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Development of high I_c long REBCO tapes with high production rate by PLD method

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Abstract

We have been developing long $REBa_2Cu_3O_{7-\delta}$ coated conductors with high performance by the combination of the IBAD and the PLD methods. To realize the low production cost for $REBa_2Cu_3O_{7-\delta}$ coated conductors, growth conditions were optimized for long tape fabrication in the "in-plume PLD method". As a result, the I_c performance was confirmed with a high production rate under the high oxygen gas pressure and high laser energy density of > 800 mTorr and > 3 J/cm^2, respectively. We successfully fabricated a 35 m long $GdBa_2Cu_3O_{7-\delta}$ coated conductor with high I_c value of 619 A/cm-w by the production rate of 30 m/h.

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Keywords: REBCO caoted conductor; in-plume PLD method; high I_c; high production rate

Introduction

$REBa_2Cu_3O_{7-\delta}$ (REBCO, RE: rare earth element) coated conductors can be expected to apply to the industrial and commercial applications, such as electrical power cables, electrical motors, current-limiter and transformers etc. By the pulsed laser deposition (PLD) method, it was found that $GdBa_2Cu_3O_{7-\delta}$ (GdBCO) coated conductors has higher critical temperature (T_c) and critical current (I_c) in self and magnetic fields than those of YBCO coated conductors [1, 2]. Recently, a hundred meters to 1 kilo meters long REBCO coated conductors with high I_c values have been actually fabricated in many research institutes in the world. For example, SRL-ISTEC fabricated a 212 m long $YBa_2Cu_3O_{7-\delta}$ coated conductor with I_c value of 245 A/cm-w in 2005, and 215 m long GdBCO coated conductor with I_c value of 220 A/cm-w in 2007 by the PLD method on the ion-beam assisted deposition (IBAD) [3] substrates [2, 4]. Fujikura Ltd. fabricated a 615 m long GdBCO coated conductor with I_c value of 609 A/cm-w by the PLD method also on IBAD substrate in 2010 [5]. According to the above results, it was found that the PLD method is suitable to obtain high performance REBCO coated conductors. However, the production cost is high due to the low production rate and the high installation cost. Therefore, we developed the optical system for multi-plume and multi-turn PLD (MPMT-PLD) system which was designed to produce plural and discrete plumes (multi plume) to enlarge the deposition area and increase the deposition rate with controlled supersaturation and the substrate forms multi loop (multi turn) around a substrate heater to enlarge deposition area [4]. On the other hand, the in-plume PLD method was also effective for high rate deposition and high I_c thick REBCO layers [6, 7]. The in-plume PLD method was performed reducing the target-substrate (T-S) distance and using the off-stoichiometric REBCO target to control the REBCO layer composition. In order to realize the low production cost for REBCO coated conductors, improving production rate of REBCO layers with suppressing the reduction of J_c performance is one of the most effective approaches.

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In this paper, to realize the higher production rate for lower production cost of REBCO layers, we optimized deposition conditions for REBCO layers in the in-plume PLD method with MPMT-PLD system.

Experimentals

The GdBCO layers were deposited by the in-plume PLD method in the MPMT-PLD system on 10 mm wide CeO_2 /$LaMnO_3$ / IBAD-MgO / $Gd_2Zr_2O_7$ / Hastelloy C-276 substrates. The in-plane and out-of-plane texturing degrees of CeO_2 cap layer were about 2 to 4 and 1 to 2, 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 mJ. The optical system is synchronized to laser pulse and controls laser beam to scan on a REBCO target. The laser repetition rate at 300 Hz is divided into 18 plumes (multi plume) which are almost the same in size and shape. Typically, the pulse repetition rate of 300 Hz and a pulse energy of 600 mJ lead a deposition rate of about 47 μm/h for a GdBCO layer. Commercial sintered off-stoichiometric $GdBa_{1.8}Cu_3O_{7-\delta}$ targets with a diameter of 6 inch were used for the deposition of the GdBCO layers. It is necessary to use off-stoichiometric REBCO targets to control the composition of the REBCO layer because in-plume PLD method was performed reducing the T-S distance [6, 7]. Moreover, this off-stoichimetric Ba-deficient composition target is also effective for fabrication of GdBCO layer with high I_c, J_c and T_c by the PLD method [8, 9]. It is thought that the formation of Ba segregation between grain boundaries might lead to suppressing the connectivity of superconducting current.

