Enhanced superconducting properties of $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ thin film with magnetic nanolayer additions

Jijie Huang¹, Meng Fan², Han Wang¹, Li Chen¹, Chen-Fong Tsai¹, Leigang Li¹ and Haiyan Wang^{1,2*}

¹Department of Material Science and Engineering, Texas A&M University, College Station, Texas 77843-3003, United States

²Department of Electrical and Computer Engineering, Texas A&M University, College Station, Texas 77843-3128, United States

Email: wangh@ece.tamu.edu

Abstract. Vertically aligned nanocomposite (VAN) $(\text{La}_{0.7}\text{Sr}_{0.3}\text{MnO}_3)_{0.5}(\text{CeO}_2)_{0.5}$ and pure $\text{La}_{0.7}\text{Sr}_{0.3}\text{MnO}_3$ layers were incorporated into $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ (YBCO) thin films as bilayer stacks for magnetic flux pinning enhancement. The films show high epitaxial quality, suggested by XRD and TEM study. The critical temperature T_c of the bilayers is about 90 K, which is close to that of pure YBCO films, while both the self-field J_c^{sf} and in-field critical current density $J_c^{in-field}$ are largely enhanced. Among all samples, the film with VAN cap layer shows the highest J_c values in all field ranges. This study demonstrates an effective way towards the tunable pinning effect for YBCO coated conductors by both defect and magnetic pinning.

Key words: flux pinning, vertically aligned nanocomposite, magnetic pinning

INTRODUCTION

Tremendous research efforts have been focused on the development of high temperature superconducting (HTS) coated conductors based on $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ (YBCO) since it was discovered in 1987 [1-5]. Significant progress has been made first to address the needs on the epitaxial growth of the YBCO coated conductors on flexible metal substrates, and later to address critical issues that limit the performance of YBCO-based coated conductors. To enable the epitaxial growth of YBCO thin films on metal substrate, certain templates are required. The two primary approaches are (1) to involve a textured metal substrate to start with, i.e., rolling-assisted biaxially textured substrates (RABiTS) [5] and (2) to build an epitaxial template on amorphous buffered metal substrates called ion-beam-assisted deposition (IBAD) substrates [6-8]. Moreover, several film growth techniques have been successfully tailored for the deposition of YBCO thin films with high epitaxial quality on these metal substrates, such as metal-organic chemical vapor deposition (MOCVD) [9,10], pulsed laser deposition (PLD) [11-13], metal-organic deposition (MOD) [14,15] as well as magnetron sputtering [16,17]. With over a decade of development, superconducting properties of YBCO coated conductors have been significantly improved and practical applications have been demonstrated in multiple areas such as HTS coated conductors, superconductor magnets, generators and fault current limiters. [4, 6, 18, 19] However, for most of the above technological applications, high critical current densities (J_c) under applied magnetic field, so called in-field performance, is required.

Various flux pinning approaches have been introduced in YBCO HTS coated conductors to better pin flux lines and thus achieve superior J_c performance, in both self-

field and in-field. Overall there are two categories, i.e., non-magnetic defect pinning and magnetic pinning. For non-magnetic defect pinning, most of the work has focused on the defect landscape design with various dimensional nanoinclusions, including nanoparticles [20, 21], nanocolumns [22, 23], as well as nanolayers [24]. Furthermore, some unique architectures were also designed, for example, Baca et al. combined Y_2O_3 nanoparticles and BaZrO_3 nanorods for overall pinning enhancement [25]. Magnetic pinning is another effective approach, because of the interaction between the magnetic inclusions and the fluxons [26-29]. Bulaevskii *et al.* demonstrated that the high value of magnetic pinning potential U_{mp} ($U_{mp} \sim \Phi_0 \mathbf{M}(\mathbf{x}) \mathbf{d}_s$, where $\mathbf{M}(\mathbf{x})$ is the magnetization of the magnetic inclusion and $\mathbf{d}_s$ the thickness of the YBCO film) can overcome the thermal activated flux flow at high temperatures [30]. Various effective magnetic pinning centers have been demonstrated, including CoFe_2O_4 nanoparticle [31], CoPt layer [32], as well as $\text{Pr}_{0.67}\text{Sr}_{0.33}\text{MnO}_3$ (PSMO) layer [33].

