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Full Length Article

40-meter-long REBCO tapes with critical current over 4,000 A/12 mm at 4.2 K and 13 T by advanced MOCVD

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ABSTRACT

$REBa_2Cu_3O_{7-\delta}$ (REBCO, RE = rare earth) tapes doped with 5% and 15% Zr have been scaled up to lengths more than 40 m in a pilot-scale advanced metal organic chemical vapor deposition (A-MOCVD) tool. The precursor compositions used for the long tapes were guided by a study of the influence of (Ba + dopant)/Cu content on the critical current density (J_c) of 5 and 15 mol.% Hf- and Zr-added tapes at 4.2 K and 13 T. The 40-m-long tapes exhibited a critical current (I_c) over 4,000 A/12 mm at 4.2 K and 13 T as well as over 1,400 A/12 mm at 20 K and 20 T. The critical current densities of a 40-m-long tape doped with 5% Zr at 4.2 K measured at the National High Magnetic Field Laboratory (NHMFL) were > 10 $MAcm^{-2}$ and >5 $MAcm^{-2}$ at 14 T and 30 T, respectively, which are over three times those of commercial REBCO tapes. The infield J_c of 5% Zr-added 40-m-long tapes was similar to those of previously-reported high-performance short samples made with 15% Zr or Hf. These results demonstrate the excellent potential of A-MOCVD for manufacturing high I_c REBCO tapes for use in ultrahigh-field magnet applications.

1. Introduction

Superconducting magnet technology is a critical enabler of the Large Hadron Collider (LHC) [1] and other particle accelerators. All superconducting magnets for particle accelerators have been built using Nb–Ti or Nb_3Sn strands and cables [2]. To meet future demands, next-generation particle accelerators require much higher magnetic fields. There are several ongoing design studies to upgrade the LHC magnets with HTS whose upper critical field (H_{c2}) exceeds 100 T at 4.2 K whereas that of Nb_3Sn is limited to 23.5 T [3,4].

Another application in which HTS is an enabler is fusion where high-field magnets contain the plasma produced in the reactor [5–7]. ITER, the most ambitious international scientific fusion project, uses superconducting magnets to confine the plasma designed to generate 500 MW power [7]. The only viable option during the design of ITER for constraining burning plasmas at the center of the reactor was Nb_3Sn. However, recent advancements in HTS materials, particularly REBCO, could considerably advance the design and development of magnetic fusion devices in a compact form owing to their wider operational temperature range, higher specific heat, higher allowable mechanical stresses and strains, and higher magnetic fields [8,9]. In 2001, MIT planned to construct a REBCO-based toroidal field (TF) coil by stacking demountable REBCO-coated structural plates to exploit the anisotropy of coated conductors by orienting their basal plane parallel to the magnetic field [8,10]. Since then many designs of magnetically-confined fusion devices have been developed based on REBCO conductor because of its superior performance at 20 K and 20 T.

At a magnetic field of 20 T, 50-kA class conductors are required for fusion and other ultrahigh-field magnets [3,11]. This necessitates the use of over 200 REBCO tape strands, which considerably increases the cost of the coils. For example, 3–4 GA-m of REBCO tape is required for a 400 MW compact fusion device; the tape itself will cost about $600 M today. The entire cost of a 400 MW existing natural gas power plant that compact fusion seeks to replace is $550 M [12]. A solution to address this cost challenge is to use tape strands of much higher I_c. With tape strands with 5x I_c, their number can be reduced ~5x from ~200 to ~40. Concerns about change in mechanical strength with fewer strands can be addressed by using dummy strands of Hastelloy. Since cables for compact fusion magnets already use a considerable amount of copper and solder to an extent that even REBCO tapes with

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severe I_c dropouts can be used [13,14], it is likely that high I_c tape strands can be safely utilized.

Our work is built on the A-MOCVD technique that was developed to grow >4-μm-thick REBCO films without any J_c degradation with film thickness, in short samples [15]. This method uses Ohmic heating of the substrate, and laminar precursor vapor flow that enables the growth of thick REBCO films in a single pass with 45% precursor-to-film conversion efficiency which is about 4x that of conventional MOCVD process [15]. Additionally, this method facilitates excellent control of $BaMO_3$ (BMO, M = Zr, Hf) nanocolumns along the *c*-axis [16,17]. When an applied magnetic field is oriented along the c-axis of the film, the BMO nanocolumns serve as pinning centers, improving critical current [18,19]. We demonstrated short REBCO samples with $J_e \sim 4{,}600$ A/mm^2 (based on a 0.1-mm-thick tape) at 4.2 K, 20 T, and 15 mol% Hf-added REBCO tapes with $J_c > 9$ MAcm^{-2} at 20 K and 9 T [17,20,21]. The number of strands for achieving the required operating current can be considerably reduced using these REBCO tapes with four to five times higher I_c than the commercially-available REBCO tapes [22–24].

