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The superconductivity and pinning properties of Y_2O_3-doped $GdBa_2Cu_3O_{7-\delta}$ films prepared by pulsed laser deposition

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Abstract

We have investigated the effect of Y_2O_3 nanoparticles on the pinning properties of Y_2O_3-doped $GdBa_2Cu_3O_{7-\delta}$ (GdBCO) films. Both undoped and Y_2O_3-doped GdBCO films were grown on CeO_2-buffered MgO (100) single crystal substrates by pulsed laser deposition (PLD) using KrF (λ=248 nm) laser. The Y_2O_3 doping contents were controlled up to ~ 2.5 area% by varying the internal angles of Y_2O_3 sectors put on the top surface of GdBCO target. Compared with the Gd_2O_3-doped GdBCO films previously reported by our group [1], the Y_2O_3-doped GdBCO films exhibited less severe critical temperature (T_c) drop and thus slightly enhanced critical current densities (J_c) and pinning force densities (F_p) at 65 K for the applied field parallel to the c-axis of the GdBCO matrix (*B//c*) with increasing the doping content. Below 40 K, the in-field J_c and F_p values of all Y_2O_3-doped GdBCO films exhibited higher than those of undoped GdBCO film, suggesting that Y_2O_3 inclusions might act as effective pinning centers.

Keywords: flux pinning, GdBCO, Pulsed Laser Deposition(PLD)

1. INTRODUCTION

Up to now, one of issues for the practical applications of the $REBa_2Cu_3O_{7-\delta}$ (REBCO) coated conductors (CCs) is the improvement of in-field J_c values [2, 3]. Generally, the artificial pinning centers (APCs) have been introduced into the REBCO matrix to enhance the pinning properties by various fabrication methods such as PLD [4], Metal Organic Deposition (MOD) [5], Metal Organic Chemical Vapor Deposition (MOCVD) [6], and Reactive Co-Evaporation Deposition and Reaction (RCE-DR) [7]. In the case of the PLD process, many authors have tried to introduce the one-dimensional APCs (1D-APCs) such as $BaMO_3$ (M=Zr, Sn, Hf, etc.) nanorods which are self-aligned along the c-axis of the REBCO matrix [8-20]. While the 1-D nanorods are known effective for the improvement of in-field J_c values for *B*//*c*, the three-dimensional APCs (3D-APCs) such as nanoparticles are known effective for the enhancement of in-field J_c values in the whole range of field orientation. [3, 21].

Recently, we have reported a significant enhancement in the pinning properties of 2.2 area% Gd_2O_3-doped GdBCO films in the magnetic fields ranging from 0.2 T to 5 T at 20 K [1]. Although the in-field J_c values of 2.2 area % Gd_2O_3-doped GdBCO films for *B*//*c* were improved at 20 K, the pinning properties of undoped GdBCO films were superior to those of Gd_2O_3-doped GdBCO films at relatively high temperatures since the Gd_2O_3-doped GdBCO films exhibited a serious decrease in T_c values with increasing the Gd_2O_3 doping content. There may exist two factors responsible for the serious decrease in the T_c values. One is due to an increased lattice strain of the GdBCO matrix at the interface with Gd_2O_3 nanoparticles. The degradation of T_c values due to a lattice distortion of the superconducting matrix has been reported by many authors [1, 12, 15, 17, 19, 22]. Since the T_c values are more rapidly degraded with increasing the Gd_2O_3 doping content in the Gd_2O_3-doped GdBCO films compared with Y_2O_3-doped YBCO films [23], there must be another factor degrading the T_c values which, we suggest, is the formation of $Gd_{1+x}Ba_{2-x}Cu_3O_{7-\delta}$ -type solid solutions of larger *x* values with increasing the Gd_2O_3 doping content. With increasing the *x* value in $Gd_{1+x}Ba_{2-x}Cu_3O_{7-x}$, it is reported that the T_c values are non-linearly degraded [24].

The additional T_c drop due to the formation of the $Gd_{1+x}Ba_{2-x}Cu_3O_{7-\delta}$ -type solid solutions may be suppressed by employing the Y_2O_3 dopant since the Y^{3+} ions cannot substitute the Ba^{2+} ion sites. Therefore, in this study, we selected Y_2O_3 as the dopant to prevent the serious T_c drop and thus to improve the in-field J_c values at relatively high temperatures. Here, we report the effect of the Y_2O_3 doping content on the T_c variation and the pinning properties of Y_2O_3-doped GdBCO films.

