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Single-Crystal like MgB_2 thin films grown on *c*-cut sapphire substrates

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Abstract

Single-crystal like MgB_2 thin film was grown on (000*l*) Al_2O_3 substrate by using hybrid physical-chemical vapor deposition (HPCVD) system. Single crystal properties were studied by X-ray diffraction (XRD) and the full width at half maximum (FWHM) of the (0001) MgB_2 peak is 0.15°, which is very close to that has been reported for MgB_2 single-crystal. It indicates that the crystalline quality of thin film is good. Temperature dependence on resistivity was investigated by physical property measurement system (PPMS) in various applied fields from 0 to 9 T. The upper critical field (H_{c2}) and irreversibility field (H_{irr}) were determined from PPMS data, and the estimated values are comparable with that of MgB_2 single-crystals. The thin film shows a high critical temperature (T_c) of 40.4 K with a sharp superconducting transition width of 0.2 K, and a high residual resistivity ratio (RRR=21), it reflects that MgB_2 thin film has a pure phase structure.

Keywords: MgB_2 thin film, Single-crystal, HPCVD.

1. INTRODUCTION

Since Nagamatsu et al., have discovered in 2001 that MgB_2 is a superconductor with high critical temperature (T_c) of 39K [1], a huge effort was expended in basic research to understand and enhance the properties of this material. Due to these efforts, many interesting results about MgB_2 were found.

MgB_2 is a conventional BCS superconductor with two superconducting gaps (Δ_σ and Δ_π), in which the Cooper pairs are formed through electron-phonon coupling [2], [3]. It has a simple crystal structure, less anisotropy and larger coherence length than the high-T_c superconductors [4-5], and high critical current density (J_c) [6-7]. This implies that MgB_2 is a very promising material for application in superconducting devices. However, the majority of investigations were performed on polycrystalline samples. Therefore, to understand fully the intrinsic properties of this material, investigations on single crystals and high quality thin films should be performed. The fabrication of high quality thin film is the first crucial step towards device applications. We used hybrid physical–chemical vapor deposition (HPCVD) technique because it meets the requirement of high-temperature and pressure required for the synthesis of single-crystal like MgB_2 thin film. In this work, we deposited single-crystal like MgB_2 thin films on c-cut sapphire substrates. The θ - 2θ and ϕ-scans were carried on the thin films by X-ray diffraction (XRD), and superconducting properties were studied by physical property measurement system (PPMS).

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2. EXPERIMENT

The HPCVD technique is a combination of physical vapor deposition and chemical vapor deposition, and it is very effective in making high quality MgB_2 thin films. The working process of HPCVD system has been described in detail in some articles [7-9]. The high purity (99.999%) Mg pieces were placed into the groove of stainless-steel susceptor. A *c*-cut Al_2O_3 substrate of 10 mm x 10 mm in size was also placed at the center of the top surface of susceptor. The total pressure inside the quartz tube was kept stable at 210 Torr with 100 sccm flow rate of H_2 gas (6N purity). The substrate and Mg pieces were inductively heated to 650 °C. Then, we introduced B_2H_6 gas (5% concentration in H_2) with flow rate of 50 sccm and the deposition of MgB_2 started. The deposition was stopped when B_2H_6 flow was shut down. The susceptor was cooled down to room temperature in flowing H_2 gas. The phase purity and crystallinity of thin film were analyzed by x-ray diffraction (XRD). The PPMS system was used to investigate the superconducting and transport properties of thin film.

3. RESULT AND DISCUSSION

Fig. 1 shows the temperature dependence of resistivity of the single-crystal like MgB_2 thin film. The T_c onset of the film is observed to be 40.4 K. The origin of high T_c in our film is most probably the epitaxial strain generated in the growth process [10]. The magnified view of a sharp superconducting transition from 40.4 K to 40.2 K is also presented in the inset of figure. The resistivity value of

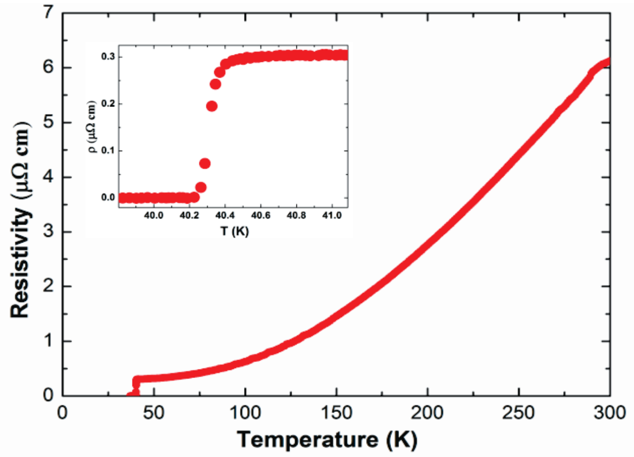

Fig. 1. Temperature dependence of resistivity for single-crystal like MgB_2 thin film grown on Al_2O_3 substrate. The inset shows the magnified view of superconducting transition in the temperature region from 39 to 41 K.

the film at room-temperature (300 K) is 6.2 μΩ cm, and it decreased to 0.3 μΩ cm at 42 K. The low residual resistivity suggests a very long electron mean free path [11]. The residual resistivity ratio (RRR) of MgB_2 thin film is as high as 21, it indicates that MgB_2 thin film has a high purity phase [12].

