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Thickness dependence of grain growth orientation in MgB_2 films fabricated by hybrid physical-chemical vapor deposition

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Abstract

We have investigated the effect of thickness of the MgB_2 film on the grain growth direction as well as on their superconducting properties. MgB_2 films of various thicknesses were fabricated on *c*-cut Al_2O_3 substrates at a temperature of 540 °C by using hybrid physical-chemical vapor deposition (HPCVD) technique. The superconducting transition temperature (T_c) was found to increase with increase in the thickness of the MgB_2 film. X-ray diffraction analysis revealed that the orientation of grains changed from *c*-axis to *a*-axis upon increasing the thickness of the MgB_2 film from 0.6 to 2.0 μm. MgB_2 grains of various orientations were observed in the microstructures of the films examined by scanning electron microscopy. It is observed that at high magnetic fields the 2.0-μm-thick film exhibit considerably larger critical current density (J_c) as compared to 0.6-μm-thick film. The results are discussed in terms of an intrinsic-pinning in MgB_2 similarly as intrinsic-pinning occurring in high-T_c cuprate superconductors with layered structure.

Keywords : MgB_2 film, grain orientation, HPCVD

1. INTRODUCTION

MgB_2 superconductor is a very promising material for practical applications because of its unique properties, such as simple crystal structure, high transition temperature (40 K), high self-field critical current density (J_c), existence of two gaps, the strongly linked nature of the intergrains, and low cost [1, 2]. Inspite of its high self-field J_c, J_c drops rapidly in high magnetic fields due to poor flux pinning. To increase the potential use of MgB_2 superconductor in practical applications, enhancements in the critical current density under high magnetic fields is essential. Some of these applications include superconducting magnets and solenoids, microelectronic devices and coated conductor wires for power applications. In these applications, strong pinning of vortices is an important requirement for operation with low noise and lower power loss. Pinning of vortices can be achieved intrinsically and extrinsically. Extensive research has already been carried out to improve the flux pinning in MgB_2 by extrinsic methods, such as chemical doping, nanoparticles addition, and proton or neutron irradiation etc [3, 4]. Takahashi *et al.* reported the evidence of intrinsic pinning in MgB_2 by measuring the magnetic torque of a single-crystalline MgB_2 when the field is applied parallel to the boron layers [5]. Recently, we have reported on the intrinsic pinning effect in three kinds of MgB_2 superconductors, such as *c*-axis-oriented single crystal film, *c*-axis-oriented columnar structure film and films without *c*-axis orientation perpendicular to the substrate surface [6]. Those films were deposited under different experimental conditions by using hybrid physical chemical vapor deposition (HPCVD) technique. It is observed that the flux pinning behavior and overall J_c of the films critically depend on the experimental conditions. Therefore, in this study, MgB_2 films are fabricated on *c*-cut Al_2O_3 substrates under the same experimental conditions except the thickness of MgB_2 films. The influence of thickness on the grain growth direction and on the superconducting properties of MgB_2 films was investigated.

2. EXPERIMENTAL

MgB_2 films of various thicknesses 0.6, 0.9, 1.4 and 2.0 μm with different orientation of grains were deposited on *c*-cut Al_2O_3 substrates (10 mm × 10 mm in size) by using HPCVD. In contrast to our previous work, where MgB_2 grain growth orientation was controlled by changing the concentration of diborane (B_2H_6) gas and substrate temperature (T_s) [6], in the present work, it is controlled by varying the thickness of the MgB_2 film at a fixed B_2H_6 gas concentration and substrate temperature. The concentration of B_2H_6 gas, having originally been 5%, is tuned by mixing with high purity (6N) hydrogen (H_2) gas. All the films of thicknesses 0.6, 0.9, 1.4 and 2.0 μm were deposited at a temperature of 540 ^{o}C. The thicknesses of MgB_2/Al_2O_3 films were examined by scanning electron microscopy (SEM). A detailed description of the growth process for

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MgB$_2$ films by using HPCVD can be found in our previous report [7].

The resistivity measurements were carried out on all the MgB$_2$ films by the standard four-probe method. The crystal structure of the films were investigated by X-ray diffraction (D8 discover, Bruker AXS) using Cu Kα as an X-ray source. The surface morphology and thickness were measured by scanning electron microscopy (SEM). The magnetization hysteresis (M–H) measurements were carried out on all the films using a magnetic property measurement system (Quantum Design MPMS).