Scaling these results from short tapes made by A-MOCVD to long length was the next imminent goal. A pilot-scale A-MOCVD system was constructed to fabricate 40–50-m-long REBCO tape in a single pass. The influence of barium and dopant content on REBCO tape performance at 4.2 K and 13 T, as well as at 20 K and 13 T, was also investigated to guide the selection of precursor chemistry for long tape fabrication.

2. Experimental method

Because of the 2.2 times longer deposition length of the pilot-scale A-MOCVD tool (Fig. 1) compared to the R&D A-MOCVD tool, the deposition time for the long 4-μm-thick-film REBCO tapes was reduced to less than half. In A-MOCVD, a 12-mm-wide substrate with an architecture of lanthanum manganate ($LaMnO_3$; 50 nm)/magnesium oxide (MgO; 50 nm)/yttrium oxide (Y_2O_3; 7 nm)/aluminum oxide (Al_2O_3; 80 nm)/Hastelloy C-276 (50 μm) was Ohmic heated using direct current [25]. Transverse laminar precursor vapor flow was used to deposit the REBCO film on this heated substrate, allowing for the growth of a thick epitaxial superconductor film [25]. A 2-μm-thick silver-shunt layer was deposited on the REBCO tapes using DC sputtering, and then the tapes were oxygenated at 500 °C for 2 h. While the barium content of the precursor was varied, the nominal contents of rare earth (0.65 mol each of gadolinium and yttrium) and copper (2.6 mol for R&D A-MOCVD and 2.3 mol for pilot A-MOCVD) precursors were kept constant. To enhance the infield performance, 5 or 15 vol.% Hf or Zr was added to the precursor. Using 2D Scanning Hall Probe Microscopy (SHPM) at a speed of 36 cm/min, the I_c uniformity of all the long tapes was determined at 77 K, 0 T [26]. Short samples were cut from each end of the long tapes for transport I_c measurements using the four-probe method. To reduce heating effects at the high currents used, the transport I_c was measured over a bridge width of ~1 mm, made by wet etching. A voltage criterion of 1 μV/cm was used to determine the critical current. Vibrating sample magnetometer (VSM) measurements were made in the direction of B ⊥ tape at 0–14 T and 4.2 K–77 K to determine the infield performance. The average sample dimensions used for VSM measurements were 3.25 mm × 3.5 mm. Transport current measurements in magnetic fields up to 32 T were performed at the National High Magnetic Field Laboratory (NHMFL), Tallahassee. Such measurements were done over ~0.5-mm-wide bridge to avoid overheating. Inductively coupled plasma mass spectrometry (ICP-MS) was used to determine the composition of the film.

3. Results and discussion

1) *Role of barium and dopant on > 5-μm-thick REBCO film performance at 4.2 K and 20 K at 13 T*

Fig. 2 depicts the critical current with respect to (Ba + dopant)/Cu ratio at orientations B⊥tape (4.2 K, 13 T and 20 K, 13 T) of the best-performing 5 mol.% Hf, 5 mol.% Zr, 15 mol.% Hf, and 15 mol.% Zr short samples with a thickness > 5 μm, fabricated in the R&D A-MOCVD tool. The I_c at 4.2 K and 20 K in a magnetic field of 13 T was calculated by multiplying the lift factor value with the transport I_c at 77 K, self-field. Lift factor is the ratio of I_c at 4.2 or 20 K, 13 T (B⊥tape) to I_c at 77 K, 0 T, measured using VSM. It is seen in Fig. 2 that regardless of the type of dopant or its concentration, at the optimum (Ba + dopant)/Cu value, the peak I_c of the thick film REBCO is >6000 A/12 mm at 4.2 K and 13 T. The peak I_c is >3,000 A/12 mm for all categories of samples at 20 K and 13 T. The corresponding (Ba + dopant)/Cu ratios for the peak-I_c REBCO samples are 0.67, 0.72, 0.76, and 0.78 for 5 mol.% Hf, 5 mol.% Zr, 15 mol.% Hf, and 15 mol.% Zr, respectively. The findings indicate that for the highest in-field I_c at 4.2 K and 20 K, the Hf-doped REBCO film requires less Ba content than the Zr-doped sample and that samples with a higher dopant content require higher Ba content. These results demon-

