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MgB_2 thin films and $MgB_2/AlN/MgB_2$ SIS junctions

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Abstract

As-grown MgB_2 thin films were fabricated by a sputtering method and a co-evaporation method. We found that the critical temperatures strongly depended on the deposition rate. The MgB_2 thin films showed critical temperatures of 29 K for the sputtering method and 35 K for the co-evaporation method with relatively low substrate temperatures. For the fabrication of all MgB_2 SIS junctions, we selected AlN as the material for the barrier layer, which has hexagonal crystal structure. In fabricating MgB_2/AlN/NbN junctions, we found that the AlN deposition with a higher substrate temperature formed insulator layers other than AlN. We also prepared $MgB_2/AlN/MgB_2$ trilayers for SIS junctions using low AlN deposition temperature condition without breaking the vacuum. The $MgB_2/AlN/MgB_2$ junctions showed a clear Josephson current and gap structures. The critical current density was 120 A/cm^2 and the ratio of sub-gap resistance and the normal resistance was 3.3 when the AlN insulator thickness was 0.14 nm. We showed current–voltage characteristics of the $MgB_2/AlN/MgB_2$ junctions with varying AlN layer thicknesses.

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Keywords: MgB_2; Co-evaporation; Sputtering; SIS

1. Introduction

Many interesting properties of magnesium diboride (MgB_2) were revealed by different institutes after its discovery in 2001 [1]. For widespread applications of MgB_2, the fabrications of high quality MgB_2 films and Josephson devices are very important key technology. Soon after discovering MgB_2, Kang et al. reported a MgB_2 thin film fabrication process with high temperature annealing, which is called the two-step method [2]. The thin films showed a high critical temperature of 39 K and at 40 K showed a resistivity 2.1 μcm, this indicated that the MgB_2 is a good conductor. However, the surface of the thin film easily deteriorated in the annealing process. As a result, the surface order parameter would also deteriorate. Therefore, a two-step process cannot be used to fabricate superconductor–insulator–superconductor (SIS) junctions. On the other hand, Zheng et al. proposed hybrid physical–chemical vapor deposition (HPCVD) methods [3] as an as-grown deposition technique, which has a critical temperature greater than 40 K. This method showed the potential of MgB_2 thin films for producing Josephson junctions. However, the substrate temperature in the processing is greater than 700 °C, which would prevent multi-layer thin films from being produced because of chemical reactivity, including solid reactions, diffusion of atoms. Therefore as-grown deposition techniques with relatively low temperature have to be developed. We have already reported the co-evaporation [4] and sputtering methods [5] as as-grown fabrication methods with relatively low substrate temperatures.

As for SIS Josephson junctions using MgB_2 thin films, Carapella, et al. reported $Nb/Al_2O_3/Al/MgB_2$ SIS junctions [6], that showed a gap structure in its dI/dV–V curves. However, the I–V characteristics showed weak nonlinear properties and no Josephson current. Kim et al. reported $MgB_2/Al_2O_3/V$ junctions [7], that showed very sharp gap properties and low leak current within the gap voltage in its dI/dV–V curves at 1 K. These prop-

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erties suggested that MgB_2 SIS junctions were very promising devices for electronics applications. We have also been studying MgB_2/AlN/NbN SIS junctions [8] in an effort to fabricate all MgB_2 junctions. The junctions showed a Josephson current, clear gap voltages and low leak current properties. In the experiments, we have shown the potential of the MgB_2 SIS junctions for producing all MgB_2 SIS junctions in near future. Using our successive fabrication processes for MgB_2/AlN/NbN SIS junctions, we have reported the successive fabrication process of MgB_2/AlN/MgB_2 SIS junctions [9]. We showed SIS-like I–V characteristics for the junctions. This suggests the potential use for this fabrication technique in future electronic applications. However, the obtained gap voltages were from the π band gap in the two-gap scenario of MgB_2 materials.

