Growth of simplified buffer template on flexible metallic substrates for $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ coated conductors

Yan Xue^{a)}, Ya-Hui Zhang^{a)}, Fei Zhang^{a)}, Rui-Peng Zhao^{a)}, Hui Wang^{b)}, Jie Xiong^{a), 1},
Bo-Wan Tao^{a)}

a) State Key Laboratory of Electronic Thin Film and Integrated Devices, University of

Electronic Science and Technology of China, Chengdu, 610054 People's Republic of China

b) Applied Research Laboratory of Superconduction and New Material, Institute of Electrical

Engineering, Chinese Academy of Sciences, Beijing, 100190 People's Republic of China

Abstract

A much simplified buffer structure, including a three-layer stack of $\text{LaMnO}_3/\text{MgO}/\text{composite } \text{Y}_2\text{O}_3\text{-Al}_2\text{O}_3$, was proposed for high performance $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ (YBCO) coated conductors. In this structure, biaxially textured MgO films were prepared on solution deposition planarized amorphous substrate through ion-beam-assisted deposition (IBAD) technology. By the use of *in situ* reflection high-energy electron diffraction monitor, X-ray diffraction and atomic force microscope, the influence of deposition parameters, such as film deposition rate, ion penetrate energy and ion beam flux, on crystalline orientation, texture, lattice parameter and surface morphology was systematically investigated. Moreover, stopping and range of ion in mater simulation was performed to study the effects of ion bombardment on MgO films. By optimizing IBAD process parameters, the best biaxial texture showed ω -scan of (002) MgO and Φ -scan of (220) MgO yield full width at half maximum values of 2.4° and 3.7° , indicating excellent biaxial texture. Subsequently, LaMnO_3 films were directly deposited on the IBAD-MgO template to improve the lattice mismatch between MgO and YBCO. Finally,

¹ Corresponding author Tel.: +86-28-83201232; fax: +86-28-83201232.
E-mail address: jiexiong@uestc.edu.cn

YBCO films grown on this simplified buffer template exhibited a critical current density of $2.4\text{MA}/\text{cm}^2$ at 77K and self-field, demonstrating the feasibility of this buffer structure.

Keywords: Coated conductors; Simplified buffer structure; Ion-beam-assisted deposition; Biaxial texture.

1. Introduction

Due to their low production cost and high current carrying capability, second-generation high-temperature superconducting coated conductors (CCs) have been intensively investigated by researchers worldwide [1–3]. A typical CCs structure consists of $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ (YBCO) functional films grown on inexpensive flexible metallic tape with intermediate buffer layers [4–6]. Normally, flexible substrates do not provide the single crystal structure (biaxial texture) required for YBCO thin films. To induce biaxial texture in buffer layers, two well established techniques have been explored to induce crystallographic alignment, i.e., incident substrate deposition [7–8] and ion-beam-assisted deposition (IBAD) [9–11]. In the IBAD approach, yttria-stabilized zirconia and $\text{Gd}_2\text{Zr}_2\text{O}_7$ are the mostly explored texturing materials [12–13]. Nevertheless, the slow evolution procedure of biaxial texture (with thickness $>500\text{nm}$) for these fluorite-structured materials limits their application prospect. Alternatively, the rock-salt materials, such as MgO, have attracted much attention because this template uses a much thinner thickness ($\sim 10\text{nm}$) to obtain a sharp in-plane texture (7°) [14], showing the potential ability for high production efficiency in a continuous process.