In this study, a unique design of vertically aligned nanocomposite (VAN) layer embedding magnetic nanopillars was introduced into YBCO thin films as either cap layer or buffer layer for flux pinning enhancement. For demonstration, a VAN composite of CeO_2 and $\text{La}_{0.7}\text{Sr}_{0.3}\text{MnO}_3$ (LSMO) is selected. The selection of LSMO: CeO_2 VAN as magnetic dopants is based on the excellent magnetic property of the LSMO phase [34-35] and that the in-plane lattice parameter of both LSMO ($3.87\text{\AA}$) and CeO_2 ($5.411\text{\AA}$ with 45° rotation) is close to orthorhombic YBCO ($a=3.82\text{\AA}$, $b=3.89\text{\AA}$). Thus, both defect pinning and magnetic pinning effects are expected in this VAN nanolayer doped system. A pure LSMO layer buffered YBCO sample was also introduced for comparison.

EXPERIMENTAL

(LSMO)_{0.5}(CeO₂)_{0.5} (L5C5)/YBCO and LSMO/YBCO bilayers were deposited by a PLD system with a KrF excimer laser (Lambda Physik 201, $\lambda=248$ nm, 300 mJ) on single crystal STO (001) substrates. The thickness of VAN nanolayer and YBCO matrix were controlled at about 20 nm (2 Hz, 2 min) and 350 nm (10 Hz, 6 min), respectively. The architecture of the bilayers thin films were prepared by alternative laser ablation of the nanocomposite and YBCO targets. The films were deposited with 300 mTorr oxygen in-flow at 780 °C, and followed by a post-annealing process under 300 Torr oxygen at 550 °C for 30 min.

The microstructure of the films was characterized by X-ray diffraction (XRD) (PANalytical X'Pert X-ray diffractometer) and transmission electron microscopy (TEM) (FEI Tecnai G2 F20). The magnetization, critical transition temperature (T_c), and critical current density (both J_c^{sf} and $J_c^{in-field}$) were measured by a physical property measurement system (PPMS). $J_c^{in-field}(H//c)$ were measured under an applied field of 0 to 5 T at 77 K, 65 K, 40 K, and 5 K by the vibrating sample magnetometer (VSM) in PPMS.

RESULTS AND DISCUSSION

Prior to incorporating L5C5 VAN and LSMO layers into YBCO, single layers of L5C5 and LSMO were grown on STO substrates for magnetic property measurements. Fig. 1 (a) and (b) show the M-H curves for the L5C5 and LSMO thin films, respectively, at different temperatures ranging from 20 K to 200 K. It is obvious that the hysteresis loops in both cases remain the same shape at different temperatures, which indicates their magnetic property remains at the superconductor working temperature range. In addition, it is clear that LSMO shows a higher magnetization and saturation remanence M_{rs} than

L5C5 VAN, partly because of the non-magnetic CeO₂ in the L5C5 nanocomposites. By comparing M_{rs} of the two samples, M_{rs} (L5C5) ≈ 450 emu/cm³ (here the magnetization of a single LSMO nanocolumn can be estimated to be 2.25×10^{-16} emu based on the volume of one single column as $5 \times 5 \times 20$ nm³), which is lower than half of M_{rs} (LSMO) ≈ 2000 emu/cm³. One possible reason is that the incorporation of a second phase (CeO₂) into LSMO may cause the suppression of the double exchange interaction between the neighboring LSMO domains, which could deteriorate the magnetic property of LSMO [34]. Other factors to be considered include the film thickness variations and samples size for VSM measurements among samples. Moreover, interestingly, the L5C5 VAN exhibits higher coercive field h_c than the pure LSMO sample, because of the thin disordered regions at the LSMO|CeO₂ interface areas [34]. This disordered 2-phase boundary may lead to increased pinning effect [36], as well as larger lattice strain in the films [37]. Overall, both L5C5 VAN and pure LSMO thin films present strong magnetization response under applied magnetic field perpendicular to the sample surface.

L5C5 VAN was then incorporated into YBCO as either cap layer or buffer layer. As a comparison, a YBCO/LSMO bilayer stack was deposited to explore the pinning properties of a pure ferromagnetic LSMO layer. Fig. 2 shows the standard θ -2 θ XRD scans of all the samples, symbols #, Δ and + represent YBCO (00 l), LSMO (00 l) and STO (00 l) peaks, respectively. Apparently, for the L5C5/YBCO/STO and YBCO/L5C5/STO, YBCO (003) and (006) peaks are perfectly overlapped with STO (001)/LSMO (001) and STO (002)/LSMO (002) peaks, which demonstrates the highly textured growth of the YBCO film, as well as the L5C5 layer. However, for the YBCO/LSMO sample, YBCO (200) peak can be identified, which will be further

discussed correlating with the TEM study below. Furthermore, CeO_2 (002) peak can be clearly identified from the L5C5 layer and no other impurity peak was identified. Again this confirms the excellent film quality of both the L5C5 and YBCO layers.

