a thick film by the S-H technique. In this study, we evaluated the superconducting properties for YBa$_2$Cu$_3$O$_7$ (YBCO) CCs fabricated by pulsed laser deposition (PLD) method with the S-H technique in order to suppress the generation of a-axis oriented grains.

2. Experimental details

We fabricated YBCO films on biaxially textured oxide buffer layer of IBAD-MgO substrates which were heated by S-H technique in pulsed laser deposition (PLD) method using a Nd:YAG pulsed laser (wavelength : $\lambda = 266$ nm, repetition frequency : $f = 10$ Hz ). Preliminary experiment, a relationship between a surface temperature of the buffer layer and a heating current was measured and the temperature controlled by the heating current was stand as $T_s$. The $T_s$ was controlled according to the following equation (1) during the film deposition.

$$ T_s(t) = T_{s\infty} - (T_{s\infty} - T_{s0}) \exp(-t / \tau) $$

In equation (1), $T_{s0}$ is initial $T_s$ at $t = 0$, $T_{s\infty}$ is final $T_s$ at $t = \infty$, and $\tau$ is the time constant. In this study, we fabricated YBCO films of which thicknesses were from about 0.4 to 4.0 μm was prepared under the conditions of $T_{s0} = 850^\circ$C, $T_{s\infty} = 1045^\circ$C, $\tau = 1250 - \infty$ sec, oxygen partial pressure $P_{O2} = 400$ mTorr, and laser energy density $D = 1.25$ J/cm$^2$. During the deposition, a back side temperature ($T_{b\infty}$) of REBCO deposited side were measured using pyrometer (emissivity : $\varepsilon = 0.30$) every 5 minutes. In other words, $T_{b\infty}$ is a temperature of hastelloy. In order to reduce oxygen deficiency, post annealing in an oxygen atmosphere of about 1 atm was performed before a measurement of transport properties. Crystal orientation of the films were checked by X-ray diffraction (XRD) method, and inductively coupled plasma (ICP) emission spectroscopy was used for evaluation of film thickness. $J_c$ were measured by the DC four-probes method.
3. Results and discussion

3.1. Thickness dependence of $T_{b.s.}$ and $\tau$

Figure 3 shows time dependence of $T_d(t)$ calculated by equation (1) when $\tau$ was changed. It is confirmed that $T_d(t)$ was increased by decreasing $\tau$. Figure 4 shows thickness dependence of $T_{b.s.}$ when $\tau$ was changed. The value on the horizontal axis was calculated from the deposition rate and the deposition time. Because $T_{b.s.}$ was observed using pyrometer, it is possibility that the emission of the plume was measured, but we confirmed that $T_{b.s.}$ did not change with and without the plume. In the case of $\tau = \infty$ corresponding to constant $T_s$ during the deposition, it is found that $T_{b.s.}$ is decreased as the film thickness increase. As the film thickness increases, the surface roughness of the YBCO film increases. Therefore, it is considered that $T_{b.s.}$ decreased due to change of the surface emissivity by surface roughening [9]. On the other hand, it was observed that $T_{b.s.}$ was maintained when $\tau = 1250$ and 1500. Decrease of surface temperature due to the surface roughening is compensated by $T_d(t)$ change.

3.2. Thickness dependence of XRD peak intensity ratio and $\tau$

The occurrence of $a$-axis grains is due to decrease of surface temperature during the deposition. In this study, it is expected that generation of $a$-axis grains was suppressed by $T_d(t)$, because $T_{b.s.}$ was maintained as mentioned above. Figure 5 shows thickness dependence of XRD intensity ratio of $I_{(200)} / (I_{(200)} + I_{(005)})$ depending on $\tau$. It is observed that the $a$-axis oriented grains increased as the film thickness increases at $\tau = \infty$, which corresponds to a conventional cold-wall heating technique. Remarkably, by increasing $T_d(t)$ during the film deposition, we enabled to suppress $a$-axis oriented grain formation during the thickening.