Up to now, in the IBAD-MgO approach towards commercial application, a typical multi-layer stack, including LaMnO_3 (LMO)/homo-epitaxial (epi) MgO/IBAD-MgO/ $\text{Y}_2\text{O}_3/\text{Al}_2\text{O}_3$ /Hastelloy, is utilized to achieve high performance in YBCO functional layer [15]. In this structure, electrochemical or mechanical polishing technology is

needed to obtain smooth surface on Hastelloy tapes. Al_2O_3 acts as a barrier to block the outward ionic species diffusion from substrate to YBCO films and Y_2O_3 is used as a seed layer for IBAD-MgO. 10nm-thick IBAD-MgO film plays a role as the template layer and epi-MgO serves as a protection layer to continue the crystalline texture from IBAD-MgO. LMO is used as a cap layer to improve the lattice mismatch between MgO and YBCO. In order to decrease the production cost, significant and impressive methods have been made. For example, one way is to decrease the number of buffer layers from five layer to four layer [16]. The other way is to use chemical solution deposition approach instead of vacuum coating technology for Al_2O_3 and Y_2O_3 process [17].

In this study, we demonstrated a three-layer simplified buffer structure (LMO/IBAD-MgO/composite $\text{Y}_2\text{O}_3\text{-Al}_2\text{O}_3$) for YBCO CCs. The amorphous composite $\text{Y}_2\text{O}_3\text{-Al}_2\text{O}_3$ (YAIO) layer, prepared by a low-cost solution deposition planarization (SDP) technology, acted both roles as barrier and seed layer for IBAD-MgO films. Subsequently, biaxially textured IBAD-MgO films were deposited on this substrate. Meanwhile, the effects of deposition rate, ion energy and ion beam flux on the evolvement of crystalline orientation, texture and surface morphology were investigated. Lastly, LMO films were directly coated on IBAD-MgO template without epi-MgO layer and the performance of the buffer layer was evaluated by depositing YBCO functional layer on the surface.

2. Material and methods

10mm-wide bare Hastelloy C-276 tape was used as a starting platform with root-mean-square (RMS) roughness of 50nm over a $5\mu\text{m}\times 5\mu\text{m}$ area. One micrometer thick YAIO layer was subsequently coated on the platform by SDP method. A detailed introduction of SDP technology could be found elsewhere [18]. After YAIO coatings, the RMS roughness value on

the surface reached 0.2nm, which was smoother than that of electrochemical and mechanical polishing technology [19].

Based on the smooth surface, 12nm-thick MgO thin films were deposited on YAIO substrate by a reel-to-reel IBAD system at room temperature. The MgO source was provided by electron beam evaporation. The deposition rate, monitored by a quartz crystal microbalance, varied from 0.05nm/s to 0.6nm/s. During the deposition process, a Kaufman ion gun was utilized to generate a neutralized beam of Ar ions with 0–800eV ion energy and 10–60mA ion beam flux. Meanwhile, the development of biaxial texture on the surface was monitored *in situ* by reflection high energy electron diffraction (RHEED). As IBAD-MgO films were too thin to be detected by X-ray diffractometer (XRD), additional 80nm-thick epi-MgO films were grown on IBAD-MgO without assisting ion beam around 600°C. Then XRD analysis (Bede D1), including θ - 2θ , ω -scans, Φ -scans, pole figure and reciprocal space measurements, was performed to characterize the crystalline quality, texture and lattice parameter. The surface morphology and roughness were investigated by atomic force microscope (AFM, Seiko SPA300HV). In addition, stopping and range of ions in matter (SRIM, 2013) simulation was utilized to investigate the effects of ion beam on IBAD-MgO [20]. Then LMO films were fabricated on IBAD-MgO layer with and without epi-MgO layer through radio-frequency magnetron sputtering. Finally, to testify the buffer layer quality, 500nm-thick YBCO films were deposited on LMO/IBAD-MgO/SDP-YAIO template by metal organic chemical vapor deposition. The detailed experiment condition was shown elsewhere [21–22].

3. Results

3.1 Influence of deposition rate to the texture and crystal quality in MgO films during IBAD

Fig.1 exhibits RHEED patterns of IBAD-MgO films deposited by varying deposition rate

from 0.05nm/s to 0.6nm/s. The film shows a fiber texture (with out-of-plane texture and without in-plane texture) with the deposition rate of 0.05nm/s. As deposition rate reaches 0.1nm/s, a typical pattern of biaxial texture is shown in the RHEED image with highly defined spots and a similar pattern is observed with the deposition rate of 0.18nm/s. However, when deposition rate increases to 0.3nm/s, an unclear ring is observed on the surface, indicating that some residual polycrystalline MgO grains exist in MgO film. With the continuous increase of deposition rate, the diffraction ring gets clearer and the texture begins to deteriorate.