The film quality and microstructural characteristics were explored further using TEM for the L5C5/YBCO/STO and YBCO/LSMO/STO samples. Fig. 3 (a) presents the schematic drawing of the designed L5C5/YBCO bilayer film. Fig. 3 (b) shows the low-magnification cross-sectional TEM (XTEM) micrograph, the different layers can be easily identified as labeled. The thickness of the YBCO layer and L5C5 layer can be estimated to be 350 nm and 20 nm, respectively. Fig. 3 (c) shows the corresponding selected area electron diffraction (SAED) pattern. The distinguished diffraction dots further confirm the high quality epitaxial growth of both YBCO and L5C5 VAN layers. Interestingly, the phase of CeO_2 presents double-epitaxial orientations, as two orthogonal diffraction patterns (red and blue) indicating the two orientation relations for CeO_2 . The high resolution TEM image of the enlarged area can be seen in Fig. 3 (d). The two layers can be easily identified with a very sharp interface, which suggests very little or no inter-diffusion between the two layers. For the YBCO layer, the film grows well along c-axis direction. For the L5C5 VAN layer, the two phases of LSMO and CeO_2 grow alternatively on the YBCO layer, with excellent epitaxial quality. This L5C5 self-assembled VAN structure is of similar quality to the previous reported L5C5 VAN directly on STO substrate [34].

The microstructure of YBCO/LSMO bilayer has also been explored and its schematic illustration is shown in Fig. 4 (a). However, both a-axis YBCO and c-axis YBCO can be clearly observed in the low mag XTEM image in Fig. 4 (b). From the

corresponding SAED pattern in Fig. 4 (b), the orientation relations between the two layers and substrate can be determined to be YBCO (006) $\parallel$ LSMO (002) $\parallel$ STO (002). The a-axis growth of YBCO is known to be harmful for the overall J_c property of YBCO film, due to the less efficient electrical current transportation and less connectivity of the film [38]. Furthermore, from the high resolution TEM image in Fig. 4 (d), the LSMO layer grow perfectly with high film quality on STO substrate with the YBCO layer on top. However, it is obvious that there is a thin interfacial reaction layer of around 5 nm between LSMO layer and YBCO layer, which can be accounted for the possible inter-diffusion between the two layers. Such interfacial diffusion layer has been reported previously in a LSMO buffered YBCO thin film [40].

To explore the defect pinning mechanism, detailed high resolution TEM study of the pure YBCO, LSMO buffered YBCO and L5C5 capped YBCO, as well as their corresponding fast Fourier transform (FFT) filtered processing, were carried out. Fig. 5 (a) and (b) show the HRTEM image near the interface area of the pure YBCO sample and its corresponding FFT image, respectively. The dislocations and stacking faults (extra half planes) are represented by “ $\perp$ ” and “ $\rightarrow$ ”, respectively. Obvious dislocations and stacking faults can be identified in the image, and most of them are near the interface area. Fig.5 (c) and (d) show the HRTEM image near the LSMO/YBCO interface area of LSMO buffered sample and the corresponding FFT image. It is obvious that there are more defects compared to the pure YBCO sample, especially close to the interfacial layer area. In addition, there are a lot of defects appear at the L5C5/YBCO interface, as shown in Fig. 5(e) and (f). These defects could provide strong defect pinning which is discussed in a later section. Furthermore, the defect density reduces in the area away from the interface,

which ensures the high film quality of the main YBCO matrix. Overall, the incorporation of the extra nanolayer produces additional defects in the interface area which could lead to enhanced defect pinning.

Furthermore, the superconducting properties of all the samples were measured and compared with the single layer YBCO film. The T_c and self-field J_c (77 K, 65 K, 40 K and 5 K) values are summarized in Table 1. Obviously, the T_c values almost remain the same after introducing the dopant layer, which indicates little or no film quality degradation. Additionally, the J_c^{sf} results show that all the bilayer samples obtain higher values than that of the single YBCO layer at all the measured temperatures, with the best in L5C5/YBCO/STO and followed by YBCO/L5C5/STO. The sample L5C5/YBCO/STO exhibits J_c^{sf} values of 5.5, 18.3, 51.9 and 121.1 MA/cm² at 77 K, 65 K, 40 K and 5 K, respectively. YBCO/LSMO presents lower values than the above two cases, probably caused by the inter-diffusion layer shown in the TEM results in Fig. 4 (d), as well as the presence of a-axis YBCO grains (Fig. 4(b)). Because the inter-diffusion is minimal (the inter-diffusion layer of 5 nm), it did not impact on the main bulk region of the YBCO matrix and thus the film still maintains a higher J_c value than that of the pure YBCO film. In addition, more dislocations in YBCO close to the interface area have been observed for the LSMO buffered case and could contribute to the enhanced J_c performance compared to pure YBCO film. Foltyn *et al.* previously reviewed that a number of defect types can act as pinning centers for superconducting property enhancement [4]. Other prior report also showed similar J_c trend for pure YBCO and LSMO buffered YBCO [35]. In addition, the sample size variation as well as sample film thickness variation could also cause some minor errors in the final J_c values measured by the VSM. Overall