The X-ray diffraction (XRD) θ-2θ scan of MgB_2 film grown on c-cut sapphire substrate is shown in Fig. 2. There are only (000*l*) diffraction peaks from MgB_2 except the substrate peak, this suggesting the phase purity and high c-axis orientation in our film. The full width at half maximum (FWHM) obtained from the rocking curve of (0001) peak is 0.15° (inset of figure 2), which is very close to that has been reported for MgB_2 single-crystal [13], indicating that the crystalline quality of the film is good.

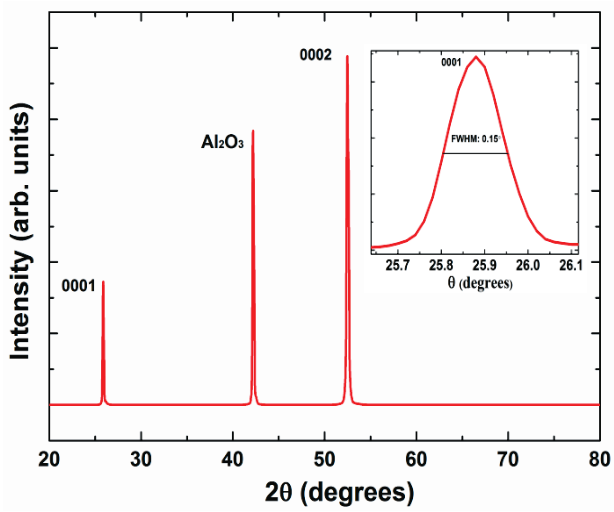

Fig. 2. The X-ray diffraction of single-crystal like MgB_2 thin film grown on (0001) Al_2O_3 substrate. The inset shows the full width at half maximum (FWHM) obtained from the (0001) peak of MgB_2.

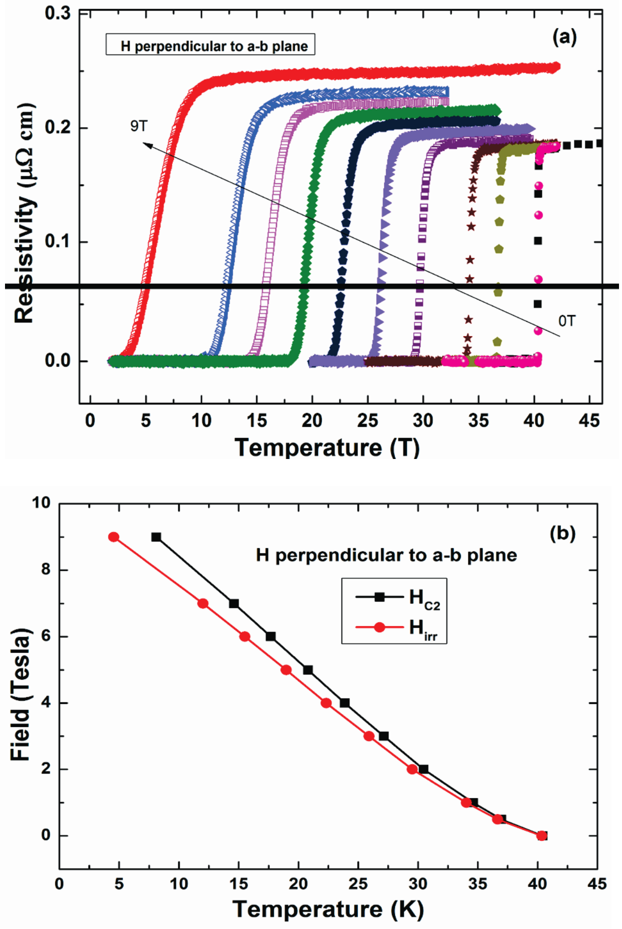

Fig. 3. (a) Resistivity transitions measured at various fields from 0 to 9 T when H was applied perpendicular to a-b plane of MgB_2 thin film. (b) Temperature dependence of H_{c2} and H_{irr}.

The upper critical field (H_{c2}) and irreversibility field (H_{irr}) were determined from resistivity measurements. Resistive transitions measured under applied field varying from 0 to 9 T are presented in Fig. 3a. The fields were applied perpendicular to the a-b plane of single-crystal like MgB_2 thin film. The H_{c2} and H_{irr} were determined from the criteria of 90 and 10% of its normal state resistance. Fig. 3b shows the temperature dependence of H_{c2} and H_{irr}.

For a two band superconductor, like MgB_2, the formula $H_{c2}(0) = 0.69T\ (dH_{c2}/dT)_{T=Tc}$, which is derived from single-band Ginzburg-Landau theory could not be apply to calculate $H_{c2}(0)$. However, $H_{c2}(0)$ value for MgB_2 can be calculated by applying a theory developed for the two band superconductors [14]. Here, just for comparison, $H_{c2}(0)$ is estimated simply by extrapolation to zero K. We obtained $H_{c2}^{\perp ab}$ = 11 T, which is slightly higher than that reported for MgB_2 single-crystal [5] but much lower than that reported for clean MgB_2 thin film grown on 6H-SiC substrate [15]. This result probably reflectes that the quality and the properties of our thin film is like that of MgB_2 single crystals.

4. CONCLUSION

In conclusion, we have grown c-axis oriented MgB_2 thin films with single-crystal quality on (0001) Al_2O_3 substrates. The crystalline structure and transport properties of the film were studied. The thin film shows a high critical temperature (T_c = 40.4 K) and a sharp superconducting transition (0.2 K). The highly c-axis oriented peaks and high-purity phase without any impurity or secondary peaks were observed in the θ-2θ scan of XRD. The H_{c2} value of thin film was found comparable with the value reported for MgB_2 single crystal. These results would provide a new horizon in fabricating high-quality MgB_2 thin film on inexpensive sapphire substrate for superconducting device applications.

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