Additional 80nm-thick epi-MgO layer was coated on IBAD-MgO to investigate the epitaxial nature of MgO films. The results of XRD θ -2 θ scans with deposition rate from 0.1nm/s to 0.4nm/s are shown in Fig.2. For all samples, there is only (002) reflection of MgO except for Ni alloy peaks from Hastelloy substrate. What's more, it is also found that the highest intensities could be achieved with the deposition rate of 0.15nm/s and 0.18nm/s. As long as increasing the deposition rate from 0.18nm/s to 0.4nm/s, the intensity of (002) peak decreases monotonically, indicative of the deterioration of crystal quality. These results demonstrate the deposition rate can significantly determine the crystalline quality in IBAD-MgO films.

It should be noted that the in-plane texture with high quality is critical in preventing the development of high-angle grain boundaries in the YBCO functional layer [23]. For this reason, it is important to investigate the full width at half maximum (FWHM) values of biaxial texture in IBAD-MgO films. The in-plane ($\Delta\Phi$) and out-of-plane ($\Delta\omega$) FWHM values are presented in Fig.3 as a function of deposition rate. It can be seen that both the out-of-plane and in-plane texture exhibit a gradual improvement with increasing deposition rate from 0.1nm/s to 0.18nm/s. As deposition rate continues to increase, the biaxial texture starts to

deteriorate. When the deposition rate increases to 0.4nm/s, no in-plane texture is detected. According to RHEED image in Fig.1e, in-plane texture still exists in this film. This result indicates that in-plane texture in MgO film is too weak to be detected by XRD analysis with the deposition rate of 0.4nm/s. As deposition rate reaches 0.6nm/s, both in-plane and out-of-plane texture can't be detected by XRD, which is consistent with RHEED results in Fig.1.

The rocking curves of ω -scan and Φ -scan, as well as pole figure of epi-MgO deposited on the optimal IBAD-MgO template are shown in Fig.4. The best texture is obtained with FWHM values of $\Delta\omega=2.4^\circ$ and $\Delta\Phi=3.7^\circ$, respectively, which is comparable to the results from other researchers [24–27]. From Fig.4c, only four equally distributed points with the interval of 90° can be seen, indicating that epi-MgO layer is epitaxial growth on IBAD-MgO layer with high quality and good in-plane orientation.

3.2 Effect of ion beam to the texture and crystal quality in MgO films during IBAD

Fig.5 shows the real-time development of biaxial texture in 12nm-thick IBAD-MgO films at different ion energies by RHEED observations. When the ion energy is 0eV, i.e., without assisted ion beam, the RHEED pattern shows a polycrystalline diffraction ring, suggesting that the film has no texture. With 400eV assisted ion energy, the scattering spots indicate the development of texture from a random out-of-plane distribution to a fiber texture. Then the transition from scattering to diffraction spots begins at 550eV ion energy. The spots are indistinct, indicating that cubic-phase MgO islands develop on the surface with poor in-plane alignment. As the ion energy increases to 800eV, the in-plane texture improves prominently, as revealed by the appearance of bright spots in the RHEED pattern.

During IBAD, the interaction between ions and atoms influence the nucleation kinetics on