2. EXPERIMENTAL

The samples fabricated by the PLD process have the following architecture: Y_2O_3-doped GdBCO/CeO_2 buffer layer/MgO (100) single crystal substrate. Prior to deposit the superconducting layer, bi-axially textured CeO_2 buffer layer was deposited on the MgO (100) single crystal substrate using RF-magnetron sputtering. Deposition

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conditions of the CeO_2 buffer layer are described in our previous report [1]. For the fabrication of Y_2O_3-doped GdBCO films, the Y_2O_3 target was cut into a sector and put on the top surface of the GdBCO target. The Y_2O_3 doping contents of Y_2O_3-doped GdBCO films could be controlled by varying the internal angles of Y_2O_3 sectors. A Lambda Physik KrF eximer laser (λ= 248 nm) with the laser frequency of 8 Hz was employed to deposit GdBCO films on CeO_2-bufferd MgO (100) single crystal substrates. Both undoped and Y_2O_3-doped GdBCO films were deposited at 800°C in the PO_2 of 300 mTorr. As-prepared samples were annealed at 500°C for 1 h in a pure oxygen gas.

The structural characteristics of samples were analyzed with an X-ray diffractometer (Bruker D8-Advance, Cu *Kα* radiation). The zero-resistivity critical temperature ($T_{c,zero}$) and normal state resistivity were measured by using a standard four-point probe technique. The magnetic hysteresis curves of samples were measured by a SQUID magnetometer (Quantum Design, MPMS XL-5). Magnetic J_c values were calculated from the M-H curves by using an extended Bean's critical state model [25], where ΔM is the hysteresis loop width, a and b ($a < b$) are width and length of the rectangular films, respectively.

$$J_c = \frac{20\Delta M}{a(1-(a/3b))}$$

3. RESULTS AND DISCUSSION

As shown in Fig. 1(a), the (00*l*) peaks of undoped and Y_2O_3-doped GdBCO films except CeO_2 buffer layer and MgO (100) substrate peaks represent that all films are well aligned along the c-axis of GdBCO. Although we have introduced the Y_2O_3 dopants into the GdBCO matrix, the Y_2O_3 peaks are unobservable. Similarly, in the previous reports [1, 26], the peaks of the Gd_2O_3 and Y_2O_3 nanoparticles were also undetectable for Gd_2O_3-doped GdBCO films and Y_2O_3-doped YBCO films, respectively. In Fig.1 (b), however, we can observe that the peak of (005) reflection for Y_2O_3-doped GdBCO films becomes broader with increasing the Y_2O_3 doping content. The full width at half maximum (FWHM) values of (005) reflection are listed in Table. I. The FWHM values of (005) reflection increase from 0.164° to 0.232° with increasing the Y_2O_3 doping content up to ~ 2.5 area%. The broadening of the (005) reflection is responsible for a residual strain induced by a lattice mismatch between Y_2O_3 dopants and GdBCO

TABLE I
$T_{C,ZERO}$, ΔT_C, FWHM VALUES OF (005) REFLECTIONS, AND MAGNETIC J_C VALUES OF SAMPLES.

Sample	$T_{c,zero}$ (K)	ΔT_c	FWHM of (005) reflection (degree)	Magnetic J_c @ 77 K, 0 T (MA/cm²)
Undoped	91.5	0.7	0.164	1.92
1.1 area%	90.7	0.9	0.214	1.16
2.5 area%	90.1	1.3	0.232	0.71