all the doped samples, especially the L5C5 VAN doped cases, have shown enhanced J_c performance compared to pure YBCO. Other nanocomposite systems have also been introduced for pinning enhancement by both defect and magnetic pinning in previous studies [11, 26]. The T_c and J_c^{sf} values of all the samples in this study were summarized and compared with some prior results in Table 1. It is obvious that L5C5/YBCO exhibits the highest J_c^{sf} values at all the measured temperatures, followed by $(\text{CoFe}_2\text{O}_4)_{0.5}(\text{CeO}_2)_{0.5}/\text{YBCO}$ with slightly lower values. Overall, the LSMO: CeO_2 and CoFe_2O_4 : CeO_2 nanocomposite systems show better performance than Fe_2O_3 : CeO_2 system for YBCO pinning enhancement. This is probably because much less inter-diffusion as well as stronger magnetic properties in the cases of the LSMO: CeO_2 and CoFe_2O_4 : CeO_2 nanocomposite systems compared to the Fe_2O_3 : CeO_2 system.

Table 1. Comparison of T_c and self-field J_c of all the samples with or without nanolayer.

Sample	Property	T_c (K)	Self-field J_c^{sf} (MA/cm ²)			
			77 K	65 K	40 K	5 K
L5C5/YBCO		90.3	5.5	18.3	51.9	121.1
YBCO/L5C5		90.1	4.9	12.5	33.1	70.7
YBCO/LSMO		89.9	1.7	8.5	26.9	73.9
$(\text{Fe}_2\text{O}_3)_{0.5}(\text{CeO}_2)_{0.5}/\text{YBCO}$ [11]		90.1	NA	5.4	23.9	81.3
YBCO/ $(\text{Fe}_2\text{O}_3)_{0.5}(\text{CeO}_2)_{0.5}$ [11]		89.8	NA	3.5	15.3	52.0
$(\text{CoFe}_2\text{O}_4)_{0.5}(\text{CeO}_2)_{0.5}/\text{YBCO}$ [26]		90.0	5.2 at 75 K	17.1	48.3	132
YBCO/ $(\text{CoFe}_2\text{O}_4)_{0.5}(\text{CeO}_2)_{0.5}$ [26]		89.9	3.1 at 75 K	7.4	25.4	43.3
Pure YBCO		90.4	1.3	3.8	13.2	42.4

The in-field (0-5 T, $H//c$) J_c values were compared in Fig. 6 at (a) 77 K, (b) 65 K, (c) 40 K and (d) 5 K to investigate the pinning properties in these bilayers. Here, the J_c values were derived by the Bean model: $Jc = 20\Delta M/a(1 - \frac{a}{3b})$, where ΔM is the opening in the hysteresis loop; a and b are the sample dimensions [41]. When the

measured temperature is at 77 K, the samples with either L5C5 cap or buffer obtain the highest J_c values under all the measured magnetic fields. And the LSMO buffered sample exhibits higher J_c than the referenced YBCO at low magnetic field, however, J_c performance depresses faster at higher fields, probably due to the inter-diffusion between LSMO and YBCO. At 65 K, L5C5/YBCO/STO shows the highest $J_c^{in-field}$ values, especially at low fields, while the YBCO/L5C5/STO catches up at higher fields. The value of YBCO/LSMO/STO is in between the above two and the reference YBCO film. The inter-diffusion as well as the a-axis YBCO growth could hinder its further improvement in pinning properties in this case. It is worth noting that the incorporated CeO_2 confines the inter-diffusion and thus the L5C5 buffered YBCO obtains much higher $J_c^{in-field}$ values. At 40 K, the plot shows a similar trend as that of 65 K, however, the LSMO buffered sample starts to approach the other two. When the measurement temperature further decreased to 5 K, L5C5/YBCO/STO still shows as the highest in all the applied field regimes. However, interestingly, the performance of LSMO buffered sample exceeds the L5C5 buffered one. One possible reason is that, at this low temperature regime, the magnetic pinning from LSMO is more evident comparing to the superconducting property degradation from the inter-diffusion issue and a-axis YBCO growth, which is consistent with previous report [39]. Overall, all the bilayer samples show pinning enhancement under magnetic field at different measurement temperatures, both defect and magnetic pinning could account for the overall enhanced pinning properties.