As the GdBCO layer thickness increased, the surface morphology became rougher. The reduction of the surface temperature of the GdBCO layer was caused by the increment of surface emissivity and the amount of *a*-axis oriented grains in the GdBCO layer. Therefore, the deposition temperature was changed in the range about 850 to 900℃ for multi-deposition process, where a set temperature was changed in each deposition run to keep the surface temperature constant even with increase in the GdBCO layer thickness [10]. As a result, it became possible to relatively reduce a decrease in J_c with increasing REBCO layer thickness. The oxygen pressure was kept at about 800 mTorr with a flow of 80 sccm oxygen. The T-S distance was set about 70 mm. Repeating cycles of depositions were determined at the substrate tape transferring speed of 60 m/h. The thickness of GdBCO layer was 800 nm for one time deposition with the substrate tape transferring speed of 60 m/h as a typical value.

Results and discussion

Figure 1 shows the GdBCO thickness dependence of (a) J_c and (b) I_c values for the GdBCO coated conductors fabricated by the in-plume and the conventional PLD methods at 77 K under self-filed. In the conventional PLD method, the deposition of REBCO layer was taken place near the forefront of the plume, which called shock front.

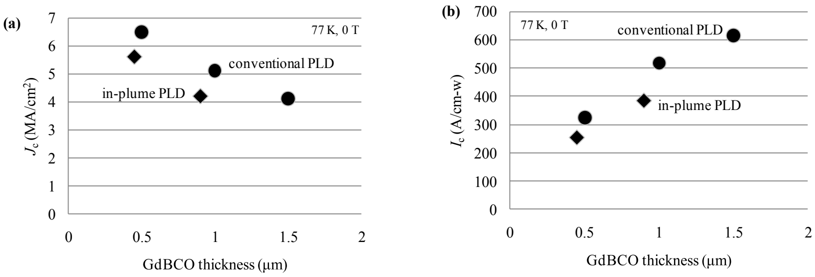

Fig. 1 GdBCO thickness dependence of (a) J_c and (b) I_c values for the coated conductors fabricated by the in-plume and conventional PLD methods at 77 K under self-filed.

For the in-plume PLD method, the GdBCO layers with 0.45 and 0.9 μm in thickness were fabricated at 60 and 30 m/h, and the conductors revealed J_c values of 5.6 and 4.2 MA/cm^2, respectively. On the other hand, in the conventional PLD method, the GdBCO layers with 0.5 and 1.0 μm in thickness were fabricated at 30 m/h and 15 m/h, and the conductors revealed J_c values of 6.5 and 5.1 MA/cm^2, respectively. These J_c and I_c characteristics in the films by the in-plume PLD method were lower than those by the conventional PLD method. It is thought that the in-plume PLD method has some difficulty in control of the REBCO layer composition and supersaturation to perform deposition at the center of plume (reducing T-S distance). Control of the REBCO layer composition is improved by using off-stoichiometric REBCO target and MPMT-PLD system [6, 7], however, J_c values are still lower than those by the conventional PLD method. To obtain high deposition rate of REBCO layers, the in-plume PLD method was performed reducing T-S distance, therefore, adhesive growth becomes dominant because supersaturation increases, as a result, crystallinity of REBCO layers may deteriorate and J_c also decrease. Therefore, although relatively high J_c is obtained also by the in-plume PLD method, improved further J_c is required.