MgO surface. Thus grain size and surface morphology is largely dependent on ion bombardment. AFM was employed to get a comprehensive picture about the surface morphology of IBAD-MgO. Fig.6 presents the AFM images of IBAD-MgO films grown on the YAlO surface with various ion energy over a $2\mu\text{m}\times 2\mu\text{m}$ scale. The RMS roughness values are 0.44nm and 0.36nm for IBAD-MgO deposited with 0V and 400V. When ion energy increases to 550eV, MgO particles emerge on the surface and RMS roughness value increases to 0.85nm. As ion energy approaches 800eV, the coverage area of MgO particles and RMS roughness value (1.8nm) shows a significant increase. In Zepeda–Ruiz *et al.*'s study, a $3\times 3\times 3$ MgO island was destroyed by a single Ar^+ ion impact (600eV); a $5\times 5\times 5$ MgO island survived with minimal damage [28]. Grove *et al.* also found that cubic-phase MgO islands are more resistant to ion bombardment than amorphous MgO atoms [29]. We believe that amorphous MgO molecules have to continuously merge into stable cubic-phase islands to survive ion bombardment with increasing ion energy, and then the coalescence procedure results in the development of surface morphology.

It is known that the total bombardment on growing film from ion beam is not only determined by ion energy, but also by ion number. SRIM simulation of IBAD was performed to study the effects of ion bombardment on MgO films. As shown in Fig.7, SRIM simulation reveals that both sputtering yield and radiation damage increase with ion energy and ion number. It can be seen that the total bombardment with ion energy of 400eV and ion number of 10000 is higher relative to that of 800eV and 5000. In fact, with ion energy of 400eV, no biaxial texture is observed by changing ion beam flux from 10mA to 60mA with various deposition rates. However, biaxial texture can be obtained with any fixed ion beam flux at 800eV, seen in Tab.1. So it can be concluded that ion energy plays a more important role during IBAD texturing

than the total ion bombardment and ion beam flux.

3.3 LMO cap layer grown on optimized IBAD-MgO layer with and without epi-MgO

Fig.8a shows θ - 2θ scan for 100nm-thick LMO layer deposited on epi-MgO layer with growth temperature of 750°C. Pure (002) phase of LMO is obtained without any impurity phase. However, when LMO layer is directly deposited on IBAD-MgO with the same process parameter, film exhibits epitaxial growth of both LMO (002) and (110) component. It has been reported that LMO (002) orientation is more stable than (110) orientation at high growth temperature [30]. Therefore, an optimized process parameter with growth temperature of 820°C has been performed to deposit LMO layer and the corresponding θ - 2θ scan is shown in Fig.8c. It can be seen that LMO (110) peak disappears from the θ - 2θ scan. This result indicates that the growth mode of LMO film transfers from polycrystalline growth to the fully (002) oriented growth with increasing growth temperature. Noted that when LMO film is directly grown on IBAD-MgO layer, there are unexpected Y_2O_3 peaks at 29.6° and 33.8°, indicating that the amorphous Y_2O_3 in YAlO layer has been crystallized during LMO process. The crystallized Y_2O_3 grains may result in the diffusion of metal elements into YBCO functional layer, ultimately deteriorating the superconducting properties [31]. On the contrast, no Y_2O_3 peaks are observed for LMO film deposited on epi-MgO layer, demonstrating that additional epi-MgO layer can act as a protection layer for avoiding the crystalline of Y_2O_3 . The FWHM values of all three samples are listed in Fig.9. The biaxial texture shows ω -scan of (002) LMO and Φ -scan of (220) LMO yield FWHM values of 3.3° and 4.6° for LMO on epi-MgO buffered IBAD-MgO template, as well as 3.5° and 7.2° for LMO on IBAD-MgO template without epi-MgO.

As shown above, LMO film requires a higher growth temperature (820°C) to develop to fully

(002) oriented epitaxy on IBAD-MgO layer than that on epi-MgO layer. This may be explained by the large lattice misfit between IBAD-MgO and LMO. It is well known that high energy assisted ions create point defects, interstitials and vacancies in IBAD-MgO films, which may have negative effects on releasing strain. As a result, the lattice is expanded with lattice parameter of 0.43-0.44nm in IBAD-MgO films and lattice mismatch of LMO (0.39nm) with respect to IBAD-MgO is ~9–11% [32]. Fig.10 gives reciprocal space maps of MgO (002) and (202) for epi-MgO. A numerical estimation of peak position can calculate the lattice parameters, which is given by