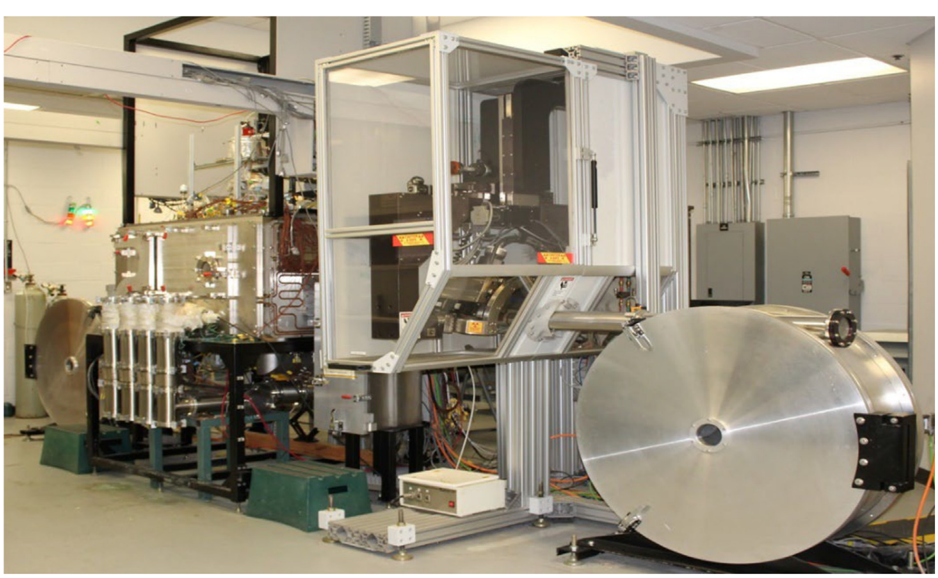

Fig. 1. Pilot scale Advanced MOCVD tool.

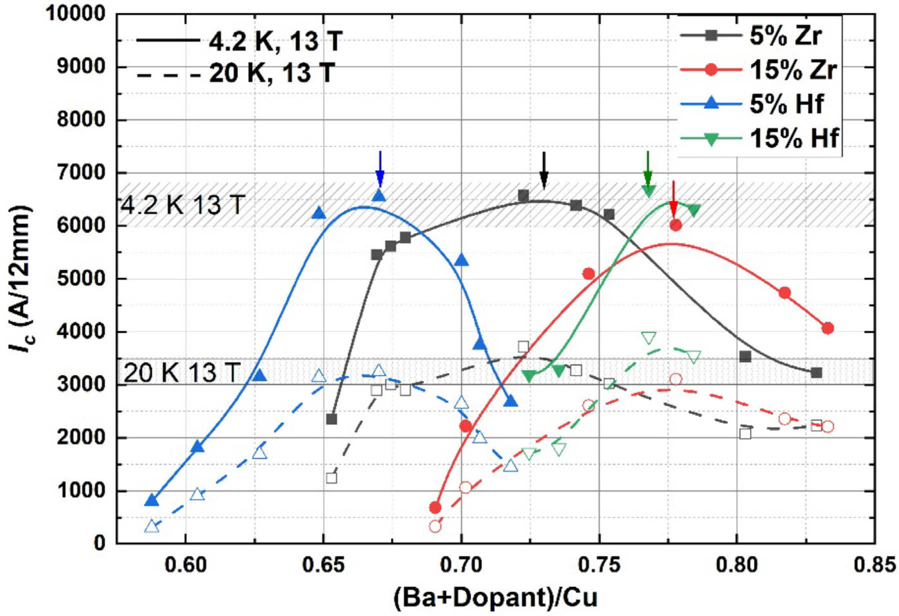

Fig. 2. Effect of (Ba + Dopant)/Cu ratio on the critical current (measured by VSM) of A-MOCVD REBCO tapes at 4.2 K and 20 K. The horizontal bands shown serve to compare the peak I_c values of the tapes at 4.2 K, 13 T and 20 K, 13 T.

strate the important role of Ba content in the REBCO film deposited using A-MOCVD for use in high-field applications at 4.2 K and 20 K. 5% Zr content was used for long tapes fabricated in this work.

2) *40-m REBCO tapes doped with Zr for high-field I_c at 4.2 K and 20 K*

The pilot-scale A-MOCVD tool was used to produce 40-m-long REBCO tapes doped with 5 mol.% or 15 mol.% Zr. Fig. 3 shows the SHPM longitudinal I_c profile at 77 K, 0 T of three 40-m-long tapes. The I_c values shown in the SHPM profile have been calibrated with the transport I_c measured at one end of the tape. Tape 1 and Tape 2 were doped with 5 mol.% Zr with 1.85 and 1.84 Ba stoichiometry respectively in the precursor, whereas Tape 3 was doped with 15 mol.% Zr with 2.08 Ba stoichiometry in the precursor. The mean I_c of Tapes 1 and 2 was ~750 A/12 mm with < 10% standard deviation, whereas the mean I_c of Tape 3 was 405 A/12 mm with ~10% standard deviation. A lower I_c at 77 K, 0 T of the tape with higher Zr content is consistent with our previous observations [15].

Fig. 4 (a and b) shows the dependence of the lift factor in I_c on magnetic fields up to 13 T applied along the *c*-axis of samples from the three 40-m tapes at 4.2 K and 20 K. For 5% and 15% Zr-doped tapes, the minimum lift factors at 4.2 K, 13 T were 4.6 and 11.2 respectively. The lift factors at 20 K are two times lower than the values at 4.2 K. While the critical current of 15% Zr tape was lower at 77 K, the lift factor of this tape is higher than that of 5% Zr-doped tapes. This result is also consistent with our prior observations [27,28]. The higher Zr content results in an increased density of BZO nanocolumns which contribute to improved pinning and a higher lift factor. The lift factor of samples from the end section of all tapes exhibited a higher value, which is attributed to a higher (Ba + Zr)/Cu composition resulting from variations in the MOCVD process.