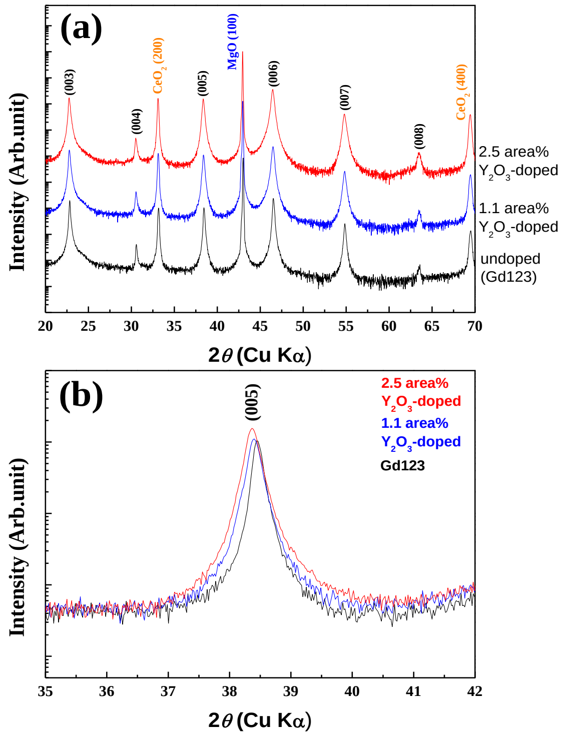

Fig. 1. (a) Theta-2theta scans and (b) the peak of (005) reflection of undoped and Y_2O_3-doped GdBCO films.

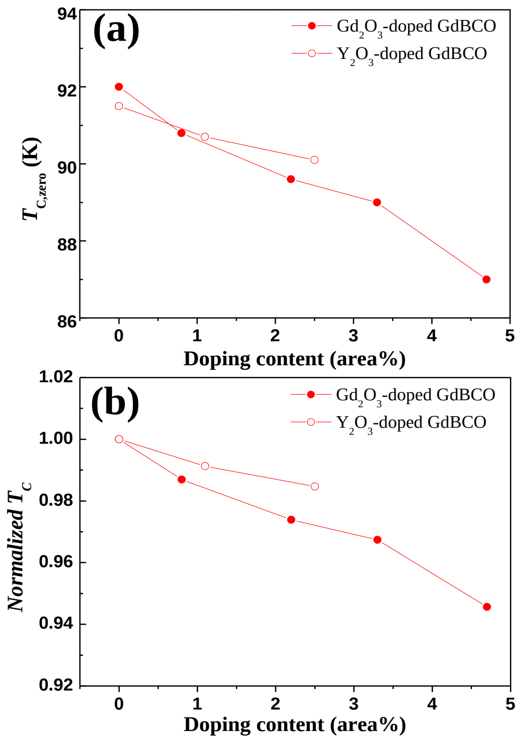

Fig. 2. The $T_{c,zero}$ values (a) and normalized T_c values (b) with increasing Y_2O_3 and Gd_2O_3 doping contents for all GdBCO samples. (close circles for the Gd_2O_3-doped GdBCO films from ref. [1], open circles for the Y_2O_3-doped GdBCO films)

matrix. With increasing the Y_2O_3 doping content, the strained area of Y_2O_3-doped GdBCO films will be increased, of which tendency has been reported by other researchers [12, 22].

In Fig. 2(a), the $T_{c,zero}$ values of samples are plotted as a function of the Y_2O_3 doping content. The $T_{c,zero}$ values normalized to $T_{c,zero}$ values of each undoped GdBCO films for Y_2O_3-doped and Gd_2O_3-doped GdBCO films are also represented in Fig. 2(b). As shown in Fig. 2(a), the $T_{c,zero}$ value of undoped sample is not exactly same with that of undoped sample of our previous report [1] probably because the samples in this study were fabricated by using another GdBCO target. The $T_{c,zero}$ values for both Y_2O_3-doped and Gd_2O_3-doped GdBCO films are degraded gradually with increasing the doping content. Interestingly, however, with increasing the doping content, the $T_{c,zero}$ values of Y_2O_3-doped GdBCO films are less degraded compared with those of Gd_2O_3-doped GdBCO films, which is in good agreement with our expectation that an additional T_c drop due to the formation of the $Gd_{1+x}Ba_{2-x}Cu_3O_{7-\delta}$ -type solid solutions can be suppressed by using the Y_2O_3 dopant.