To further explore the flux pinning effect from the introduced L5C5 and LSMO, the calculated in-field pinning force F_p values of all the samples were plotted and

compared in Fig. 7 (a) 77 K, (b) 65 K, (c) 40 K and (d) 5 K. At high temperature of 77 K, the L5C5 capped and buffered show similar F_p values to each other and higher values than other samples. At 65 K, both L5C5 capped and buffered YBCO shows the highest F_p values along the applied field, with highest pinning force under the applied field (B_{max}) of ~ 1 T. At a lower temperature of 40 K, L5C5 buffered starts to show lower F_p value than the capped one, which is possibly due to the minor inter-diffusion and film quality degradation. B_{max} of all the samples are out-of-range at this temperature. Interestingly, the F_p of the LSMO buffered sample surpassed L5C5 buffered YBCO film, which is consistent with the above $J_c^{in-field}$ results. Here, the defect pinning is caused by the increased density of defects in the interface area, as discussed above based on the TEM results and the corresponding FFT analysis. For the magnetic pinning, it is worth to further discuss the pinning potential of the LSMO magnetic domains in this case. The magnetic pinning in this case can be considered as a “periodic ferromagnetic nanodot array” model [42], or “ferromagnetic/superconducting multilayer” model [32]. Here, the later model is selected for the discussion as the L5C5 layer can be treated as a ferromagnetic layer, similar to the role of the CoPt layer introduced by Jan *et al* [32]. Thus, the pinning potential for a single vortex line created by the magnetic domain can be estimated to be $U_{mp} \sim \Phi_0 \mathbf{M} d_s$, here Φ_0 is the flux quantum, $\mathbf{M}$ is the magnetization of the magnetic domain, and d_s is the thickness of the superconductor layer [30, 32]. And the pinning force provided by the magnetic domain is $f_m \sim U_{mp}/\lambda$, where λ is the penetration depth. Hence, the magnetic potential and magnetic pinning force in different temperatures under different applied fields can be estimated, on the basis of the measured magnetization of the LSMO magnetic domain in Fig. 1.

Based on the above results, (LSMO)_{0.5}(CeO₂)_{0.5} VAN and LSMO nanolayer can provide effective flux pinning centers for YBCO thin films. Both defect and magnetic pinning effects played a role in the pinning enhancement for all the doped samples. The pinning mechanisms at different measured temperatures are quite different. In this study, magnetic pinning is more obvious at lower temperatures, which is consistent with the previously reported (Fe₂O₃)_{0.5}(CeO₂)_{0.5} [39] system but the trend is opposite to several other systems [30, 33]. To fully understand the flux pinning mechanisms in different cases, future study is needed to focus on the relationship between the pinning energy and thermal induced flux flow. Moreover, the composition variation study is also important for determining the best composition ratio of LSMO and CeO₂, to achieve the optimum pinning effect for YBCO thin films.

CONCLUSION:

In summary, (LSMO)_{0.5}(CeO₂)_{0.5} VAN structure and pure LSMO nanolayers were introduced into YBCO thin films, with excellent epitaxial quality. J_c^{sf} and $J_c^{in-field}$ of the bilayer samples were largely enhanced compared to the pure YBCO film, which illustrates that effective pinning centers are introduced. In this study, L5C5 capped YBCO film shows the best in-field performance than the other cases, because of the minimized inter-diffusion between YBCO and the dopants, as well as limited a-axis YBCO outgrowth compared to the pure LSMO nanolayer doped case. This work demonstrates that the VAN structure is a very flexible and tunable approach for the

pinning enhancement for YBCO coated conductors by combining magnetic and defect pinning effects.

ACKNOWLEDGMENTS

This work was partially supported by the Air Force Office of Scientific Research (Contract No. FA9550-09-1-0114) and the TEM effort was funded by the National Science Foundation (DMR-0846504).

