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IBAD-MgO technology for coated conductors

William Jo*

Department of Physics, Ewha Womans University, Seoul 03760, Korea

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Abstract

Ion-beam assisted deposition (IBAD) technology has been successfully applied to high-temperature superconductor coated conductors (CC) as textured substrates. Since the coated conductors were proposed as a potential framework for utilizing the superior transport characteristics of $YBa_2Cu_3O_7$ and related cuprate oxides, several methods including rolling-assisted bi-axial textured substrates (RABiTS) and inclined substrate deposition (ISD), as well as IBAD, have been attempted. As of 2016, most companies that are trying to commercialize CC adapt IBAD technology except for American Superconductors who use RABiTS predominantly. For the materials in the IBAD process, initial efforts to use yttria-stabilized zirconia (YSZ) or related fluorites in Fujikura in Japan have quickly given way to MgO which technique was developed by Stanford University in the USA. In this review, we present a historical overview of IBAD technology, in particular, for the application of CC. We describe the key scientific understanding of nucleation, the texturing mechanism, and the growth of large bi-axial grains and discuss some potential new IBAD materials and systems for large-scale production.

Keywords: Ion-beam assisted deposition, Coated conductors, Texturing Mechanism, New IBAD Materials, and Large-scale Production

1. INTRODUCTION

Since the discovery of high-temperature superconductors (HTS) in 1986, a great amount of efforts has been applied to using the materials to develop resistance-less wires. Unlike the so-called first generation HTS wires of Bi-2212 using power-in-tube methods, a full thin-film technology has been applied to produce HTS wires, which are now termed 'coated conductors (CC)'. HTS exhibits strong asymmetric transport properties and grain-boundary dependence as critical characteristics. It is critical to build up a bottom crystalline substrate with bi-axially oriented texture. The first successful demonstration given by Oak Ridge National Lab was rolling-assisted bi-axial textured substrates (RABiTS) [1], which is a metallurgical texturing procedure. American Superconductors use this method for their robust production of CC [2]. Another method to generate bi-axial texture by thin-film processes is ion-beam assisted deposition (IBAD). Initially, fluorite yttria-stabilized zirconia (YSZ) was a candidate for texturing material but its slow growth rate and imperfect in-plane alignment hindered the progress of CC development. In 1997, an alternative validation with simple cubic MgO at Stanford University [3] led SuperPower to immediately utilize this technique for the mass-production of CC [4]. During the transfer of IBAD-MgO technology to companies, the efforts of researchers in the Los Alamos National Lab (LANL) should be recognized [5]. Nowadays, the majority of companies that are developing CC use IBAD-MgO technology. It will be very important for future markets to understand the science and technology of the IBAD-MgO process. We review the historical background of IBAD-MgO technology for CC, the status of CC application in major companies, and the science and technology of the IBAD process and remaining issues. The advantages of IBAD-MgO for CC are fast growth-rate, robust control of bi-axial texture, simple architecture of stacking layers, and wide range of deposition parameters and compact arrangements of evaporation- and ion-beams.

* Corresponding author: wmjo@ewha.ac.kr

2. HISTORICAL REVIEW

The ion beam is a very unique tool for thin-film technologies. Ion beam assisted sputtering is widely used to grow thin-films where sputtering yields of atomic species are concerned. Densification of thin-films is also achieved with ion-beams. Iijima *et al.* of Fujikura in Japan verified the application of ion-beams for bi-axial textured oxides [6]. The material that they selected was YSZ, of which the crystal structure is fluorite and the channeling angle 55 degree from the direction of materials evaporation. Bi-axial texture was beautifully grown with 2 μm-thick YSZ layers, of which the growth rate was very slow, and the in-plane alignment larger than 10 degree, even in thick-layers of YSZ. For the commercialization of CC, it is critical to increase the speed of growth. Simple cubic MgO, of which the channeling angle is 45 degree, has risen as a substitute candidate for YSZ, since its growth rate is much faster and only a few nanometer of layer is enough to get 10 or less in-plane azimuthal spread in the IBAD process. When Hammond *et al.* of Stanford University developed this elegant technology [3, 7, 8], the underlying texturing mechanism was still lacking.

TABLE 1
COMPANIES THAT USE IBAD TECHNOLOGY FOR CC MANUFACTURING.

