Transactions of the Materials Research Society of Japan 29[4] 1327-1330 (2004)

Preparation of MgB_2/AlN/MgB_2 multi-layers for Josephson tunnel junctions

A. Saito[a], H. Shimakage[b,c], A. Kawakami[b], Z. Wang[b,c], M. Mukaida[a], and S. Ohshima[a]

[a]Department of Electrical Engineering, Yamagata University, 4-3-16 Johnan, Yonezawa 992-8510, Japan
Fax: 81-238-26-3289, e-mail: atsu@yz.yamagata-u.ac.jp
[b]Kansai Advances Research Center Communications Research Laboratory, 588-2, Iwaoka, Nishi-ku, Kobe 651-2492, Japan
Fax: 81-78-969-2199, e-mail: simakage@crl.go.jp
[c]CREST-JST

The characteristics of MgB_2/AlN/MgB_2 multi-layers were evaluated. The multi-layers were deposited on sapphire (001) substrates by using a carrousel-type sputtering system in the same vacuum run. To determine the superconductivity of an initially grown layer in the upper MgB_2 layer, we investigated the dependence of critical temperature T_c on the thickness of bare MgB_2 thin films at various substrate temperatures T_s. At T_s=267°C, 10-nm-thick MgB_2 thin films had a $T_{c,onset}$ of 13 K. At T_s=291°C, films thinner than 30 nm had no superconductivity. The results indicate that T_s=291°C and T_s=267°C are suitable for the fabrication of lower and upper layers, respectively. In 2θ/θ x-ray diffraction, the intensity of the (002) MgB_2 peak in the MgB_2/AlN/MgB_2 multi-layers was higher than that in single layers.

Key words: MgB_2 thin film, MgB_2/AlN/MgB_2 multi-layers, carrousel-type sputtering, initially grown layer, 2θ/θ x-ray diffraction

1. INTRODUCTION

The recent discovery of superconductivity in MgB_2 at 39 K by Akimitsu et al. [1] has generated interest not only for the study of the physics of superconductivity but also for its commercial use in electronic applications. The high gap energy, which is expected in MgB_2 materials, is advantageous to the fabrication of high-frequency devices. Moreover, MgB_2 films can act as a neutron detector because of a high nuclear reaction cross section of ^{10}B and neutrons. Many researchers have been investigating the fabrication process of MgB_2 thin films and junctions for use in the above devices [2-7].

We have made some advances in the development of as-grown MgB_2 thin films, which were fabricated by using a carrousel-type multiple-target sputtering system. Despite the fact that the thin films were deposited on sapphire c-plane substrates at a low substrate temperature (T_s), the as-grown MgB_2 thin films showed a critical temperature (T_c) of 28 K [8,9]. Additionally, we fabricated MgB_2/AlN/NbN Josephson tunnel junctions with as-grown MgB_2 films, and the junctions showed excellent quasiparticle and Josephson tunneling characteristics [10]. The surface morphology of the as-grown MgB_2 thin films was very flat and smooth, and the AlN barrier on the lower MgB_2 electrode had satisfactory insulating characteristics.

We need methods that would enable the fabrication of MgB_2 superconductor/insulator/superconductor (SIS) junctions with inherent MgB_2 characteristics. In this paper, we describe the preparation of MgB_2/AlN/MgB_2 multi-layers for the purpose of making tunnel junctions. We evaluated the superconductivity and crystallinity of an initially grown layer in the upper MgB_2 layer because is important for multi-layer junctions.

2. EXPERIMANTAL RESULTS

2.1. Film preparation and electrical properties

As-grown MgB_2 thin films were deposited on c-plane (001) sapphire substrates using a carrousel-type sputtering system with a load-lock apparatus. The substrates were intentionally heated during the deposition by using a lamp heater at a T_s=267 and 291°C. The T_s was corrected by using an empirical relation between the actual temperature and the temperature measured by a thermocouple at the inner wall of the carrousel. The actual temperatures at the surface of the sapphire substrates were measured by the thermocouple with Ag paste. Note that the

T_s values in this report are different from those in previous reports [8,9]. This is because we improved the thermal contacts between the sapphire substrate and substrate holder and used an advanced empirical relation to correct the T_s. As a result, the stability and reproducibility of the substrate heating were improved. The sputtering conditions have been described in detail in a previous report [8,9].

The resistivity vs. temperature (ρ-T) curves for the MgB_2 thin films were measured by a standard four-probe method. The temperature was measured using a carbon-glass resistor (model CGR-1-1000) calibrated by Lake Shore Cryotronics, Inc. The films were patterned using conventional photolithography and electron cyclotron resonance etching techniques.