Figure 2 shows the production rate dependence of GdBCO layer thickness and I_c values at 77 K under self-filed. Deposition rate of the in-plume PLD method was about twice as high as that of the conventional one in SRL-ISTEC with some reduction of J_c performance. Production cost of the REBCO layers is calculated by using costs of equipment, material, labor, land etc., and REBCO layers characteristics are also important issues such as J_c, production rate, thickness and material yield. Therefore, improvement of production rate is one of the effective approaches for the reduction of technical cost unless J_c is extremely low. Figure 3 shows the production rate dependences of production cost of both processes. The J_c characteristics of in-plume PLD tapes are still lower than those of conventional PLD ones, however, the production costs of the in-plume PLD method in lower than those of the conventional ones. Therefore, we tried to optimize deposition conditions to obtain both the increase in deposition rate and the improvement in J_c characteristics of REBCO layers in the in-plume PLD method.

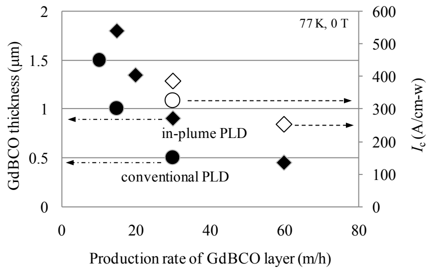

Fig. 2 Production rate dependence of GdBCO layer thickness and I_c values at 77 K under self-filed.

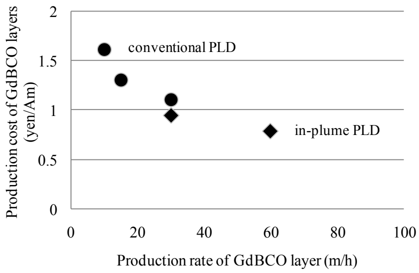

Fig. 3 Production rate dependence of production cost of in-plume and conventional PLD method.

We investigated the influence of deposition conditions, especially, laser energy density and oxygen gas pressure for the in-plume PLD method. Since these factors influence density of arriving adsorbed atoms, adsorbed atoms mobility and average deposition rate, it is thought to be effective to improve the deposition rate. Figure 4 indicates dependence of I_c values at 77 K under self-field in the almost same thickness films on the laser energy density. Previously, it was considered that the laser energy density of almost 2 J/cm^2 is suitable to obtain the films with high superconducting characteristics in the single plume PLD system. If the energy density increases in the system, it is thought that the supersaturation becomes high and the growth mode will change to the adhesive one. As a result, it becomes difficult to maintain the high crystallinity in the films. However, the supersaturation could be controlled by other deposition conditions and especially in the MPMT-PLD system, the freedom for the control could be expanded. Actually, the values of the laser energy density in Fig. 4 are much higher than 2 J/cm^2. And the peak of J_c value could be recognized to be at 3.4 J/cm^2.

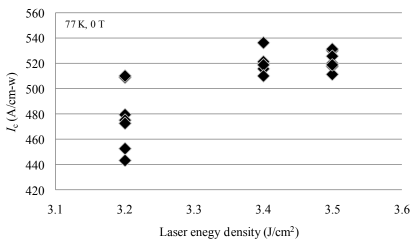

Fig. 4 Dependence of I_c values at 77 K under self-filed in same thickness films on laser energy density.

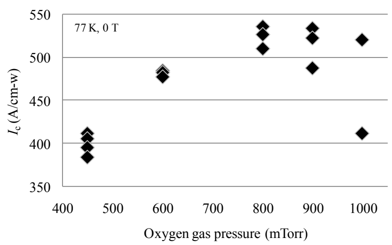

Fig. 5 Oxygen gas pressure in a deposition chamber dependence of I_c for GdBCO coated conductors at 77 K under self-filed.

Figure 5 shows oxygen gas pressure in a deposition chamber dependence of I_c for GdBCO coated conductors at 77 K under self-filed. The I_c values increases with increasing the oxygen gas pressure up to 800 mTorr. The oxygen gas may suppress the divergence of the plume. It is known that in reactant gas atmospheres, such as oxygen and nitrogen, the reaction of the plume and atmosphere gas occurs only at boundary plane. Under the oxygen gas pressures more than several hundred mTorr, the plume will be shielded by the surrounding oxygen gas and travels long distance without reacting oxygen gas. Therefore, the quantity of arriving adsorbed atoms increases, which leads to an increase of deposition rate of REBCO layers, and I_c value of GdBCO layer also could be improved. Although it is thought that J_c may decrease by increasing oxygen gas pressure due to the same reason as that in the case of high energy density, high J_c can be obtained by optimizing including other deposition conditions in the MPMT-PLD system. In this study, the increment of I_c values was recognized up to the oxygen gas pressure of 800 mTorr.