REFERENCES

1. M. K. Wu, J. R. Ashburn, C. J. Torng, P. H. Hor, R. L. Meng, L. Gao, Z. J. Huang, Y. Q. Wang, and C. W. Chu, "Superconductivity at 93 K in a New Mixed-Phase Y-Ba-Cu-O Compound System at Ambient Pressure," *Phys. Rev. Lett.* **58(9)**, 908 (1987)
2. 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 $\text{YBa}_2\text{Cu}_3\text{O}_{7-x} + \text{BaZrO}_3$," *Nature Materials* **3**, 439 (2004)
3. X. Obradors, T. Puig, A. Pomar, F. Sandiumenge, N. Mestres, M. Coll, A. Cavallaro, N. Roma, J. Gazquez, J. C. Gonzalez, O. Castano, J. Gutierrez, A. Palau, K. Zalamova, S. Morlens, A. Hassini, M. Gibert, S. Ricart, J. M. Moreto, S. Pinol, D. Isfort, and J. Bock, "Progress towards all-chemical superconducting $\text{YBa}_2\text{Cu}_3\text{O}_7$ -coated conductors," *Supercond. Sci. Technol.* **19**, S13 (2006)
4. 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," *Nature Materials* **6**, 631 (2007)
5. A. Goyal, P. M. Paranthaman, and U. Schoop, "The RABiTS approach: Using rolling-assisted biaxially textured substrates for high-performance YBCO superconductors," *MRS Bulletin* **29(8)**, 552 (2004)