Fig. 5 (a and b) shows the influence of the applied magnetic field up to 13 T, oriented along the *c*-axis, on the J_c of the end section of 40-m tapes at 4.2 K and 20 K, respectively. All three 40- m tapes consist of 4-μm-thick REBCO films, and the critical current density presented in Fig. 5 was calculated based on this thickness. The graphs show that below 6 T at 4.2 K and 20 K, 5% Zr-doped tapes exhibit higher J_c than 15% Zr-doped tapes. However, both 5% and 15% Zr-doped tapes follow a considerably similar field dependence of J_c in applied magnetic fields > 6 T. The corresponding log (J_c vs. applied magnetic field) plot is shown in the inset Fig. 5 (a and b). The log plots illustrate that field dependence of J_c of both 5% and 15% Zr tapes followed a power law trend $J_c = H^{-\alpha}$, at magnetic fields > 6 T, which is the accommodation field for all three tapes. At 13 T, J_c of all 40-m tapes is > 9 MA/cm^2 at 4.2 K and > 4.4 MA/cm^2 at 20 K. These exceptional results of 40-m tapes show the consistency of the A-MOCVD to produce multiple tapes with J_c > 9 MA/cm^2 at 4.2 K, 13 T. The maximum J_c of 10.3 MA/cm^2 at 4.2 K, 13 T was achieved in the 5% Zr-doped tape.

The electromagnetic properties including critical current, lift factor, and n-value at the start and end sections of the tapes described in Fig. 5 are summarized in Table 1. The n-value is calculated by fitting a part of the I-V curve, and is sensitive to experimental noise and number of data points in the transition region. Across all tapes, n-values ranged from 20 to 30, and are comparable with those of commercial tapes [29]. The alpha values at 4.2 K and 20 K are also included in Table 1. Based on the alpha values, the I_c of the tapes at 4.2 K, 20 T and 20 K, 20 T can be determined and are presented in Table 1. At 4.2 K, the I_c of all 40-m tapes is > 4,000 A/12 mm and > 3,000 A/12 mm at 13 T and 20 T, respectively. A maximum I_c of 4,525 A/12 mm at 4.2 K and 13 T was achieved in Tape 2. At 20 K, 20 T, the I_c of the tapes is > 1,400 A/12 mm.

The J_c criterion used in VSM measurements is more stringent (~1.5 × 10^{-7} V/cm at the sample perimeter) [30,31] compared to the standard 1 μV/cm criterion used in transport measurements. As a result, J_c values obtained from VSM are not directly comparable to those from transport measurements. So, we calibrated the VSM data with the 77 K transport measurement. The critical current of tape 2 was measured using both VSM and four-probe methods which shows agreement with each other. At 4.2 K and 20 T, VSM measurement recorded 3360 A/12 mm, while the four-probe method yielded a slightly higher value of 3645 A/12 mm. To verify the VSM results, transport I_c of the end section of Tape 2 was measured at NHMFL at 4.2 K in magnetic fields up to 32 T applied along the c-axis and is reported in Fig. 6. For comparison, the previously reported data on 15% Zr- or Hf-doped short REBCO samples prepared by our R&D A-MOCVD tool and measured at NHMFL, and Lawrence Berkeley National Laboratory (LBNL) are shown in Fig. 6 [20,21]. Considerably high J_c values of 10.67 MA/cm^2 have been achieved at 4.2 K, 14 T, and