The field dependence of magnetic J_c values at 77, 65, 40, and 20 K, which were calculated using a modified Bean model [25], are represented in Fig. 3. In Fig. 3(a), Y_2O_3-doped GdBCO films exhibit a gradual degradation of self-field J_c value with increasing the Y_2O_3 doping content at 77 K. This tendency of self-field J_c degradation was also observable in previous reports [8, 22]. The magnetic J_c values of undoped GdBCO films for $B//c$ are higher than those of Y_2O_3-doped GdBCO films at 77 K in Fig. 3(a) while the J_c values of 1.1 area% Y_2O_3-doped GdBCO films are slightly higher than those of undoped GdBCO films in the magnetic fields ranging from 0.05 to 4.5 T at 65 K in Fig. 3(b). In Fig. 3(c), the 1.1 and 2.5 area% Y_2O_3-doped GdBCO film exhibit enhanced J_c values in the magnetic fields from 0.03 T to 4 T and from 0.3 T to 4 T at 40 K, respectively. This tendency differs from the behavior of J_c-B curves at 77 K. Unlike Gd_2O_3-doped GdBCO films in our previous study [1], exhibiting degraded J_c values with increasing the magnetic fields at the temperature of 65 K due to a severe T_c drop, 1.1 area% Y_2O_3-doped GdBCO film shows slightly improved J_c values for $B//c$ at 65 K since the T_c drop of Y_2O_3-doped GdBCO films was less than that of Gd_2O_3-doped GdBCO films. Therefore, it is crucial to minimize the T_c degradation in order to enhance the pinning properties at relatively high temperatures when the 3D-APCs such as nanoparticles are introduced into the superconducting matrix by the PLD process.

Fig.4 shows the F_p values of undoped and Y_2O_3-doped GdBCO films for $B//c$ at 77, 65, 40, and 20 K. The maximum F_p values for the undoped GdBCO films are higher than those of Y_2O_3-doped GdBCO films for $B//c$ at 77 K in Fig. 4(a). Among all the samples, the maximum F_p values of 1.1 area% Y_2O_3-doped GdBCO film are higher than those of other samples at 65 K in Fig. 4(b). Especially, in Fig. 4(c), the 2.5 area% Y_2O_3-doped GdBCO film shows the enhanced F_p values at 40 K compared with undoped GdBCO films. However, the 2.2 area% Gd_2O_3-doped GdBCO film exhibits degraded F_p values in the magnetic fields ranging from 3.2 T to 4.8 T at 40 K compared with the undoped GdBCO films in our previous report [1] since

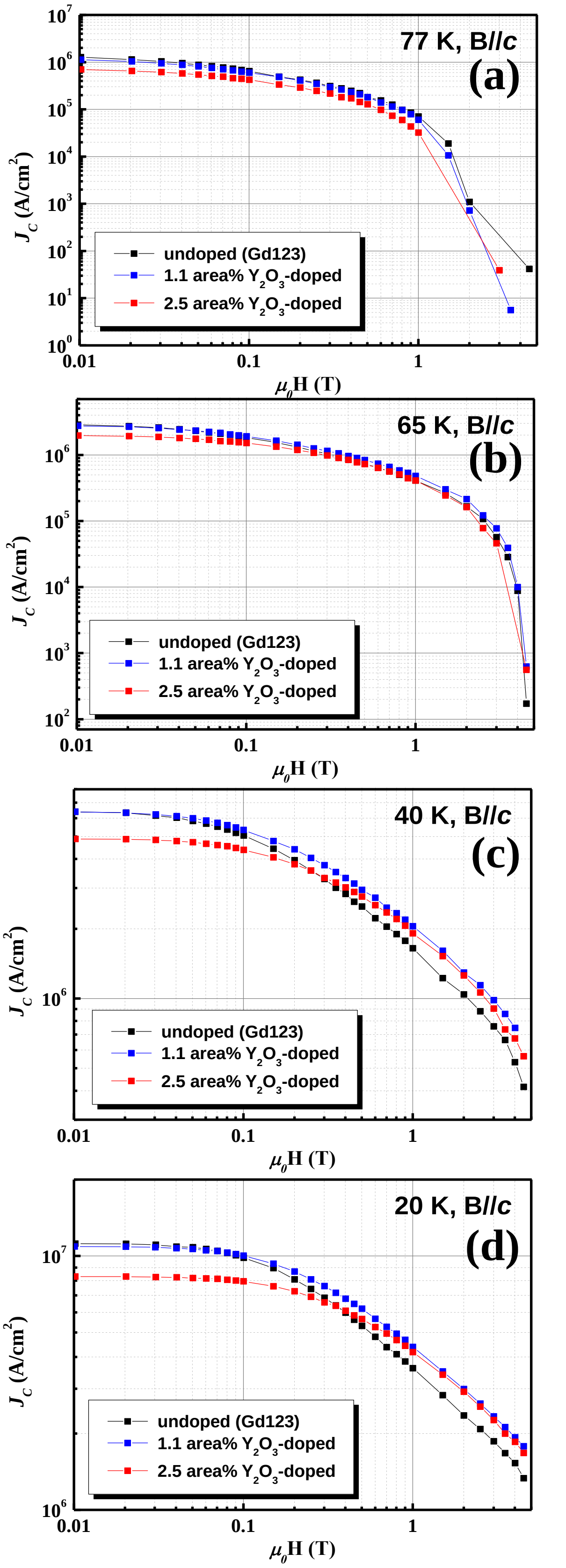

Fig. 3. Field dependence of magnetic J_c for undoped and Y_2O_3-doped GdBCO films at (a) 77, (b) 65, (c) 40, and (d) 20 K.