6. D. Larbalestier, A. Gurevich, D. M. Feldmann, and A. Polyanskii, "High-Tc superconducting materials for electric power applications," *Nature* **414**, 368 (2001)
7. P. N. Arendt, and S. R. Foltyn, "Biaxially Textured IBAD-MgO Templates for YBCO-Coated Conductors," *MRS Bulletin* **29(8)**, 543 (2004)
8. M. Inoue, T. Kiss, D. Mitsui, T. Nakamura, T. Fujiwara, S. Awaji, K. Watanabe, A. Ibi, S. Miyata, Y. Yamada, and Y. Shiohara, "Current Transport Properties of 200 A-200 m-Class IBAD YBCO Coated Conductor Over Wide Range of Magnetic Field and Temperature," *IEEE Tran. Appl. Supercond.* **17(2)**, 3207 (2007)
9. A. Molodyk, M. Novozhilov, S. Bitkowsky, S. Street, A. Delaney, L. Castellani, and A. Ignatiev, "Development of MOCVD Technology for Integrated YBCO Layer/Buffer Layer Fabrication for Coated Conductors," *IEEE Tran. Appl. Supercond.* **19(3)**, 3196 (2009)
10. T. Aytug, M. Paranthaman, E. D. Specht, Y. Zhang, K. Kim, Y. L. Zuev, C. Cantoni, A. Goyal, D. K. Christen, V. A. Maroni, Y. Chen, and V. Selvamanickam, "Enhanced flux pinning in MOCVD-YBCO films through Zr additions: systematic feasibility studies," *Supercond. Sci. Technol.* **23**, 014005 (2010)
11. C. T. Tsai, J. Huang, J. H. Lee, F. Khatkhatay, L. Chen, A. Chen, Q. Su, and H. Wang, "Tunable flux pinning landscapes achieved by functional ferromagnetic $\text{Fe}_2\text{O}_3\text{:CeO}_2$ vertically aligned nanocomposites in $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ thin films," *Physica C* **510**, 13 (2015)
12. M. Lorenz, H. Hochmuth, D. Natusch, M. Kusunoki, V. L. Svetchnikov, V. Riede, I. Stanca, G. Klstner, and D. Hesse, "High-quality Y-Ba-Cu-O Thin Films by PLD - Ready for Market Applications," *IEEE Tran. Appl. Supercond.* **11**, 3209 (2001)
13. J. Yang, H. Zhang, X. L. Feng, H. Z. Liu, and Q. Zhou, "Reel-to-reel fabrication of meter-long YBCO coated conductor," *J. Phys.: Conf. Ser.* **234**, 022043 (2010)
14. S. Ghalsasi, Y. X. Zhou, J. Chen, B. Lv, and K. Salama, "MOD multi-layer YBCO films on single-crystal substrate," *Supercond. Sci. Technol.* **21**, 045015 (2008)
15. M. Sohma, K. Tsukada, I. Yamaguchi, K. Kamiya, W. Kondo, S. Mizuta, T. Manabe, and T. Kumagai, "Structural aspect of high- J_c MOD-YBCO films prepared on large area CeO_2 -buffered YSZ substrates," *J. Phys.: Conf. Ser.* **43**, 349 (2006)
16. B. Blagoev, E. Mateev, V. Strbik, T. Nurgaliev, and L. S. Uspenskaya, "Magnetron sputtering of polycrystalline LSMO/YBCO structures on sapphire substrates," *J. Phys.: Conf. Ser.* **223**, 012015 (2010)
17. E. Yin, M. Rubin, and M. Dixon, "Sputtered YBCO films on metal substrates," *J. Mater. Res.* **7(7)**, 1636 (1992)
18. R. F. Service, "Superconductivity. New wave of electrical wires inches closer to market," *Science* **308(5720)**, 348 (2005)
19. D. Christen, "Superconductors: Pumping up for wire applications," *Nature Materials* **3** 421 (2004)
20. T. Haugan, P. N. Barnes, R. Wheeler, F. Meisenkothen, and M. Sumption, "Addition of nanoparticle dispersions to enhance flux pinning of the $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ superconductor," *Nature* **430(7002)**, 867 (2004)
21. I. Birlik, M. Erbe, T. Freudenberg, E. Celik, L. Schultz, and B. Holzapfel, "Flux pinning improvement of ybco superconducting films with BaZrO_3 nanoparticles prepared by chemical solution deposition method," *J. Phys.: Conf. Ser.* **234**, 012004 (2010)
22. D. M. Feldmann, T. G. Holesinger, B. Maiorov, S. R. Foltyn, J. Y. Coulter, and I. Apodaca, "Improved flux pinning in $\text{YBa}_2\text{Cu}_3\text{O}_7$ with nanorods of the double perovskite Ba_2YNbO_6 ," *Supercond. Sci. Technol.* **23**, 095004 (2010)
23. A. Goyal, S. Kang, K. J. Leonard, P. M. Martin, A. A. Gapud, M. Varela, M. Paranthaman, A. O. Ijaduola, E. D. Specht, 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 $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ films,” *Supercond. Sci. Technol.* **18**, 1533 (2005)
24. C. Tsai, Y. Zhu, L. Chen, and H. Wang, “Correlation Between Flux Pinning Properties and Interfacial Defects in $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}/\text{CeO}_2$ Multilayer Thin Films,” *IEEE Tran. Appl. Supercond.* **21(3)**, 2758 (2011)
 25. F. J. Baca, T. Haugan, P. Barnes, T. Holesinger, B. Maiorov, R. Lu, X. Wang, J. Reichart, and J. Wu, “Interactive Growth Effects of Rare-Earth Nanoparticles on Nanorod Formation in $\text{YBa}_2\text{Cu}_3\text{O}_x$ Thin Films,” *Adv. Funct. Mater.* **23**, 4826 (2013)
 26. J. Huang, C. F. Tsai, L. Chen, J. Jian, F. Khatkhatay, K. Yu, and H. Wang, “Magnetic properties of $(\text{CoFe}_2\text{O}_4)_x:(\text{CeO}_2)_{1-x}$ vertically aligned nanocomposites and their pinning properties in $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ thin films,” *J. Appl. Phys.* **115**, 123902 (2014)
 27. D. Bagarinao, and H. Yamasaki, “Microstructural defects associated with enhanced magnetic flux pinning in YBCO/DyBCO/YBCO multilayered thin films,” *Supercond. Sci. Technol.* **24**, 065017 (2011)
 28. J. Huang, C. F. Tsai, L. Chen, J. Jian, K. Yu, W. Zhang, and H. Wang, “Enhanced Flux Pinning Properties in $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}/(\text{CoFe}_2\text{O}_4)_{0.3}(\text{CeO}_2)_{0.7}$ Multilayer Thin Films,” *IEEE Tran. Appl. Supercond.* **25(3)**, 7500404 (2015)
 29. M. G. Blamire, R. B. Dinnar, S. C. Wimbush, and J. L. MacManus-Driscoll, “Critical current enhancement by Lorentz force reduction in superconductor-ferromagnet nanocomposites,” *Supercond. Sci. Technol.* **22**, 025017 (2009)
 30. L. N. Bulaevskii, E. M. Chudnovsky, and M. P. Maley, “Magnetic pinning in superconductor-ferromagnet multilayers,” *Appl. Phys. Lett.* **76**, 2594 (2000)
 31. C. F. Tsai, L. Chen, A. Chen, F. Khatkhatay, W. Zhang, and H. Wang, “Enhanced Flux Pinning Properties in Self-Assembled Magnetic CoFe_2O_4 Nanoparticles Doped $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ Thin Films,” *IEEE Tran. Appl. Supercond.* **23(3)**, 8001204 (2013)
 32. D. B. Jan, J. Y. Coulter, M. E. Hawley, L. N. Bulaevskii, M. P. Maley, Q. X. Jia, B. B. Maranville, F. Hellman, and X. Q. Pan, “Flux pinning enhancement in ferromagnetic and superconducting thin-film multilayers,” *Appl. Phys. Lett.* **82**, 778 (2003)
 33. X. X. Zhang, G. H. Wen, R. K. Zheng, G. C. Xiong, and G. J. Lian, “Enhanced flux pinning in a high- T_C superconducting film by a ferromagnetic buffer layer,” *Europhys. Lett.* **56**, 119 (2001)
 34. A. Chen, Z. Bi, H. Hazariwala, X. Zhang, Q. Su, L. Chen, Q. X. Jia, J. L. MacManus-Driscoll, and H. Wang, “Microstructure, magnetic, and low-field magnetotransport properties of self-assembled $(\text{La}_{0.7}\text{Sr}_{0.3}\text{MnO}_3)_{0.5}:(\text{CeO}_2)_{0.5}$ vertically aligned nanocomposite thin films,” *Nanotechnology* **22**, 315712 (2011)
 35. T. Petrison, M. S. Gabor, C. Tiusan, V. Galluzzi, G. Celentano, S. Popa, A. Boulle, and T. Petrison, “Magnetic pinning effects of epitaxial $\text{La}_x\text{Sr}_{1-x}\text{MnO}_3$ nanostructured thin films on $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ layers,” *J. Appl. Phys.* **112**, 053919 (2012)
 36. L. M. Berndt, V. Balbarin, and Y. Suzuki, “Magnetic anisotropy and strain states of (001) and (110) colossal magnetoresistance thin films,” *Appl. Phys. Lett.* **77**, 2903 (2000)
 37. Y. C. Wang, J. Ding, J. B. Yi, B. H. Liu, T. Yu, and Z. X. Shen, “High-coercivity Co-ferrite thin films on (100)- SiO_2 substrate,” *Appl. Phys. Lett.* **84**, 2596 (2004)
 38. A. Goyal (ed) *Second Generation HTS Conductors* (Boston, MA: Kluwer Academic) (2004)
 39. C. F. Tsai, J. H. Lee, and H. Wang, “Microstructure and superconducting properties of $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ thin films incorporated with a self-assembled magnetic vertically aligned nanocomposite,” *Supercond. Sci. Technol.* **25**, 075016 (2012)
 40. T. Aytug, M. Paranthaman, H. Y. Christen, S. Saathyamurthy, D. K. Christen, and R. E. Ericson, “Single buffer layers of LaMnO_3 or $\text{La}_{0.7}\text{Sr}_{0.3}\text{MnO}_3$ for the development of $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ -coated conductors: a comparative study,” *J. Mater. Res.* **17(09)**, 2193 (2002)
 41. C. P. Bean, “Magnetization of Hard Superconductors,” *Phys. Rev. Lett.* **8**, 250 (1962)
 42. W. J. Yeh, B. Cheng, and T. Ragsdale, “Pinning Forces in Superconductors from Periodic Ferromagnetic Dot Array,” *Journal of Modern Physics* **1**, 364 (2010)