Figure 1 shows a typical ρ-T curve for a bare MgB_2 thin film deposited on a c-plane sapphire substrate at a T_s of 291°C, which was better condition for the deposition of superconducting thin films with the highest T_c value by sputtering [8,9]. The thickness of the film was 200 nm. The normal-state resistivity at 40 K was 50 μΩcm, and the residual resistivity ratio (RRR = ρ(295 K)/ρ(40 K)) was 1.26. The inset shows the transition to superconductivity on a larger scale. The resistivity of the film began to exhibit superconductivity ($T_{c,onset}$=T(0.9ρ(40 K))) at 28.4 K, and the resistivity abruptly decreased to zero. The $T_{c,offset}$ which was defined as T(0.1ρ(40 K)) was 28.3 K. As shown in the inset (Fig. 1), the film had a transition width (ΔT_c) of 0.1 K, which was taken at the onset (10%) and offset (90%) points of the resistance transition. To our knowledge, our films have the highest T_c values ever reported for as-grown MgB_2 films made by conventional sputtering methods.

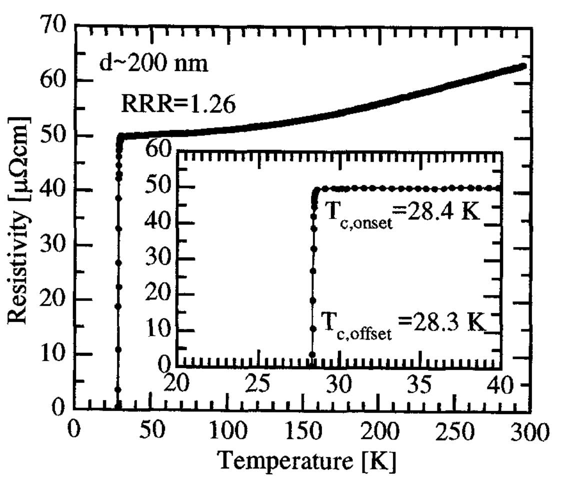

Fig. 1. Resistivity vs. temperature (ρ-T) curves at T_s = 291°C. The inset is a magnified view near the T_c region.

Superconductivity of the initially grown layer in upper MgB_2 layers is one of the most important factors for Josephson junctions with multi-layers. To determine the superconductivity of the initially grown layer, we investigated the dependence of the T_c on the film thickness d. Figure 2 (a) shows T_c vs. d characteristic at T_s=291°C. The solid line was calculated based on Cooper's theory using the maximum T_c value of 28.4 K [11]. The T_c of the films deposited at T_s=291°C decreased gradually as the film thickness decreased. The films thinner than 30 nm showed semiconductor-like ρ-T behavior as shown in Fig. 2 (a). To improve the superconductivity of the initially grown layer, we tried the low temperature depositions at T_s=267°C which is a better condition to close to the stoichiometric composition for the growth of thick films [8]. Figure 2 (b) shows T_c vs. d

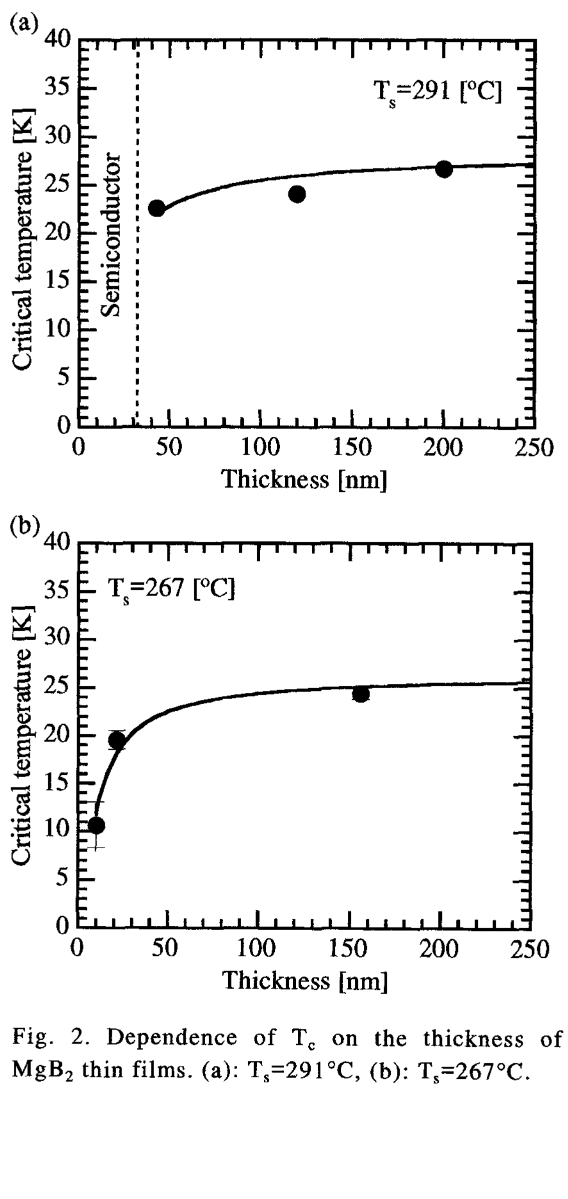

Fig. 2. Dependence of T_c on the thickness of MgB_2 thin films. (a): T_s=291°C, (b): T_s=267°C.