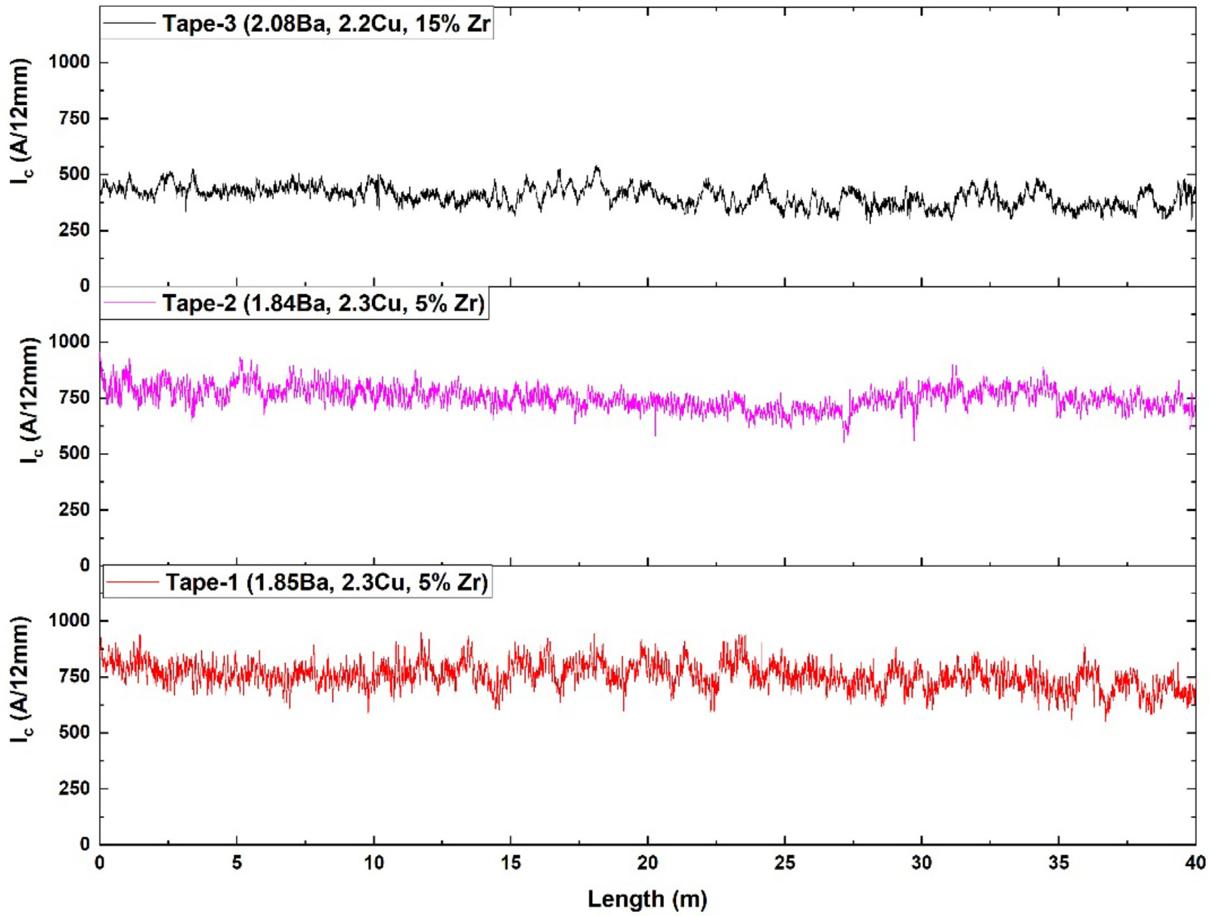

Fig. 3. I_c profiles at 77 K, 0 T of three 40-m-long REBCO tapes fabricated in pilot-scale A-MOCVD tool for 4.2 K and 20 K applications.

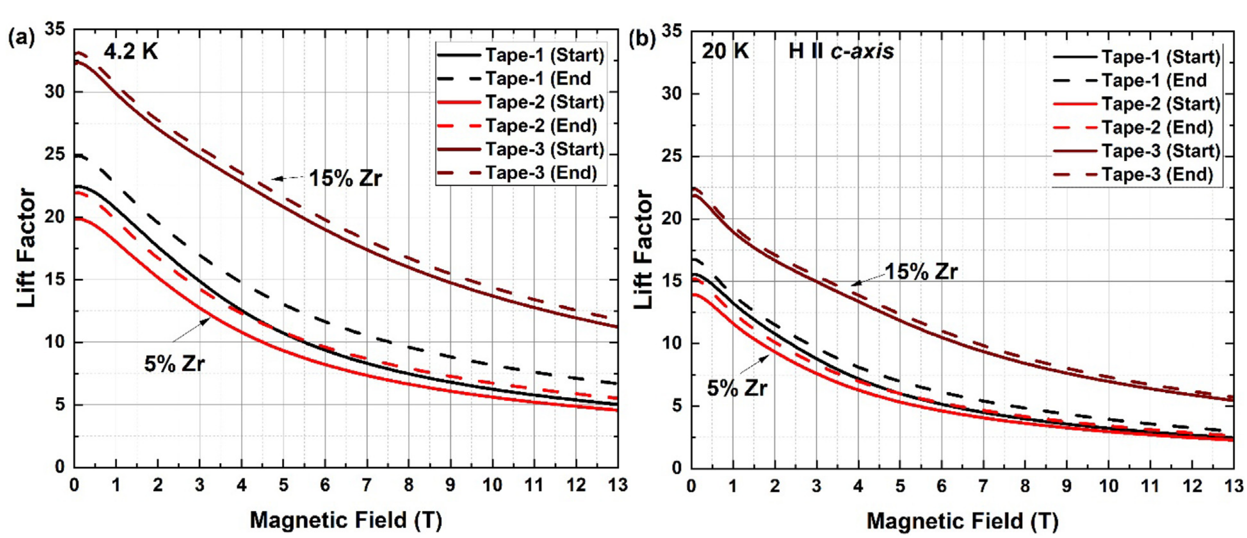

Fig. 4. Lift factor measured by VSM at (a) 4.2 K and (b) 20 K of the start and end sections of three 40-m tapes.