Figures:

Fig. 1 M-H curves for (a) $(\text{LSMO})_{0.5}(\text{CeO}_2)_{0.5}$ VAN and (b) LSMO at 20 K, 50 K, 100 K and 200 K under magnetic field in the c direction.

Fig. 2 θ - 2θ XRD patterns of all the bilayer samples compared with the pure YBCO film.

Fig. 3 Schematic and microstructure images of $(\text{LSMO})_{0.5}(\text{CeO}_2)_{0.5}$ capped YBCO thin film, (a) schematic illustration, (b) low-magnification TEM image, (c) the selected area electron diffraction (SAED) pattern, (d) high resolution TEM micrograph in the interface area.

Fig. 4 Schematic and microstructure images of LSMO buffered YBCO thin film, (a) schematic illustration, (b) low-magnification TEM image, (c) the selected area electron diffraction (SAED) pattern, (d) high resolution TEM micrograph of the selected area.

Fig. 5 Cross-sectional HRTEM image of (a) pure YBCO on STO, (c) LSMO buffered YBCO, (e) L5C5 capped YBCO, and their corresponding representative FFT filtered images (b), (d), (f).

Fig. 6 In-field $J_c(H//c)$ comparison of all the samples in a log-log scale at measured temperature of (a) 77 K, (b) 65 K, (c) 40 K and (d) 5 K.

Fig. 7 Calculated pinning force F_p (H/c) plots as a function of applied field (0-5 T) of all the samples measured at (a) 77 K, (b) 65 K, (c) 40 K and (d) 5 K.