Company	Materials for IBAD	Materials for HTS	Growth Method for HTS
SuperPower	MgO	(Y,Gd)Ba2Cu3O7	MOCVD
SuNAM	MgO	GdBa2Cu3O7	Dual Co-Evaporation
Fujikura	YSZ, GZO, MgO	YBa2Cu3O7	PLD
STI	MgO	YBa2Cu3O7	Co-Evaporation
Bruker	YSZ (ABAD*)	YBa2Cu3O7	PLD

However, the method immediately attracted attention of the whole CC community. The technology was accredited to SuperPower Ltd. With the help of LANL. SuperPower showed a 1 kilometer-long CC, which is believed to be commercial grade. The best in-plane width of IBAD-MgO is 4 degree and many labs regularly achieve 7 degree of IBAD-MgO. Following this achievement, Table 1 lists many CC companies that use IBAD-MgO. SuNAM in Korea is a leader in IBAD-MgO elaboration for their ultra-fast growth of long HTS CCs [9]. Originally, the method was implemented in the Korea Electrotechnology Research Institute (KERI) where researchers are recently developed solution deposition polishing (SDP) independently of LANL [10]. STI in the USA is also developing IBAD-MgO through technical support from LANL. Bruker in Germany is also a key player in this technology but they use YSZ rather than MgO while they call their tool Alternating Beam Assisted Deposition (ABAD), which is in principle, the same as the IBAD process. Some companies in China, Russia, and other countries are also starting to use IBAD-MgO technology.

3. STATUS OF CC

The key technical hurdle of the IBAD-MgO process is ion-beams. The apparatus to generate energetic ion-beams consists of two groups of with (Kaufmann-type) or without grids. In designing the IBAD process chamber, the main concerns are flux and divergence of the ion-beams. The flux and divergence, as well as the evaporation-beam fluxes, eventually determine the growth zone and area. A commercial grade process system is not yet currently available in the market. Figure 1 describes an in-line process system with IBAD-MgO and HTS layers, which was proposed by R. H. Hammond [11]. Recent progress in the display and photovoltaics industry assures the possibility of wide deposition of IBAD-MgO and the HTS layers. As the out-of plane texturing of MgO is going to be off of the normal axis, we need to control the thickness of IBAD-MgO thinner than 10 nm and deposit additional homo epi-MgO on top of the IBAD-MgO layers. This results in a tricky procedure during the growth of the whole MgO layer. Following the preparation of the MgO layer,

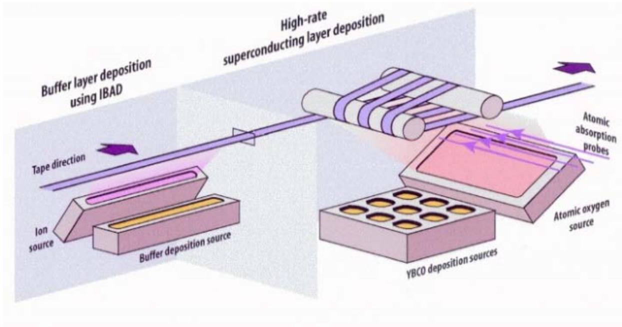

Fig. 1. The proposed continuous growth of CC using IBAD-MgO and high-rate single-chamber co-evaporation [11].

HTS layers are grown by a variety of methods. Metal-organic chemical vapor deposition (MOCVD), co-evaporation, pulsed-laser deposition (PLD) and metal-organic deposition (MOD) are typical routes to produce HTS layers. The surface of MgO needs to be modified by deposition of buffer layers, in order to improve in-plane alignment or the adhesion of subsequent layers. The problem for realization of a simple process is taking care of buffer layers between the IBAD-MgO and the HTS layers, which are normally $LaMnO_3$ or CeO_2. If we can omit the additional steps and simplify the CC architecture with IBAD-MgO/HTS, the cost of CC will reduce drastically.

4. SCIENTIFIC ISSUES

A. Texturing mechanism

IBAD-MgO is easy to apply to the CC process. However, the process to reproduce in-plane alignment or bi-axial texture is very delicate. General understanding of nucleation, texturing, and grain growth is lacking. Since MgO is quickly textured during the process, it is generally believed to be textured in early deposition almost simultaneously with the nucleation. But, this is hard to prove in the microstructure because the layers are too thin. Table 2 lists the mechanisms underlying the initial nucleation, texturing, and growth rate of the IBAD-MgO. Following the original observation of IBAD growth of MgO by the Stanford group [3], extensive experimental and theoretical studies have been performed [12-14]. One of the striking results in IBAD-MgO is that as the thickness of the layer increases, the in-plane alignment is tilted, which is not true in the case of IBAD-YSZ. It is not yet clear whether the initial growth of MgO ultra-thin grains allows texturing, or if the amorphous MgO layers form during early nucleation [7, 8]. In addition, it should be determined if globally-occurring biaxial texturing is a function of the thickness of IBAD-MgO.