3. RESULTS AND DISCUSSION

The temperature dependences of the normalized resistivity for the MgB$_2$/Al$_2$O$_3$ films of various thicknesses 0.6, 0.9, 1.4 and 2.0 μm are plotted in Fig. 1. The MgB$_2$ films have superconducting transition temperature (T_c) ranging between 39.4 and 40.1 K with superconducting transition width (ΔT_c) of 0.2 – 0.4 K. The T_c was found to increase with the increase in the film thickness, and reached its maximum value of 40.1 K for 1.4-μm-thick film, above which it starts to decrease. The increase in T_c is most probably due to the tensile strain in the films which reported to be the possible cause of higher T_c in MgB$_2$ films, and the thicker the film the larger the tensile strain [8]. The 2.0-μm-thick film has a T_c of 39.4 K which is comparable with the previously reported a-axis-oriented MgB$_2$ films [6].

Fig. 2 shows the X-ray diffraction patterns (XRD) for MgB$_2$ films of thicknesses 0.6 and 2.0 μm. It is observed that the 0.6-μm-thick MgB$_2$ film has a preferred orientation along the (00l) plane in addition to small diffraction peaks of (100), (102) and (200) of different MgB$_2$ planes. The 0.9-μm-thick MgB$_2$ film also has a similar XRD data as 0.6-μm-thick film with preferred orientation along the (00l) plane. We found that with increasing the thickness of the MgB$_2$ film the peak intensities of c-axis oriented diffraction peaks become weak, and almost disappear for thickness of 2.0 μm. In other words, the orientation of grains changed from c-axis to a-axis upon increasing the thickness of film. The impurity peaks of MgB$_4$ were observed in all the films as were noticed in our previous report on differently oriented MgB$_2$ films [6].

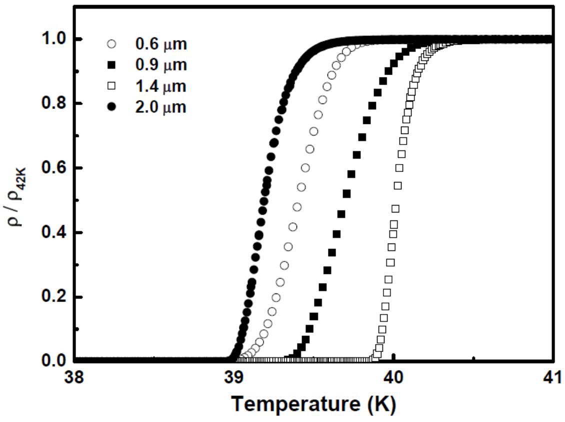

Fig. 1. Temperature dependences of the normalized resistivity of MgB$_2$/Al$_2$O$_3$ films of various thicknesses 0.6, 0.9, 1.4 and 2.0 μm fabricated at 540 °C.

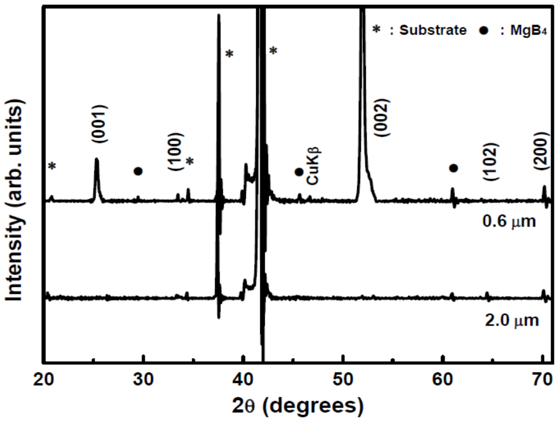

Fig. 2. X-ray diffraction patterns for MgB$_2$ films of thicknesses 0.6 and 2.0 μm. The orientation of grains changed from c-axis to a-axis on increasing the thickness of the MgB$_2$ film.

The surface morphologies of MgB$_2$/Al$_2$O$_3$ films were examined by scanning electron microscopy (SEM). The SEM images of MgB$_2$ films of thicknesses 0.6 and 2.0 μm are shown in Figs. 3a and 3b. Grains of various orientations could be seen in both the SEM images, which is consistent with XRD results. In addition, the MgB$_2$ grains of 2.0-μm-thick film, Fig. 3b, are well connected and have a dense microstructure as compared to the grains of thinner film, Fig. 3a. It indicates that thick MgB$_2$ layer results in compact and dense microstructure.