characteristic at T_s=267°C. The solid line was also calculated by Cooper's theory using the maximum T_c value of 26.0 K [11]. Interestingly, the films thinner than 30 nm deposited at T_s=267°C still had superconductivity, although the maximum T_c value of the film deposited at T_s=267°C was lower than that of the films deposited at T_s=291°C. Figure 3 shows the temperature dependence of normalized resistance R/R(295 K) in a 10-nm-thick MgB_2 thin film at T_s=267°C. The inset is an enlarged view near the T_c region. This result corresponds to that for the 10-nm-thick film in Fig. 2 (b). No patterning was carried out to measure the resistivity in order to avoid the deterioration of the film. The $T_{c,onset}$ and $T_{c,offset}$ of this film were 13.1 K and 8.3 K, respectively. These results indicate that T_s=267°C may be a better deposition temperature for upper MgB_2 thin films than T_s=291°C.

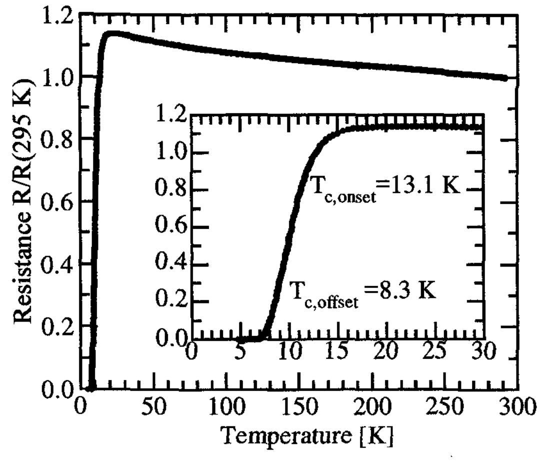

Fig. 3. Temperature dependence of normalized resistance R/R(295 K) in 10-nm-thick MgB_2 thin films at T_s=267°C. The inset is an enlarged view near the T_c region.

2.2. Multi-layer deposition and crystal structures

MgB_2/AlN/MgB_2 trilayers were deposited on c-plane (001) sapphire substrates in a single vacuum run. The lower 200-nm-thick MgB_2 layers were deposited at T_s=291°C. The 1.5-nm-thick AlN layers were reactively sputtered using an Al target, 6 inches in diameter, in pure N_2 gases under a total pressure of 0.67 Pa while the carrousel was rotated at 50 rpm. The upper 100-nm-thick MgB_2 layers were deposited at T_s=267°C. All other conditions for the upper layers were the same as those for the base MgB_2 layers.

The crystal structures of the MgB_2 thin films and the MgB_2/AlN/MgB_2 trilayers were studied using 2θ/θ x-ray diffraction (XRD). Figure 4 shows the XRD 2θ/θ patterns of an MgB_2(200 nm thick) single layer (Fig. 4 (a)) and the MgB_2(200 nm)/AlN(1.5 nm)/MgB_2(100 nm) trilayer (Fig. 4 (b)). Both (001) and (002) reflections of the MgB_2 phase were observed in the scans of the single MgB_2 layers and multi-layers. The intensity of the (002) MgB_2 peak in the MgB_2/AlN/MgB_2 multi-layers was higher than that in the single layer. Notice that the intensity of the (002) reflection in the multi-layers shown in Fig. 4 (b) is proportional to the total thickness of the MgB_2 thin films. These results indicate that the lower and upper MgB_2 layers in the multi-layers have c-axis orientation, which makes them suitable for use in the fabrication of MgB_2 Josephson tunnel junctions.