2. Fabrication of as-grown MgB_2 thin films

2.1. Co-evaporation method

We have developed the co-evaporation deposition technique for as-grown MgB_2 thin films [4]. The deposition fabrication process is described in detail elsewhere [10]. The boron (B) was evaporated by electron beam deposition, and the magnesium (Mg) was evaporated by thermal heating. The deposition rate was monitored to stabilize the MgB_2 fabrication rate. The substrate temperature was also constantly regulated by SiC heater. As the Mg is easily oxidized because of its high reactivity, an important role for MgB_2 deposition is to prevent the Mg from being oxidized. One solution is to use a high vacuum chamber before fabricating MgB_2. Ueda and Naito [11] used a high vacuum chamber at a pressure of 5×10^{-7} Torr for their molecular beam epitaxy process, and obtained a T_C of around 35 K. However, it is difficult to maintain a high vacuum for long period of time. Here, we propose process conditions with high Mg deposition rate that acts to accelerate the MgB_2 deposition rate, which results in helping to prevent the Mg oxidization. We tested the proposed conditions and found that by increasing the Mg deposition temperatures, the substrate temperature can be increased, and it is expected that MgB_2 thin films with better quality could be obtained. Fig. 1 shows the resistivity of MgB_2 thin films produced by using the co-evaporation method dependence on temperature. The Mg deposition rate, B deposition rate, and the substrate temperature were 10 nm/s, 1.5 nm/s, and 363 °C, respectively. The $T_{C,onset}$ and $T_{C,offset}$ were 35.9 K and 35.2 K, where, $T_{C,onset}$ and $T_{C,offset}$ were defined as the temperatures at which the resistance starts to decrease and becomes zero. Although the vacuum of our deposition chamber was around 2×10^{-6} Torr, the T_C was relatively high, which indicated that a high Mg deposition rate had the same effect as a high vacuum background. We are still improving our co-evaporation set-up to increase the Mg deposition rate, which would hopefully produce high quality MgB_2 thin films.

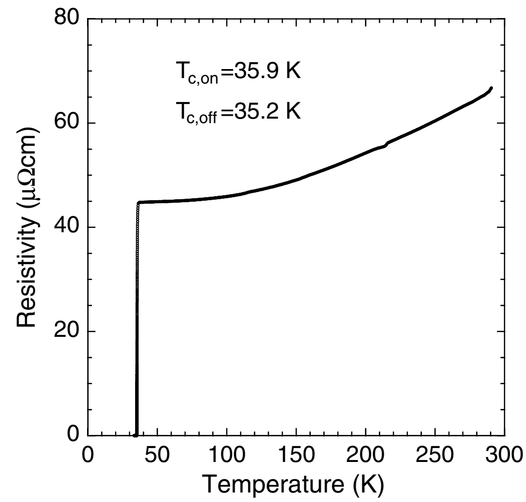

Fig. 1. Resistivity–temperature curve of MgB_2 thin films produced by co-evaporation method.

2.2. Sputtering method

We have also developed a sputtering method for as-grown MgB_2 thin films [5]. The sputtering process is described in detail elsewhere [12]. In the process chamber, we have individual Mg and B targets, and the Mg was deposited by using dc magnetron sputtering and B was deposited by ac magnetron sputtering. The targets were located in a circle on a central sample holder, and the sample holder was rotated to sequentially deposit Mg and B. Fig. 2 shows the resistivity of MgB_2 thin films made by sputtering method depending on temperature. The substrate temperature was constant at 290 °C and the Ar pressure was 5 mTorr. The $T_{C,onset}$ and $T_{C,offset}$ were 29.2 K and 29.1 K, which showed a very small transition temperature, although the T_C was lower than that of MgB_2 made by co-evaporation. As our target sizes were 6 inches in diameter, we achieved a good surface uniformity, which

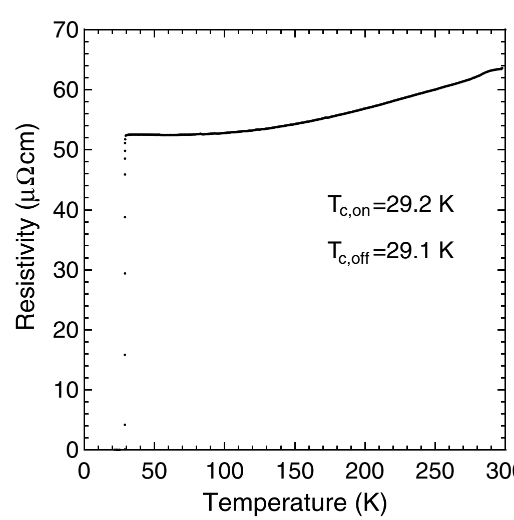

Fig. 2. Resistivity–temperature curve of MgB_2 thin films produced by sputtering method.