$$h^2 / a^2 + k^2 / b^2 + l^2 / c^2 = 1 / d_{hkl}^2, (1)$$

where a is the lattice parameter of in-plane orientation and c represents the lattice parameter of out-of-plane orientation. d_{hkl} corresponds to the interplanar spacing of (hkl) surface, which is expressed as

$$2d_{hkl} \sin \theta = \lambda, (2)$$

where θ is the angle between X-ray and MgO sample, λ is the wavelength of X-ray. The epi-MgO film yield lattice parameters of $a=0.418\text{nm}$ and $c=0.422\text{nm}$, which are close to the bulk MgO (0.421nm). The lattice mismatch between LMO and epi-MgO is 6.5% for in-plane alignment and 7.3% for out-of-plane alignment, respectively, which is lower than that between LMO and IBAD-MgO. Apparently, LMO film growth on IBAD-MgO has to overcome more lattice-mismatch induced strain than that on epi-MgO film.

Subsequently, 500nm-thick YBCO films were deposited on the optimized LMO/IBAD-MgO/YAlO template. The critical current density (J_c) of the film was measured with a J_c -scan Leipzig system and the J_c value was found to be $2.4\text{MA}/\text{cm}^2$ at 77K and self-field. This demonstrates the feasibility of a simplified buffer layer structure, which can

reduce the number of processing steps and potentially reduce production cost for YBCO CCs.

We have deposited YBCO films on the usual buffer template with the same process and a J_c value of $3.2\text{MA}/\text{cm}^2$ is obtained. It should be prospective that the recrystallization characteristic of Y_2O_3 results in a low performance for YBCO on simplified buffer layer.

More work is needed to further optimize the biaxial texture in buffer layers and to optimize the process of YBCO functional layer on such a simplified buffer structure, which we believe is possible.

4. Conclusions

In this work, we have induced a promising simplified buffer structure (LMO/IBAD-MgO/SDP-YAlO) for YBCO superconducting films, the structure of which offers a potentially low-cost alternative for conductor fabrication. The influence of film deposition rate, ion energy and ion beam flux on the microstructure and surface morphology of IBAD-MgO was systematically investigated. It was found that ion energy plays a more important role during IBAD texturing than total bombardment change and pure ion beam flux change. The best FWHM values of 2.4° out-of-plane texture and 3.7° in-plane texture have been obtained with deposition rate of 0.18nm/s , ion energy of 800eV and ion beam flux of 60mA . Subsequently, LMO cap layer was separately deposited on this template with and without epi-MgO layer. Due to the high lattice-mismatch induced strain energy between LMO and IBAD-MgO, detailed θ - 2θ scans revealed that LMO films deposited on IBAD-MgO layer require a higher growth temperature to develop to fully (002) orientation than that on epi-MgO layer. By optimizing LMO deposition parameter, biaxially textured LMO films could be epitaxial grown on IBAD-MgO layer with FWHM values of 3.5° out-of-plane texture and 7.2° in-plane mosaic, respectively. This offers a high-quality template for

high-performance YBCO CCs.

Acknowledgments

We gratefully acknowledge the support of the National Science Foundation of China under Grant No. 91421110, National Basic Research Program (973) of China through Grant No. 2015CB358600, Sichuan Youth Science and Technology Innovation Research Team Funding (No.2011JTD0006), and Sichuan Provincial Fund for Distinguished Young Academic and Technology Leaders (No. 2014JQ0011) for this work.