A group of the Argonne National Laboratory proposed an analogous method to IBAD, called Inclined Substrate Deposition (ISD) [15]. In this method, initial nucleation is important for the further growth of textured grains. However, it was not easy to obtain in-plane alignment of

TABLE 2
TEXTURING MECHANISM IN IBAD-MGO.

Mechanism	Characterization	Main Results	Ref.
Nucleation-controlled process	RHEED, TEM	Nuclei size and density Initial conditions including substrates	[3]
Texturing at early nucleation	Quartz crystal monitor, RHEED	Coverage of substrates Deposition flux Ion beam flux Sputter yield	[7], [8]
Solid phase crystallization	RHEED, TEM	Critical thickness	[12]
Texture development during island nucleation	Molecular dynamics	Size of MgO island Ion beam orientation	[13]
Radiation damage anisotropy	Rutherford backscattering spectrometry combined with ion channeling	Annealing temperature Crystallographic orientation	[14]

less than 10 degree, indicating that the method is not proper for coated conductors even though it has the advantage of cheap capital costs.

Additionally, few reports on IBAD-MgO have been made for ferroelectrics or functional oxides other than HTS [16-18]. The perfection of crystallization (*i.e.,* mosaic spread, in-plane alignment, out-of-plane orientation, and surface roughness) still requires intense study. Extending the range of applications requires large area growth of IBAD-MgO, but faces fundamental limits due to the divergent nature of ion beam irradiation. The question thus arises of how to increase the deposition area without incurring further capital costs of ion guns and evaporation systems.

It is important during the IBAD process to control the ion-to-atom ratio. The deposition conditions of the IBAD process are usually characterized by the ratio of incoming ions and atoms or molecules onto the substrates. However, it is very tricky during the growth to measure the ionic fluxes and the evaporation rate. Quartz crystal monitors and Faraday cups are normally used to measure evaporation species and ionic fluxes, respectively. If the ionic flux is too weak, the texturing process is weak and slow. The resulting MgO layers will have large in-plane alignment. If the ionic flux is too strong, the damaged grains will have non-crystallized orientation. However, the results depending on the deposition systems are controversial. The effects of ion-to-atom ratio on in-plane alignment need further study.

Understanding the rate of growth also remains of particular interest, as well as the optimal thickness to provide the best biaxial texturing. The biaxial texturing mechanism is known to depend upon anisotropic sputtering, ion channeling, and anisotropic grain damage. Recently, we performed a systematic study of this issue with samples grown by KERI [19]. Ambiguities regarding the directions of ions, atoms, and positions of growth yet remain, but the results are quite striking for understanding the effects of growth rate and further the role of homo epi-MgO layers. Figure 2(a) shows a high-resolution transmission electron microscopic (HR-TEM) image. The MgO sample was grown on amorphous SDP-Y_2O_3 coated hastelloy. The figure clearly shows the IBAD-MgO layer and the homo epi-MgO layer, with different microstructural grains and distribution of dislocations. The homo epi-MgO layer tends to cover the IBAD-MgO layer, and to have better crystalline quality. Figures 2(b) and (c) show the peak positions match well the simple cubic structure of MgO but some spots (Fig. 2(b), arrowed) are evident between the two major {100} peaks in the IBAD-MgO diffraction patterns. The spots disappear in the homo epi-MgO layer (Fig. 2(c)), which is consistent with the observation of the microstructures. It will be challenging to determine whether we can really use only MgO layers for HTS deposition due to lattice mismatch and the formation of hydroxide of magnesium. However, an in-line deposition of HTS onto the MgO layers without breaking vacuum will be an interesting goal in CC production since the critical current density of HTS on MgO crystals easily exceeds 3 MA/cm^2.