Figure 6 shows the longitudinal I_c distribution of a 35 m long GdBCO coated conductor at 77 K under self-field by the in-plume PLD method. During the GdBCO layer deposition in this figure, the laser energy density on a GdBCO target of 3.4 J/cm^2 and the oxygen gas pressure in a deposition chamber of 800 mTorr were used based on the abovementioned acknowledgement. This GdBCO coated conductor reveled high I_c value of 619 A/cm-w with high production rate of 30 m/h (2 times deposition of 60 m/h). The thickness of GdBCO layer was about 1.6 μm, and J_c value was about 3.8 MA/cm^2.

Moreover, this GdBCO coated conductor has very uniform in longitudinal I_c distributions of 0.60 % as a standard deviation. Figure 7 indicates two dimensional J_c distributions of the 35 m long GdBCO coated conductor by SHPM (Scanning Hall Probe Microscopy) with Reel-to-Reel system [11]. The amplitude of the sheet current density corresponded to that of critical current density almost in all the area of the coated conductor except for the region where current direction changed [11]. Figure 7 shows what was restored to 10 mm wide GdBCO coated conductor after measuring by dividing into 5 mm wide GdBCO coated conductor. According to this result, it could be confirmed that the GdBCO coated conductor has also very uniform in-plane J_c distributions of 0.97 % as a standard deviation.

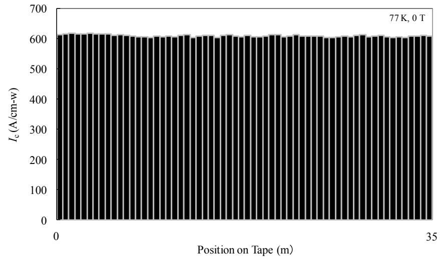

Fig. 6 Longitudinal I_c distribution of a 35 m long GdBCO coated conductor at 77 K under self-filed by in-plume PLD method. This GdBCO coated conductor reveled high I_c value of 619 A/cm-w with high production rate of 30 m/h. Moreover, this GdBCO coated conductor has very uniform in longitudinal I_c distributions of 0.60 % as a standard deviation.

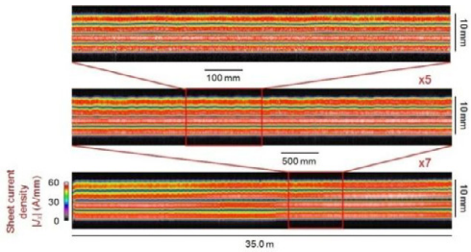

Fig. 7 Two dimensional J_c distribution of a 35 m long GdBCO coated conductor by SHPM with Reel-to-Reel system. This figure shows what was restored to 10 mm wide GdBCO coated conductor after measuring by dividing into 5 mm wide GdBCO coated conductor. This GdBCO coated conductor has also very uniform in-plane J_c distributions of 0.97 % as a standard deviation.

Conclusion

In order to realize the low production cost for REBCO coated conductors, we tried to optimize deposition conditions for the in-plume PLD method to obtain both the increase in deposition rate and the improvement in J_c characteristics of REBCO layers. We investigated the influence of deposition conditions, especially, laser energy density and oxygen gas pressure. As a result, we successfully fabricated a 35 m long GdBCO coated conductor with high I_c of 619 A/cm-w at 77 K under self-filed with high production rate of 30 m/h. Moreover, this GdBCO coated conductor has very uniform I_c distributions not only in longitudinal direction but also in two dimensional one of 0.60 and 0.97 % as a standard deviation, respectively.

Acknowledgments

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