References

- [1] S. Kang, A. Goyal, J. Li, A.A. Gapud, P.M. Martin, L. Heatherly, J.R. Thompson, D.K. Christen, F.A. List, M. Paranthaman, D.F. Lee, High-performance high-TC superconducting wires, *Science*. 311 (2006) 1911-1914
- [2] H.S. Kim, S.S. Oh, H.S. Ha, D. Youm, S.H. Moon, J.H. Kim, S.X. Dou, Y.U. Heo, S.H. Wee, A. Goyal, Ultra-High Performance, High-Temperature Superconducting Wires via Cost-effective, Scalable, Co-evaporation Process, *Scientific Reports*. 4 (2014) 4744
- [3] S. E. Sebastian, N. Harrison, F. F. Balakirev, M. M. Altarawneh, P. A. Goddard, R. Liang, D. A. Bonn, W. N. Hardy, G. G. Ionazarich, Normal-state nodal electronic structure in underdoped high-Tc copper oxides, *Nature*. 511 (2014) 61-64
- [4] X. Xiong, K.P. Lenseth, J.L. Reeves, A. Rar, Y. Qiao, R.M. Schmidt, Y. Chen, Y. Li, Y.Y. Xie, V. Selvamanickam, High throughput processing of long length IBAD MgO and epi-buffer templates at superpower, *IEEE. Trans. Appl. Supercond.* 17 (2007) 3375-3378
- [5] Y. Takahashi, Y. Yoshida, Y. Takai, Y. Takahashi, M. Yoshizumi, T. Lzumi, Y. Shiohara, T. Kato, Thickness dependence of I_c and J_c of LTG-SmBCO coated-conductor on IBAD-MgO tapes, *Physica C*. 471 (2011) 937-939
- [6] Y. Wang, C.S. Li, L.H. Jin, Z.M. Yu, J.Q. Feng, H. Wang, P. Odier, P.X. Zhang, Epitaxy of buffer layer and superconducting performance development of YBCO on bi-layer buffers coated on Ni5W by all CSD, *J. Alloy. Compd.* 644 (2015) 554-561
- [7] M. Durrschnabel, Z. Aabdin, M. Bauer, R. Semerad, W. Prusseit, O. Eibl, $\text{DyBa}_2\text{Cu}_3\text{O}_{7-x}$ superconducting coated conductors with critical currents exceeding 1000A.cm^{-1} , *Supercond. Sci. Technol.* 25 (2012) 105007
- [8] J. Cho, K. Lee, C. Cheon, N. Cho, J.S. Kim, Characterization of the biaxial textures of MgO thin films grown by E-beam evaporation, *J. Eur. Ceram. Soc.* 30 (2010) 481-484
- [9] V. Matias, R.H. Hammond, Ion beam induced crystalline texturing during thin film deposition, *Surf. Coat. Tech.* 264 (2015) 1-8
- [10] S. Miyata, A. Ibi, T. Lzumi, Y. Shiohara, Surface roughness of MgO thin film and its critical thickness for optimal biaxial texturing by ion-beam-assisted deposition, *J. Appl. Phys.* 109 (2011) 113922
- [11] T.P. Weber, B. Ma, U. Balachandran, M. McNallan, Fabrication of biaxially textured magnesium oxide thin films by ion-beam-assisted deposition, *Thin Solid Films*. 476