the $T_{c,zero}$ value of 89.6 K for 2.2 area % Gd_2O_3-doped

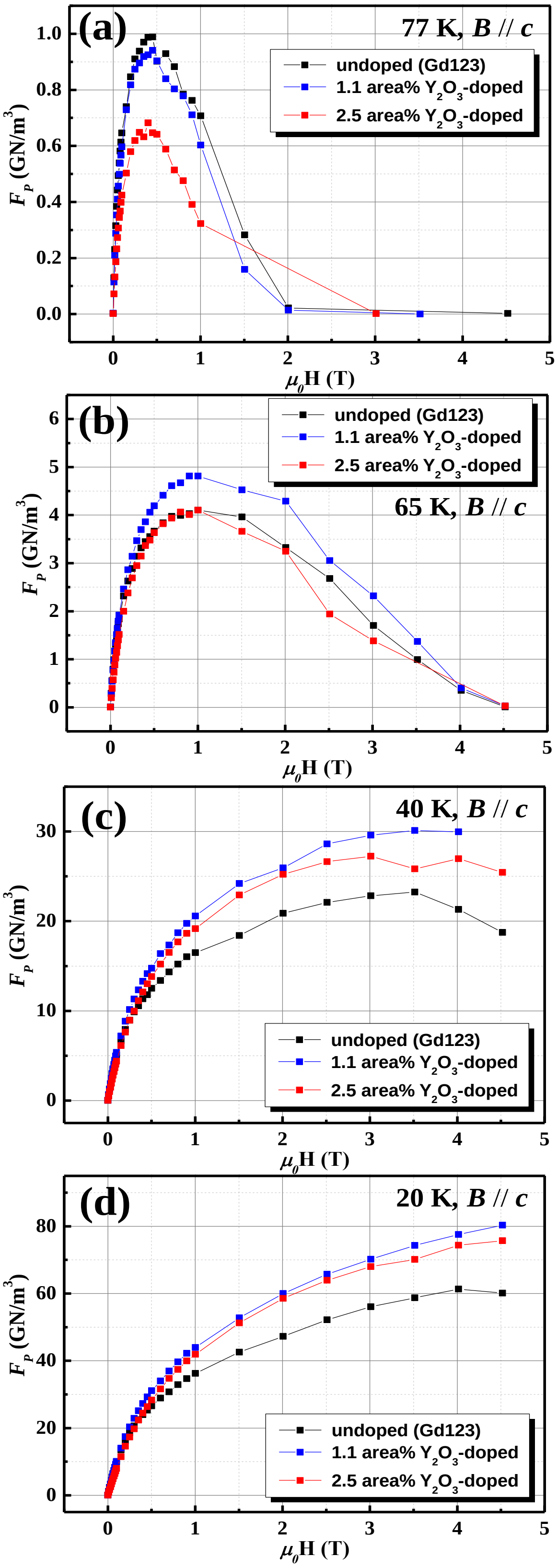

Fig. 4. The pinning force density (F_p) versus applied field for undoped and Y_2O_3-doped GdBCO films at (a) 77, (b) 65, (c) 40, and (d) 20 K.

GdBCO film was inferior to that of 90.1 K for 2.5 area % Y_2O_3-doped GdBCO film.