5.62 MA/cm^2 at 4.2 K, 30 T for the long tape. These values are close by to the previously-reported values for 0.9-μm thick, 15 mol% Zr; 4.6-μm thick [28], 15 mol% Zr; and 4-μm thick, 15 mol% Hf-added REBCO tapes [21] processed in short length by A-MOCVD. Notably, these tapes performed 2.5 times better than the best commercial HTS tapes [23]. Our demonstration of high critical currents even over 40-m

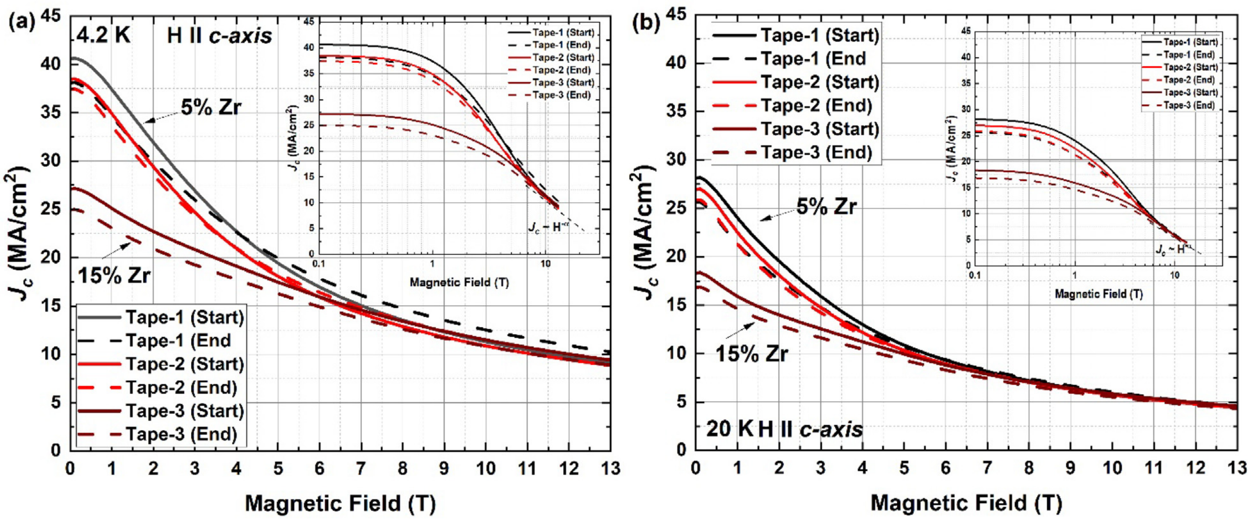

Fig. 5. J_c (measured by VSM) at 4.2 K (left) and 20 K (right) at the start and end sections of three 40-m tapes.

Table 1
Electromagnetic properties of three 40-m Advanced MOCVD tapes.

Temperature	Tape ID	Tape 1 (Start)	Tape 1 (End)	Tape 2 (Start)	Tape 2 (End)	Tape 3 (Start)	Tape 3 (End)
77 K	Transport I_c	869	735	930	819	403	362
	n-value	24.6	19.8	29.6	25.0	19.7	20.3
4.2 K	Lift factor @ 13 T	5.04	6.69	4.6	5.5	11.21	11.79
	I_c @ 13 T	4,379	4,917	4,259	4,525	4,517	4,267
	Alpha value	0.81	0.75	0.77	0.74	0.73	0.72
	I_c @20 T	**3,106**	**3,563**	**3,064**	**3,360**	**3,297**	**3,138**
20 K	Lift factor @ 13 T	2.47	3.0	2.3	2.63	5.45	5.72
	I_c @ 13 T	2,146	2,197	2,120	2,193	2,196	2,070
	Alpha value	0.99	0.99	0.95	0.95	0.9	0.9
	I_c @20 T	**1,402**	**1,436**	**1,413**	**1,462**	**1,494**	**1,408**