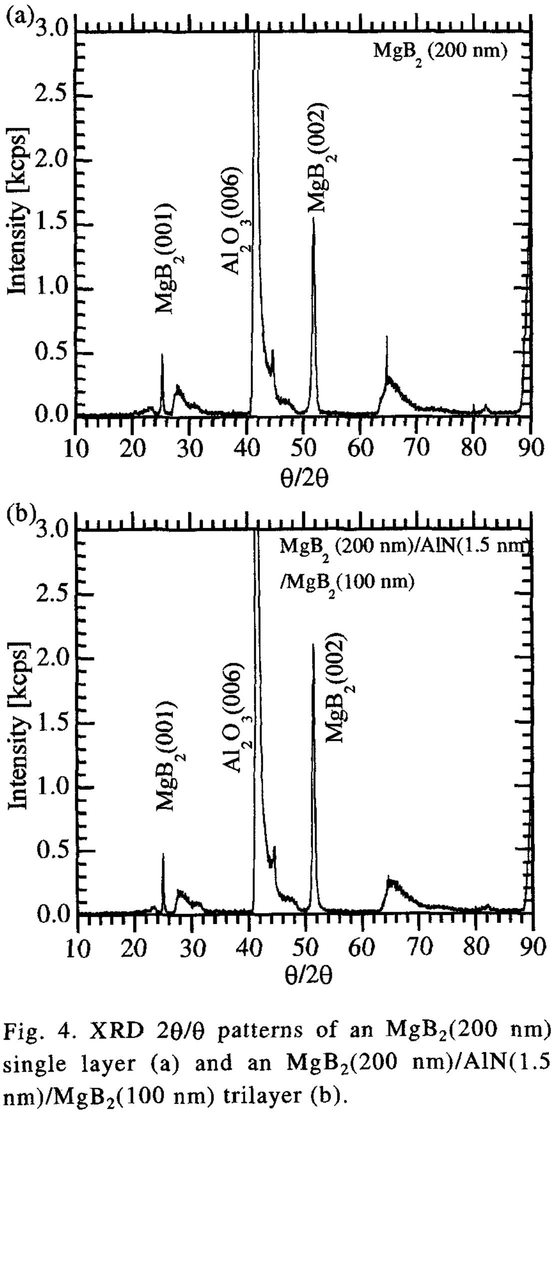

Fig. 4. XRD 2θ/θ patterns of an MgB_2(200 nm) single layer (a) and an MgB_2(200 nm)/AlN(1.5 nm)/MgB_2(100 nm) trilayer (b).

3. CONCLUSION

MgB_2/AlN/MgB_2 multi-layers were deposited on sapphire (001) substrates for the purpose of making Josephson tunnel junctions. To investigate the superconductivity of an initially grown layer in the upper MgB_2 layer, we measured the dependence of T_c on the thickness of as-grown MgB_2 thin films at various T_s. At T_s=267°C, 10-nm-thick MgB_2 thin films showed a $T_{c,onset}$ of 13 K at various T_s. From 2θ/θ XRD measurements of single MgB_2 layers and MgB_2/AlN/MgB_2 multi-layers on sapphire (001) substrates, we found that the upper MgB_2 layers had c-axis orientation. These results indicate that MgB_2/AlN/MgB_2 multi-layers can be used in trilayer structures of MgB_2 SIS junctions. An evaluation of the junctions' dc characteristics is currently underway.

References

[1] J. Nagamatsu, N. Nakagawa, T. Muranaka, Y. Zenitani, and J. Akimitsu, Nature (London) **410**, 63 (2001).
[2] W. N. Kang, H. J. Kim, E. M. Choi, C. U. Jung and S. I. Lee, Science, **292**, 1521 (2001).
[3] K. Ueda and M. Naito, Appl. Phys. Lett., **79**, 2046 (2001).
[4] X. H. Zeng, A. V. Pogrebnyakov, M. H. Zhu, J. E. Jones, X. X. Xi, S. Y. Xu, E. Wertz, Qi Li, J. M. Redwing, J. Lettieri, V. Vaithyanathan, D. G. Schlom, Zi-Kui Liu, O. Trithaveesak, and J. Schubert, Appl. Phys. Lett., **82**, 2097 (2003).
[5] G. Carapella, N. Martucciello, G. Costabile, C. Ferdeghini, V. Ferrando, and G. Grassano, Appl. Phys. Lett., **80**, 2949 (2002).
[6] M. H. Badr, M. Freamat, Y. Sushko, and K. W. Ng, Phys. Rev. **B65**, 184516 (2002).
[7] D. Mijatovic, A. Brinkman, I. Oomen, G. G. Rijnders, H. Hilgenkamp, H. Rogalla, and D. H. A. Blank, Appl. Phys. Lett., **80**, 2141 (2002).
[8] A. Saito, A. Kawakami, H. Shimakage, and Z. Wang, Jpn. J. Appl. Phys., **41**, L127 (2002).
[9]A. Saito, A. Kawakami, H. Shimakage, and Z. Wang, Supercond. Sci. Technol., **15**, 1325 (2002).
[10] A. Saito, A. Kawakami, H. Shimakage, H. Terai, and Z. Wang, J. Appl. Phys., **92**, 7369 (2002).
[11] L. N. Cooper, Phys. Rev. Lett., 6 (1961) 689.

(Received October 13, 2003; Accepted March 5, 2004)