Although the Y_2O_3-doped GdBCO films have a lower T_c drop compared with Gd_2O_3-doped GdBCO films, the J_c values of Y_2O_3-doped GdBCO films are still lower than undoped GdBCO films for $B//c$ at 77 K. M. Miura *et al.* [27] reported that a coherent interface of PLD-films between the matrix and second phase affected the T_c and self-field J_c values at 77 K. The BHO-doped GdBCO films by PLD showed the degradation in T_c and self-field J_c values since it has been reported that oxygen deficiency can be induced at the coherent interface region and thus it will be increased with increasing BHO doping contents up to ~ 6 vol% [27]. On the other hand, the T_c values of the BHO-doped (Y,Gd)BCO films by MOD were unaltered with increasing BHO doping contents up to ~ 12 vol%. In addition to MOD-films, the GdBCO CCs fabricated by RCE-DR exhibit the high $T_{c,zero}$ value of ~ 94 K and self-field J_c values of 660 A/cm even though the GdBCO CCs have a large amount of Gd_2O_3 nanoparticles dispersed in the GdBCO matrix [7]. Interestingly, the T_c and self-field J_c values of samples fabricated by the MOD and RCE-DR processes are almost unaffected by the amount of a dopant. The samples fabricated by the MOD and RCE-DR processes have an incoherent interface between the superconducting matrix and dopants due to an *ex-situ* annealing process where the second phases are formed before the growth of the superconducting matrix. However, the T_c and self-field J_c values of samples by the PLD process are sensitive to an amount of doping content due to the formation of a coherent interface between the second phase and the superconducting matrix, and hence leading to the serious T_c drop with increasing the doping content.

4. SUMMARY

The pinning properties of Y_2O_3-doped GdBCO films by the PLD process have been investigated. With increasing the Y_2O_3 doping content, the FWHM values of (005) reflection for Y_2O_3-doped GdBCO films were increased, indicating that the strain area induced by a lattice distortion might be increased. Also, the $T_{c,zero}$ and ΔT_c values of Y_2O_3-doped GdBCO films were gradually degraded with increasing the Y_2O_3 doping content up to 2.5 area%. Interestingly, the Y_2O_3-doped GdBCO films exhibited the less T_c drop compared with Gd_2O_3-doped GdBCO films. The 1.1 area% Y_2O_3-doped GdBCO films show slightly improved magnetic J_c and maximum F_p for $B//c$ at relatively high temperature of 65 K compared with undoped GdBCO films. Below 40K, all Y_2O_3-doped GdBCO films show improved pinning properties for $B//c$ compared with undoped sample. Consequently, the Y_2O_3 dopants for PLD-GdBCO films turn out to be effective for the improvement of the pinning properties at relatively low temperatures while the pinning properties of Y_2O_3-doped GdBCO films was improved insignificantly at relatively high temperatures.

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REFERENCES

[1] W. Oh, J. Kim, and S. Yoo, "Enhanced pinning properties of $GdBa_2Cu_3O_{7-\delta}$ films with the Gd_2O_3 nanoparticles", *IEEE Trans. Appl. Supercond.*, vol. 27, p. 8000605, Jan. 2017.

[2] S. R. Foltyn, L. Civale, J. L. Macmanus-driscoll, Q. X. Jia, B. Maiorov, H. Wang, and M. Maley, "Materials science challenges for high-temperature superconducting wire", *Nat. Mater.*, vol. 6, pp. 631-642, Sep. 2007

[3] K. Matsumoto, and P. Mele, "Artificial pinning center technology to enhance vortex pinning in YBCO coated conductors", *Supercond. Sci. Technol.*, vol. 23, p.014001, Dec. 2009

[4] H. Kutami, T. Hayashida, S. Hanyu, C. Tashita, M. Igarashi, H. Fuji, Y. Hanada, K. Kakimoto, Y. Iijima, and T. Saitoh, "Progress in research and development on long length coated conductors in Fujikura", *Physica C*, vol. 469, pp. 1290-1293, May. 2009

[5] M. Rupich, X. Li, C. Thieme, S. sathyamurthy, S. Fleshler, D. Tucker, E. Thompson, J. Schreiber, J. Lynch, D. Buczek, K. Demoranville, J. Inch, P. Cedrone, and J. Slack, "Advances in second generation high temperature superconducting wire manufacturing and R&D at American Superconductor Corporation", *Supercond. Sci. Technol.*, vol. 23, p. 014015, Dec. 2009

[6] V. Selvamanickam, Y. Chen, X. Xiong, Y. Xie, M. Martchevski, A. Rar, Y. Qiao, R. Schmidt, A. Knoll, K. Lenseth, and C. Weber, "High performance 2G wires: From R&D to pilot-scale manufacturing", *IEEE Trans. Appl. Supercond.*, vol. 19, no. 3, pp. 3225-3230, Jul. 2009