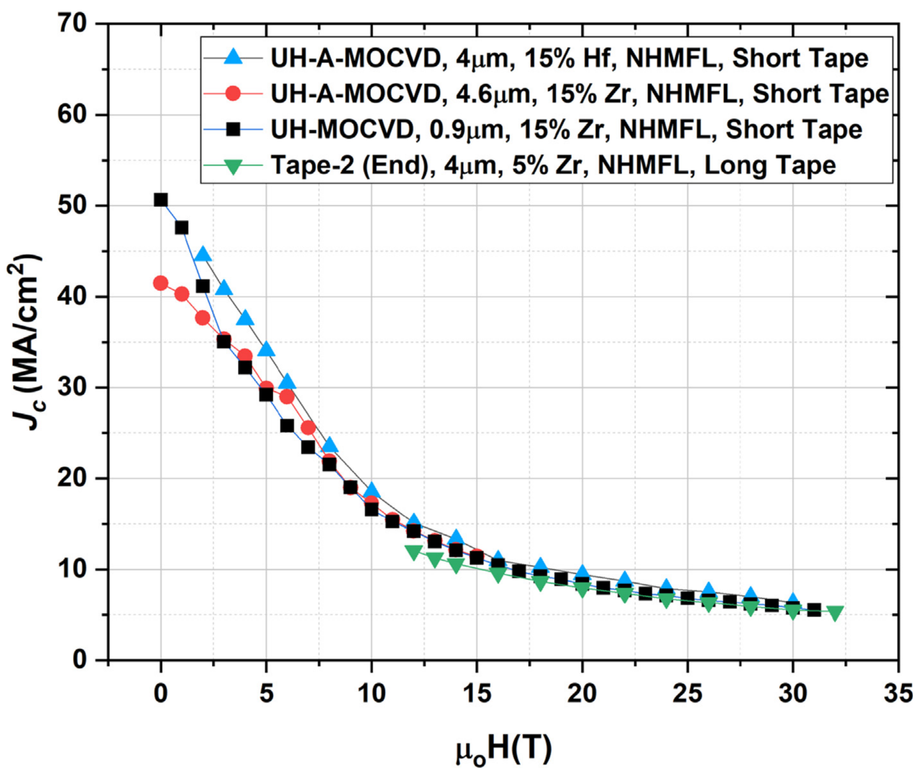

Fig. 6. Critical current density of 40-m long tape versus magnetic field applied along the c-axis at 4.2 K. Data of short samples taken from [20,21,28] are included.

lengths by A-MOCVD confirms the scalability of this method to produce high-performance tapes.

4. Conclusion

Most of the previously-reported A-MOCVD REBCO tapes with the best critical currents in high magnetic fields and low temperatures are those with ≥15% dopant content. In this work, we have shown that by optimizing the barium level in Zr- or Hf-doped REBCO film, a similar superior performance can be achieved in 5% Zr-doped thick-film tapes. Guided by these results on optimum precursor composition, 4-μm-thick-film REBCO tapes with 5 mol% Zr doping were fabricated in lengths over 40 meters in a pilot-scale A-MOCVD tool, in a single pass. Critical currents of these tapes along their length have been measured using 2D SHPM. The infield performance at the end section of each long tape has been measured at 4.2 K and 20 K in magnetic fields up to 13 T (B ⊥ tape). At 13 T, considerably high critical currents >4,000 A/12 mm and > 1,400 A/12 mm have been obtained at 4.2 K and 20 K respectively in the long tapes. We measured the J_c of the end section of a 40-m-long 5% Zr-doped REBCO tape at 4.2 K and fields up to 32 T at NHMFL. Remarkably high critical densities over 10 MA/cm^2 have been obtained at 4.2 K and 14 T. The performance of this tape is on par with the previously-reported high I_c tapes with film thickness <5 μm. Such a superior performance reveals the potential of A-MOCVD to fabricate of long REBCO tapes for ultrahigh-field magnets.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: [Venkat Selvamanickam reports a relationship with AMPeers that includes: equity or stocks. Venkat Selvamanickam serves on the Advisory Editorial Board of this journal. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.].