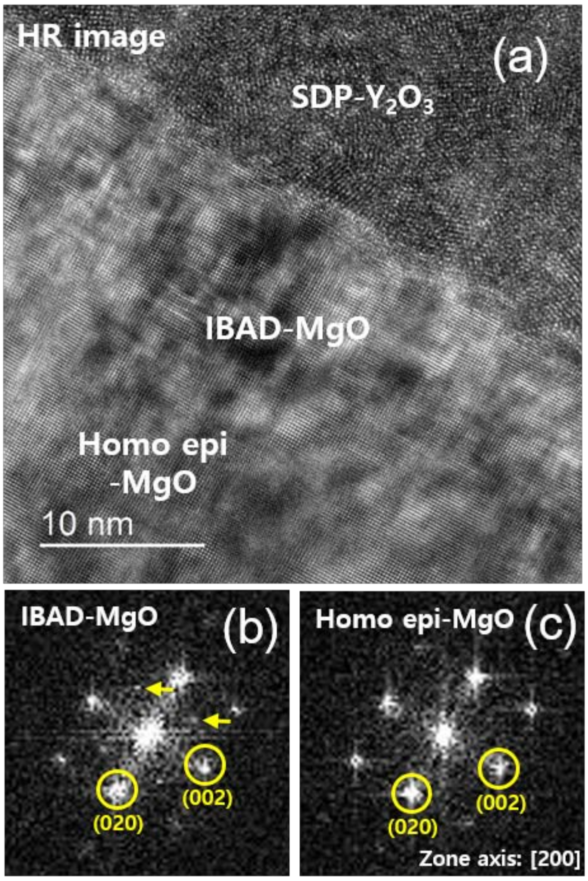

Fig. 2. (a) HR-TEM micrograph shows cross-sectional image of IBAD-MgO and homo epi-MgO layers on SDP-Y2O3 layers, (b) FFT diffraction patterns on the IBAD-MgO area, and (c) FFT diffraction patterns of the homo epi-MgO area. The yellow arrows in (b) indicate streaks between {100} planes, which might be a lattice-doubled structure or a defect peak [19].

B. Instrumentation

One of the tasks in the deposition systems of IBAD-MgO process is to decide whether the deposition is done within a multi-turn or a single-pass. In the case of the IBAD process, a single-pass will be sufficient because it needs only 10 nanometer of thickness. However, we have to deposit additional homo epi-MgO layers in the same chamber. Inevitably, we have to coat the layers with a multi-turn. If so, the uniform zone of growth should be large enough to obtain the same thickness of MgO layers.

The strong demand of in-line growth of CC for reel-to-reel growth of the materials is disputable since some groups are still working on a batch type chamber for HTS layers even though they use a reel-to-reel growth for MgO and buffer layers. It is not proper in this review to discuss the advantages and disadvantages of batch-type deposition. However, the deposition of such complex oxides in a cylindrical carousel is not a feasible ambition in the wire business.

C. New materials

MgO is probably an ideal material for the IBAD process. But people want to discover other candidates for better performance, and are more likely to avoid intellectual properties conflicts with MgO. It is rare to find practical examples of IBAD-XO, where X could be Ca, Ni, Co, Fe, Mn, Sr, or Ba. Some researchers are looking for nitrides rather than oxides. TiN and CrN are primary candidates. Other than MgO, the materials are mostly very reactive and multi-valent. It is too early to decide whether the materials are proper for the IBAD process, and further, good for HTS. A bottom line requirement would be simple cubic structure, and chemical stability as well. Lattice matching with HTS in the *a*-*b* plane is a crucial factor but we can always find an alternative maneuver like 45 degree rotation to get a better matching with $\sqrt{2}\mathrm{x}\sqrt{2}$. In this regard, it would be wise to try CaO and SrO more systematically since they are not magnetic and have lattice parameters of 0.48 and 0.52 nm, respectively since YBCO has approximately the *a*-axis lattice parameter of 0.38 nm.

5. CONCLUSION

IBAD-MgO processes are scalable to high rates and throughputs. Several groups demonstrated deposition time of 1 – 2 seconds. The homo epi-MgO templates have better texture than the IBAD-MgO. Other simple cubic structure materials with similar IBAD texturing have been demonstrated, including NiO and CaO. IBAD-MgO templates have been applied to coated conductors with 4 degree in-plane texture on the MgO. We can pursue further questions, such as, what are the mechanisms for texture formation? One of the clues is texture scaling with cumulative radiation damage. We may be able to improve the speed of growth and in-plane of the IBAD-MgO layers in a wide deposition zone.

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