[7] J. H. Lee, H. Lee, J. W. Lee, S. M. Choi, S. I. Yoo, and S. H. Moon, "RCE-DR, a novel process for coated conductor fabrication with high performance", *Supercond. Sci. Technol.*, vol. 27, pp. 044018, Mar. 2014

[8] J. L. Macmanus-driscoll, S. R. Foltyn, Q. X. Jia, H. Wang, A. Serquis, L Civale, B. Maiorov, M. E. Hawley, M. P. Maley, and, D. E. Peterson, "Strongly enhanced current densities in superconducting coated conductors of $YBa_2Cu_3O_{7-x}$ + $BaZrO_3$", *Nat. Mater.*, vol. 3, pp. 439-443, May. 2004

[9] A. Goyal, S. Kang, K. J. Leonard, P. M. Martin, A. A. Gapud, M. Varela, M. Paranthaman, A. O. Ijaduola, E. D. Dpecht, J. R. Thompson, D. K. Christen, S. J. Pennycook, and F. A. List, "Irradiation-free, columnar defects comprised of self-assembled nanodots and nanorods resulting in strongly enhanced flux-pinning in $YBa_2Cu_3O_{7-\delta}$ films", *Supercond. Sci. Technol.*, vol. 18, pp.1533-1538, Oct. 2005

[10] Y. Yamada, K. Takahashi, H. Kobayashi, M. Konishi, T. Watanabe, A. Ibi, T. Muroga, and S. Miyata, T. Kato, T. Hirayama, and Y. Shiohara, "Epitaxial nanostructure and defects effective for pinning in $Y(RE)Ba_2Cu_3O_{7-x}$ coated cnoductors", *Appl. Phys. Lett.*, vol. 87, p.132502, Sep. 2005

[11] P. Mele, K. Matsumoto, T. Horide, A. Ichinose, M. Mukaida, Y. Yoshida, S. Horii, and R. Kita, "Ultra-high flux pinning properties of $BaMO_3$-doped $YBa_2Cu_3O_{7-x}$ thin films", *Supercond. Sci. Technol.*, vol. 21, p.032002, Feb. 2008

[12] M. Peurla, P. Paturi, Y. P. Stepanov, H. Huhtinen, Y. Y. Tse, A. C. Bodi, J. Raittila, and R. Laiho, "Optimization of the BaZrO3 concentration in YBCO films prepared by pulsed laser deposition", *Supercond. Sci. Technol*, vol. 19, pp. 767-771, Jun. 2006

[13] K. Takahashi, H. Kobayashi, Y. Yamada, A. Ibi, H. Fukushima, M. Konishi, S. Miyata, Y. Shiohara, T. Kato, and T. Hirayama, "Investigation of thick PLD-GdBCO and ZrO_2 doped GdBCO coated conductors with high ritical current on PLD-CeO_2 capped IBAD-GZO substrate tapes", *Supercond. Sci. Technol.*, vol. 19, no. 9, pp. 924-929, Jul. 2006.

[14] K. Schlesier, H. Huhtinen, P. Paturi, Y. P. Stepanov, and R. Laiho., "Structural and Superconducting Properties of undoped and BZO-doped GdBCO thin films", *IEEE Trans. Appl. Supercond.*, vol. 19, no. 3, pp.3407-3411, Jun. 2009.

[15] S. Lee, N. Chikumoto, T. Yokoyama, T. Machi, K. Nakao, and K. Tanabe., "Development of In-Plume Pulsed Laser Deposition of high-I_c GdBCO films for coated conductors", *IEEE Trans. Appl. Supercond.*, vol. 19, no. 3, pp.3192-3195, Jun. 2009.

[16] K. Kaneko, K. Furuya, K.Yamada, S. Sadayama, J. S. Barnard, P. A. Midgley, T. Kato, T. Hirayama, M. Kiuchi, T. Matsushita, A. Ibi, Y. Yamada, T. Izumi, and Y. Shiohara, "Three-dimensional analysis of $BaZrO_3$ pinning centers gives isotropic superconductivity in GdBCO", *J. Appl. Phys.*, vol. 108, pp. 063901, Sep. 2010.

[17] K. Ko, S. Choi, J. Lee, R. Ko, S. Moon, C. Park, and S. Yoo, "Optimization of the $BaSnO_3$ Doping Content in GdBCO coated conductors by pulsed laser deposition", *IEEE Trans. Appl. Supercond.*, vol. 24, no. 6, pp. 6600908, Dec. 2014.