(2005) 79-83

- [12] Y. Iijima, M. Kimura, T. Saitoh, K. Takeda. Development of Y-123-coated conductors by IBAD process, *Physica C*. 335 (2000) 15–19
- [13] K. Takahashi, H. Kobayashi, Y. Yamada, A. Ibi, H. Fukushima, M. Konishi, S. Miyata, Y. Shiohara, T. Kato, T. Hirayama. Investigation of thick PLD-GdBCO and ZrO₂ doped GdBCO coated conductors with high critical current on PLD-CeO₂ capped IBAD-GZO substrate tapes, *Supercond. Sci. Technol.* 19 (2006) 924-929
- [14] C.P. Wang, K.B. Do, M.R. Beasley, T.H. Geballe, R.H. Hammond. Deposition of in-plane textured MgO on amorphous Si₃N₄ Substrates by ion-beam-assisted deposition and comparisons with ion-beam-assisted deposited yttria-stabilized-zirconia, *Appl. Phys. Lett.* 71 (1997) 2955-2957
- [15] V. Selvamanickam, Y. Chen, X. Xiong, Y.Y. Xie, M. Martchevski, A. Rar, Y. Qiao, R.M. Schmidt, A. Knoll, K.P. Lenseth, C.S. Weber, High performance 2G wires: From R&D to pilot-scale manufacturing, *IEEE. Trans. Appl. Supercond.* 19 (2009) 3225-3230
- [16] O. Polat, T. Aytug, M. Paranthaman, K.J. Leonard, A.R. Lupini, S.J. Pennycook, H.M. Meyer, K. Kim, X. Qiu, S. Cook, J.R. Thompson, D.K. Christen, A. Goyal, X. Xiong, V. Selvamanickam. An evaluation of phase separated, self-assembled LaMnO₃-MgO nanocomposite films directly on IBAD-MgO as buffer layer for flux pinning enhancements in YBa₂Cu₃O_{7-δ} coated conductors, *J. Mater. Res.* 25 (2010) 437-443
- [17] M.P. Paranthaman, T. Aytug, L. Stan, Q. Jia, C. Cantoni, S.H. Wee. Chemical solution derived planarization layers for highly aligned IBAD-MgO templates, *Supercond. Sci. Technol.* 27 (2014) 022002
- [18] R. Ko, B. Kang, D. Kim, D. Ha, C. park, S. Yoon, Y. Kim. Effect of solution concentration on the surface properties of Y₂O₃ solution-coated film on flexible Metal Substrate, *Met. Mater. Int.* 19 (2013) 1343-1345
- [19] V. Matias, J. Hänisch, E.J. Rowley, C. Sheehan, P.G. Clem, N. Kumasaka, I. Kodaka. Preparation of Substrates for IBAD-MgO Coated Conductors, *Mrs Proceedings.* (2007) 1001
- [20] J.F. Ziegler, M.D. Ziegler, J.P. Biersack, SRIM- The stopping and range of ions in mater, *Nucl. Instr. Meth. B.* 268 (2010) 1818-1823
- [21] F. Zhang, J. Xiong, K. Yang, Y. Xia, Y. Xue, X. Zhao, B. Tao. Epitaxial Growth and Characterization of RF-Sputtered LaMnO₃ Cap Layers on Homo-Epi MgO/IBAD–MgO Templates, *J. Supercond. Nov. Magn.* 27 (2014) 543-546
- [22] F. Zhang, J. Xiong, X. Liu, R. Zhao, X. Zhao, B. Tao, Y. Li. Double-sided reel-to-reel metal-organic chemical vapor deposition system of YBa₂Cu₃O_{7-δ} thin films, *J. Vac. Sci. Technol. A.* 32 (2014) 041512 - 041512-5
- [23] A. Goyal, D. P. Field, R. Held, J. Mannhart, Grain boundary networks in high-performance, heteroepitaxial, YBCO films on polycrystalline, cubic-textured metals, *Phil. Mag. Lett.* 91 (2011) 246-255
- [24] A. J. Elliot, R. N. Vallejo, R. Lu, J. Z. Wu, Development of textured magnesium oxide templates on amorphous polymer surfaces using ion-beam-assisted deposition, *Appl. Phys. Express.* 4 (2011) 065502
- [25] V. Matias, J. Hanisch, E.J. Rowley, K. Guth. Vary fast biaxial texture evolution using high rate ion-beam-assisted deposition of MgO, *J. Mater. Res.* 24 (2009) 125-129
- [26] R. Hühne, K. Güth, R. Gärtner, M. Kieszun, F. Thoss, B. Rellinghaus, L. Schultz, B. Holzapfel. Application of textured IBAD-TiN buffer layers in coated conductor