Figure 3. Time dependence of $T_d(t)$ calculated from equation (1) when $\tau$ was changed.

Figure 4. Thickness dependence of $T_{b.s.}$ when $\tau$ was changed.

Figure 5. Thickness dependence of XRD intensity ratio of $I_{(200)} / (I_{(200)} + I_{(005)})$ depending on $\tau$. 

\[ I(200)/(I(200)+I(005))x100\% \]
3.3. Thickness dependence of $J_c$, $I_c$ and $\tau$

It has been reported that $J_c$ decreases as the film thickness increases due to $a$-axis oriented grains [1]. Therefore, it is expected that $J_c$ is maintained in this study because $a$-axis oriented grains were suppressed by changing $T_b(t)$. Figure 6 and Figure 7 show thickness dependence of $J_c$ and $I_c$ when $\tau$ is changed. It was found that $J_c$ was maintained at $\tau = 1250$ and 1500. So, $I_c$ tends to increase linearly and maximum $I_c$ reached about 800 A/cm-width in the film at $\tau = 1500$ in 4 µm thick. The $J_c$ reached 2.0 MA/cm$^2$ (77 K, 0 T). On the other hand, it is confirmed that $J_c$ decreased as the film thickness increases at $\tau = \infty$. Thus, $I_c$ tends to be constant. These facts mean that $J_c$ cannot be maintained as thickness increases by using only S-H technique. It is expected to improve the property of thick YBCO CCs using S-H system and gradual increase of $T_b(t)$.

4. Summary

We evaluated the superconducting properties for YBCO CCs fabricated by PLD method with S-H technique in order to suppress the generation of $a$-axis oriented grains. In addition, $T_b$ was gradually changed during the film deposition. It is observed that $T_b(s)$ decreased, the $a$-axis oriented grain mixture ratio increased and $J_c$ decreased as the film thickness increases when $\tau = \infty$, which corresponds to a conventional cold-wall technique. On the other hand, it was confirmed that $a$-axis grains were suppressed and $J_c$ was maintained by finite $\tau$. The $J_c$ reached 2.0 MA/cm$^2$ (77 K, 0 T) at $\tau = 1500$ sec. in 4 µm thick YBCO CCs. It is expected to improve the property of thick YBCO CCs by using S-H system and gradual increase of $T_b(t)$.

Acknowledgement

This work was partly supported by JSPS (16K20898 and 16H04512), JST-ALCA project. The metal substrates were provided from AIST.

References

[1] Ibi A, Fukushima H, Kuriki R, Miyata S, Takahashi K, Kobayashi H, Konishi M, Watanabe T, Yamada Y and Shiohara Y 2006 Physica C, 445 525
[2] Sekiguchi A 2016 J. Vac. Soc. Jpn, 7 171
[3] Ozaki T, Yoshida Y, Miura M, Ichino Y, Takai Y, Matsumoto K, Ichinose A, Horii S and Mukaida M 2007 IEEE Trans. Appl. Supercond. 17 3270
[4] Kakimoto K et al. 2010 Supercond. Sci. Technol. 23 014016
[5] Zhai H Y, Christen H M, Martin P M, Zhang L and D. Lowndes D H 2003 IEEE Trans. Appl. Supercond. 13 2622
[6] Majkic G, Galstyan E, and Selvamanickam V 2015 IEEE Trans. Appl. Supercond. 25 6605304
[7] Zhao R, Zhang F, Liu Q, Xia Y, Lu Y, Cai C, Xiong J, Tao B and Li Y 2017 Supercond. Sci. Technol. 30 025023
[8] Majkic G, Pratap R, Xu A, Galstyan E and Selvamanickam V 2018 Sci. Rep. 8 1
[9] Sievers S, Mattheis F, Krebs H U, and Freyhardt H C 1996 Japan. J. Appl. Phys. 35 L74