[18] H. Tobita, K. Notoh, K. Higashikawa, M. Inoue, T. Kiss, T. Kato, T. Hirayama, M. Yoshizumi, T. Izumi, and Y. Shiohara, "Fabrication of $BaHfO_3$ doped $GdBa_2Cu_3O_{7-\delta}$ coated conductors with the high I_c of 85 A/cm-w under 3T at liquid nitrogen temperature (77K)", *Supercond. Sci. Technol.*, vol. 25, no. 6, pp. 062002, May. 2012.

[19] T. Matsushita, H. Nagamizu, K. Tanabe, M. Kiuchi, E.S. Otabe, H. Tobita, M. Yoshizumi, T. Izumi, Y. Shiohara, D. Yokoe, T. Kato, and T. Hirayama, "Improvement of flux pinning performance at high magnetic fields in GdBCO coated conductors with BHO nano-rods through enhancement of B_{c2}", *Supercond. Sci. Technol*, vol. 25, no. 12, pp. 125003, Oct. 2012.

[20] T. Yoshida, A. Ibi, T. Takahashi, M. Yoshizumi, T. Izumi, and Y. Shiohara, "Fabrication of $Eu_1Ba_2Cu_3O_{7-\delta}$ + $BaHfO_3$ coated conductors with 141 A/cm-w under 3 T at 77 K using the IBAD/PLD process", Physica C., vol. 504, pp. 42-46, Apr. 2014

[21] A. A. Gapud, D. Kumar, S. K. Viswanathan, C. Cantoni, M. Varela, J. Abiade, S. J. Pennycook, and D. K. Christen, "Enhancement of flux pinning in $YBa_2Cu_3O_{7-\delta}$ thin films embedded with epitaxially grown Y2O3 nanostructures using a multi-layering process", *Supercond. Sci. Technol*, vol. 18, pp. 1502-1505, Oct. 2005

[22] M. Malmivirta, L. D. Yao, S. Inkinen, H. Huhtinen, H. Palonen, R. Jha, V. P. S. Awana, S. van Dijken, and P. Paturi, "The angular dependence of the critical current of $BaCeO_3$ doped $YBa_2Cu_3O_{6+x}$ thin films, *IEEE Trans. Appl. Supercond.*, vol. 25, no. 3, p.6603305, Jun. 2015

[23] P. Mele, R. Guzman, J. Gazquez, T. Puig, X. Obradors, S. Saini, Y. yoshida, M. Mukaida, A. Ichinose, K. Matsumoto, and M. I. Adam, "High pinning performance of $YBa_2Cu_3O_{7-x}$ films added with Y_2O_3 nanoparticulate defects", *Supercond. Sci. Technol*, vol. 28, p. 024002, Dec. 2014

[24] K. Zhang, B. Dabrowski, C. U. Segre, D. G. Hinks, I. K. Schuller, J. D. Jorgensen, and M. Slaski, "Solubility and superconductivity in $RE(Ba_{2-x}RE_x)Cu_3O_{7+\delta}$ systems (RE = Nd, Sm, Eu, Gd, Dy)", *J. Phys. C: Solid state Phys.*, vol. 20, pp. L935-L940, 1987

[25] E.M. Gyorgy, R.B. van Dover, K.A. Jackson, L.F. Schneemeyer, and J.V. Waszczak, "Anisotropic critical currents in $Ba_2YCu_3O_7$ analyzed using an extended bean model", *Appl. Phys. Lett.*, vol. 55, pp.283, May. 1989

[26] P. Mele, M. I. Adam, T. Suzuki, Y. Yoshida, S. Awaji, A. Ichinose, S. Saini, A. K. Jha, and K. Matsumoto, "Effect of simultaneous addition of 1D and 3D artificial pinning centers in hybrid $YBa_2Cu_3O_{7-x}$ multilayers", *Sci. Adv. Mater.*, vol. 9, pp.1042-1050, Jun. 2017

[27] M. Miura, B. Maiorov, M. Sato, M. Kanai, T. Kato, T. Kato, T. Izumi, S. Awaji, P. Mele, M. Kiuchi, and T. Matsushita, "Tuning nanoparticle size for enhanced functionality in perovskite thin films deposited by metal organic deposition", *NPG. Asia. Mater.*, vol.9, p. e447, Sep. 2017