The critical current density (J_c) of all the films was estimated from magnetization hysteresis loops using the Bean's critical state model [9]. The magnetic field dependence of J_c at 5 K for MgB$_2$ films of thicknesses 0.6 and 2.0 μm with different orientation of grains are shown in Fig. 4. The 0.6-μm-thick MgB$_2$ film shows higher J_c at self-field and in the low field region which is similar to the highly c-axis-oriented film as reported before [10]. Whereas, a crossover of the $J_c(H)$ at 2.3 T was observed for the a-axis-oriented MgB$_2$ film of thickness 2.0 μm when compared to the 0.6-μm-thick film. At high magnetic fields the 2.0-μm-thick film (without c-axis orientation) exhibit considerably larger critical current density. This result is attributed to an intrinsic-pinning anisotropy in MgB$_2$ as we observed before for MgB$_2$ films with different c-axis orientations [6]. The present results also show that MgB$_2$ exhibits strong intrinsic pinning in the in-plane direction

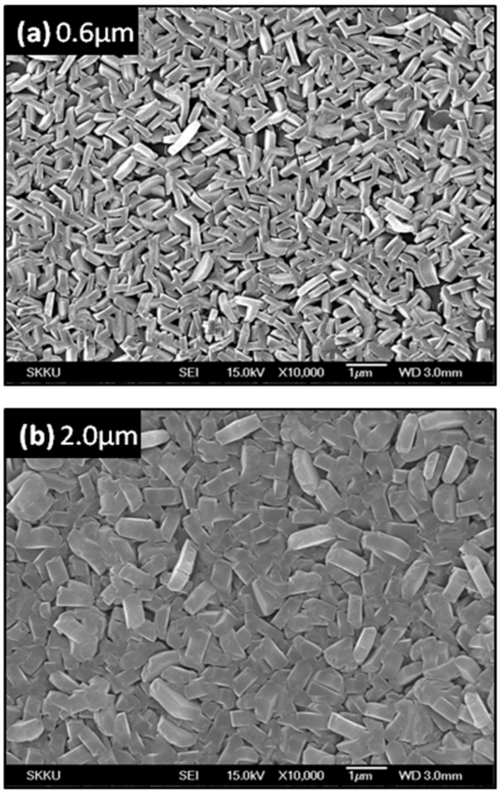

Fig. 3. The surface morphologies of MgB_2/Al_2O_3 films of thicknesses (a) 0.6 μm and (b) 2.0 μm deposited at 540 °C. The thicker film has a denser microstructure as compared to the thinner one.

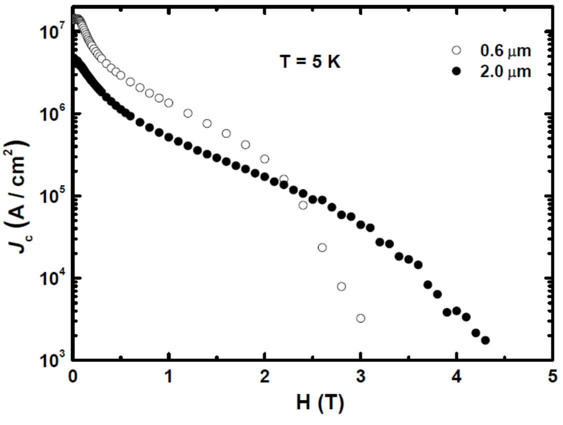

Fig. 4. The critical current density as a function of magnetic field measured at 5 K for MgB_2 films of thicknesses 0.6 and 2.0 μm.

caused by the large superconducting energy gap in the *ab* plane like high-T_c cuprate superconductors with a layered structure [11].

4. CONCLUSION

In summary, MgB_2 films of various thicknesses were deposited on *c*-cut Al_2O_3 substrates by using hybrid physical–chemical vapor deposition (HPCVD) technique. The effect of thickness of the MgB_2 film on the grain growth direction as well as on the superconducting properties of MgB_2 films was studied. It was found that the orientation of grains changed from *c*-axis to *a*-axis on increasing the thickness of the MgB_2 film. MgB_2 grains of various orientations were observed in all the films by SEM analysis. At high fields the 2.0-μm-thick film showed considerably larger critical current density as compared to 0.6-μm-thick film. These findings suggest that the HPCVD is capable of producing highly *c*-axis and a-axis-oriented films which would be very promising for the fabrication of high J_c MgB_2 wires and tapes for practical applications.

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