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References

[1] Rossi L. Superconductivity: its role, its success and its setbacks in the Large Hadron Collider of CERN. Supercond Sci Technol 2010;23:34001.
[2] Scanlan RM, Malozemoff AP, Larbalestier DC. Superconducting materials for large scale applications. Proc IEEE 2004;92:1639–54.
[3] Council NR. High Magnetic Field Science and Its Application in the United States: Current Status and Future Directions. National Academies Press; 2013.
[4] Bottura L, De Rijk G, Rossi L, Todesco E. Advanced accelerator magnets for upgrading the LHC. IEEE Trans Appl Supercond 2012;22:4002008.
[5] Sorbom BN, Ball J, Palmer TR, Mangiarotti FJ, Sierchio JM, Bonoli P, et al. ARC: a compact, high-field, fusion nuclear science facility and demonstration power plant with demountable magnets. Fusion Eng Des 2015;100:378–405.
[6] Reinders LJ. The Revival of Obsolete Practices: Stellarators, Magnetic Mirrors and Pinches *The Fairy Tale of Nuclear Fusion*. Springer 2021. p 349–69
[7] Greenwald M, Whyte D, Bonoli P, Hartwig Z, Irby J, LaBombard B, et al. The high-field path to practical fusion energy. PSFC Rep. PSFC/RR-18-2; 2018.
[8] Bromberg L, Tekula M, El-Guebaly LA, Miller R, Team A. Options for the use of high temperature superconductor in tokamak fusion reactor designs. Fusion Eng Des 2001;54:167–80.
[9] Uglietti D. A review of commercial high temperature superconducting materials for large magnets: from wires and tapes to cables and conductors. Supercond Sci Technol 2019;32:53001.
[10] Segantin S, Whyte D, Zucchetti M. Fusion energy and the ARC project. Int J Ecosyst Ecol Sci 2017;7:839–48.
[11] Riva N, Granetz R, Vieira R, Hubbard A, Pfeiffer A, Harris P, et al. Development of the first non-planar REBCO stellarator coil using VIPER cable. Supercond Sci Technol 2023;36:105001.
[12] U.S. Energy Information Administration 2020 *Capital Cost and Performance Characteristic Estimates for Utility Scale Electric Power Generating Technologies*.
[13] Hartwig ZS, Vieira RF, Sorbom BN, Badcock RA, Bajko M, Beck WK, et al. VIPER: an industrially scalable high-current high-temperature superconductor cable. Supercond Sci Technol 2020;33:11LT01.
[14] Salazar EE, Badcock RA, Bajko M, Castaldo B, Davies M, Estrada J, et al. Fiber optic quench detection for large-scale HTS magnets demonstrated on VIPER cable during high-fidelity testing at the SULTAN facility. Supercond Sci Technol 2021;34:35027.
[15] Pratap R, Majkic G, Galstyan E, Mohanasundaram G, Chakradhar S, Selvamanickam V. Growth of high-performance thick film REBCO tapes using advanced MOCVD. IEEE Trans Appl Supercond 2019;29:6600905.
[16] Galstyan E, Pratap R, Paidpilli M, Majkic G, Selvamanickam V. Pinning characteristics of Zr and Hf-added REBCO coated conductors made by advanced MOCVD in low-to-high magnetic fields. IEEE Trans Appl Supercond 2021;31:8000405.
[17] Paidpilli M, Pratap R, Kochat M, Galstyan E, Goel C, Majkic G, et al. Growth of high-performance 4–5μm thick film REBCO tapes doped with hafnium using advanced MOCVD. IEEE Trans Appl Supercond 2021;31:6600405.
[18] Aytug T, Paranthaman M, Specht ED, Zhang Y, Kim K, Zuev YL, et al. Enhanced flux pinning in MOCVD-YBCO films through Zr additions: systematic feasibility studies. Supercond Sci Technol 2009;23:14005.
[19] Yamada Y, Takahashi K, Kobayashi H, Konishi M, Watanabe T, Ibi A, et al. Epitaxial nanostructure and defects effective for pinning in Y(RE)$Ba_2Cu_3O_{7-x}$ coated conductors. Appl Phys Lett 2005;87:132502.
[20] Majkic G, Pratap R, Xu A, Galstyan E, Higley HC, Prestemon SO, et al. Engineering current density over 5 kA mm− 2 at 4.2 K, 14 T in thick film REBCO tapes. Supercond Sci Technol 2018;31:10LT01.
[21] Majkic G, Pratap R, Paidpilli M, Galstyan E, Kochat M, Goel C, et al. In-field critical current performance of 4.0 μm thick film REBCO conductor with Hf addition at 4.2 K and fields up to 31.2 T. Supercond Sci Technol 2020;33:07LT03.
[22] Tsuchiya K, Kikuchi A, Terashima A, Norimoto K, Uchida M, Tawada M, et al. Critical current measurement of commercial REBCO conductors at 42 K. Cryogenics (Guildf) 2017;85:1–7.
[23] Molodyk A, Samoilenkov S, Markelov A, Degtyarenko P, Lee S, Petrykin V, et al. Development and large volume production of extremely high current density $YBa_2Cu_3O_7$ superconducting wires for fusion. Sci Rep 2021;11:1–11.
[24] Zhao Y, Zhu JM, Jiang GY, Chen CS, Wu W, Zhang ZW, et al. Progress in fabrication of second generation high temperature superconducting tape at Shanghai Superconductor Technology. Supercond Sci Technol 2019;32:44004.
[25] Majkic G, Galstyan E, Selvamanickam V. High performance 2G-HTS wire using a novel MOCVD system. IEEE Trans Appl Superconductivity 2015;25:6605304.
[26] Li Y, Chen S, Paidpilli M, Jain R, Goel C, Selvamanickam V. A reel-to-reel scanning hall probe microscope for characterizing long REBCO conductor in magnetic fields up to 5 Tesla. IEEE Trans Appl Supercond 2022;32:9000206.
[27] Galstyan E, Gharahcheshmeh MH, Delgado L, Xu A, Majkic G, Selvamanickam V. Microstructure characteristics of high lift factor MOCVD REBCO coated conductors with high Zr content. IEEE Trans Appl Supercond 2015;25:6954395.
[28] Xu A, Delgado L, Khatri N, Liu Y, Selvamanickam V, Abraimov D, et al. Strongly enhanced vortex pinning from 4 to 77 K in magnetic fields up to 31 T in 15 mol.% Zr-added (Gd, Y)-Ba-Cu-O superconducting tapes. APL Mater. 2014;2:46111.
[29] Chudy M, Zhong Z, Eisterer M, Coombs T. N-Values of commercial YBCO tapes before and after irradiation by fast neutrons. Supercond Sci Technol 2015;28(3).
[30] Majkic G, Pratap R, Galstyan E, Selvamanickam V. Correlation of In-Field Performance of Thick REBCO Films between 0–14 T and 4.2-77 K. IEEE Trans Appl Supercond 2019;29:6602005.
[31] Polat A, Sinclair JW, Zuev YL, Thompson JR, Christen DK, Cook SW, et al. Thickness dependence of magnetic relaxation and E-J characteristics in superconducting (Gd-Y)-Ba-Cu-O films with strong vortex pinning. Phys Rev B - Condensed Matter Mater Phys 2011;84:024519.