- architectures, *Supercond. Sci. Technol.* 23, (2010) 014010
- [27] V. Selvamanickam, S. Sambandam, A. Sundaram, S. Lee, A. Rar, X. Xiong, A. Alemu, C. Boney, A. Freundlich. Germanium films with strong in-plane and out-of-plane texture on flexible, randomly textured metal substrates, *J. Cryst. Growth.* 311 (2009) 4553-4557
- [28] L.A. Zepeda-Ruiz, D.J. Srolovitz, Effects of ion beams on the early stages of MgO growth, *J. Appl. Phys.* 91 (2002) 10169-10180
- [29] J.R. Groves, R.H. Hammond, V. Matias, R.F. DePaula, L. Stan, B.M. Clemens, Biaxial texture development in the ion beam assisted deposition of magnesium oxide, *Nucl. Instr. Meth. B.* 272 (2012) 28-32
- [30] H.S. Kim, S.S. Oh, H.S. Ha, R.K. Ko, D.W. Ha, T.H. Kim, D.J. Youm, N.J. Lee, S.H. Moon, S.I. Yoo, C. Park. Deposition of LaMnO₃ buffer layer on IBAD-MgO template by reactive DC sputtering, *Physica C.* 469 (2009) 1554-1558
- [31] S. Tsukui, R.E. Koritala, M. Li, K.C. Goretta, M. Adachi, J.E. Baker, J.L. Routbort, Oxygen and cation diffusion in YBCO coated conductors, *Physica C.* 392–396 (2003) 841-846
- [32] P.N. Arendt, S.R. Foltyn, Biaxially textured IBAD-MgO templates for YBCO coated conductors, *MRS Bulletin.* 29 (2004) 543-550

Table.1 Detailed in-plane texture results for IBAD-MgO deposited with different deposition rate and ion beam flux. The $\times$ represents MgO films with no biaxial texture and * represents MgO films with out-of-plane texture alone.

Deposition rate	10mA	20mA	30mA	40mA	50mA	60mA
0.06 nm/s	13.5	7.9	9.3	11.7	$\times$	$\times$
0.1 nm/s	$\times$	12.9	7.3	6	*	*
0.12 nm/s	$\times$	12	8.4	5.9	6.2	7.3
0.15 nm/s	$\times$	$\times$	9.8	5.5	4.8	5.3
0.18 nm/s	$\times$	$\times$	12.2	9.7	8.6	3.7

Captions:

Fig.1 RHEED images of IBAD-MgO films depositing with deposition rates of (a)0.05nm/s, (b)0.1nm/s, (c)0.18nm/s, (d)0.3nm/s,(e)0.4nm/s, (f)0.6nm/s

Fig.2 XRD θ - 2θ scans of MgO films as a function of deposition rate.

Fig.3 FWHM values of ω -scans and Φ -scans of MgO films with different deposition rates.

Fig.4 XRD (a) ω -scan of (002) MgO, (b) Φ -scan of (220) MgO and (c) pole figure for epi-MgO film grown on the optimal IBAD-MgO template.

Fig.5 RHEED patterns of IBAD-MgO as a function of ion energy (a)0eV, (b)400eV, (c)550eV, (d)800eV.

Fig.6 AFM images of IBAD-MgO at different ion energy:(a)0eV, (b)400eV, (c)550eV, (d)800eV.

Fig.7 SRIM simulations of (a)sputtering yields and (b)ion radiation damage under Ar ion bombardment with different ion energy and ion number.

Fig.8 XRD θ - 2θ scans of for LMO films deposited on (a)epi-MgO buffered IBAD-MgO template, (b)IBAD-MgO template with growth temperature of 750°C, (c)IBAD-MgO template with growth temperature of 820°C. The $\blacklozenge$ and $*$ symbols represent peaks of LMO(110) and MgO(002), respectively.

Fig.9 FWHM values for LMO films deposited on (a)epi-MgO buffered IBAD-MgO template, (b)IBAD-MgO template with growth temperature of 750°C, (c)IBAD-MgO template with growth temperature of 820°C.

Fig.10 Reciprocal space maps of (a)(002) reflection and (b)(202) reflection of epi-MgO film on the optimal IBAD-MgO template.

Graphical Abstract

Fig.1a

Fig.1b

Fig.1c

Fig.1d

Fig.1e

Fig.1f

Fig.2

Fig.3

Fig.4a

Fig.4b

Fig.4c

Fig.5a

Fig.5b

Fig.5c

Fig.5d

Fig.6a

Fig.6b

Fig.6c

Fig.6d

Fig.7a

Fig.7b

Fig.8

Fig.9

Fig.10a

Fig.10b