Magnetic and Magneto-Optical Properties of MnSb Films Grown on Sapphire Substrate

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We have grown MnSb films on sapphire substrates by hot wall epitaxy. A series of films with thicknesses of 80, 155 and 230 nm was prepared to determine the thickness dependence of their magnetic and magneto-optical properties. Our results indicate that the thinnest and thickest films possess largest coercivity and saturation magnetization, respectively. The largest Kerr rotation angle was also found in the thickest film for both the longitudinal and polar Kerr rotations, reaching a maximum of 0.31°. We attribute this behavior to the thickness dependence of both the film magnetization orientation and its atomic composition.

1. Introduction

MnSb has a NiAs-type crystalline structure with lattice constants \( a = 0.413 \) nm and \( c = 0.579 \) nm [1]. This compound has attracted much attention due to its numerous potential applications, such as in thermomagnetic writing [2], erasable magnetic holography [3], and magneto-optical readout using laser beams [4].

Recently, the epitaxial growth of MnSb on GaAs substrates by hot-wall epitaxy (HWE) [5–10] have been successfully developed by several groups. It was also reported that a larger Kerr rotation angle can be obtained if MnSb thin film is grown on sapphire (\( \text{Al}_2\text{O}_3(0001) \)). While extensive research has been done to investigate the magnetic and magneto-optical properties of the MnSb/sapphire system [11, 12], very few studies have examined the thickness dependence of these properties. In this paper, we present magnetic, magneto-optical measurements for MnSb thin films grown on sapphire substrates as a function of film thickness.

In our experiment, HWE method was used to grow MnSb thin films on a sapphire substrate. Our goal is to study the structural, magnetic and magneto-optical properties of MnSb films with varying thicknesses, obtained by increasing the length of the deposition time while keeping the same growth conditions.

2. Experimental Method

The epitaxial growth was carried out in a HWE system, using bulk Mn and Sb as source materials. Before growth, the substrates were etched according to the following steps: 1. ultrasonic cleaning in acetone for 10 min; 2. etched in HCl: \( \text{HNO}_3 = 3:1 \) for 5 min; 3. rinsed with de-ionized \( \text{H}_2\text{O} \) and dried prior to loading into a
vacuum chamber. They were thermal cleaned at 700 °C for three hours before deposition.

A series of three Mn$_{1+x}$Sb films were prepared, with $x$ being 0.37, 0.26, and 0.17 for a thickness of 80 nm, 155 and 230 nm, respectively. The temperatures of the substrate, Mn and Sb sources were maintained at 280, 750 and 520 °C, respectively. During growth, the Mn flux was $1 \times 10^{19}$ atoms m$^{-2}$s$^{-1}$ and the Sb/Mn flux ratio was fixed at 36. The base pressure during MnSb deposition in the vacuum was $2.3 \times 10^{-6}$ Torr.

An X-ray diffractometer was employed to analyze the structure of the samples. Magnetization was measured using a vibrating sample magnetometer (VSM). In order to obtain the relationship between the Kerr rotation angle and the film thickness, a homemade magneto-optical Kerr effect (MOKE) system was used to determine the rotation angles for various film thicknesses [12]. In this study, both longitudinal and polar Kerr effects are investigated.

3. Results and Discussion

Figure 1 shows the X-ray diffraction pattern of the three MnSb epitaxial films. The inset illustrates the XRD result ($\theta$–$2\theta$ scan) of the 230 nm film, which indicates that the crystal orientation of the film is (00.1). With decreasing film thickness, it can be seen that the peak not only has become broader but also tends to shift further away from the corresponding bulk position. The maximum shift in angular position is 0.13° for a film of 80 nm thick, and its full width at half maximum (FWHM) is 0.22°. The 230 nm film, however, exhibits negligible shift, and its FWHM is just 0.1°.

The XRD patterns of the three films have similar diffraction lines with no additional lines except for a difference in the MnSb(10.1)/Al$_2$O$_3$(0001) intensity ratio of 1.1, 1.1, 1.5 for 80, 155, and 230 nm, respectively. It may thus be concluded that all the films are

![Fig. 1. X-ray spectra of MnSb thin films. All peaks are shifted relative to the bulk position (indicated by a vertical dashed line). But, while there is a negligible shift for the 230 nm film, a large shift of 0.13° is observed for the 80 nm film. The inset shows a wider scan of the 230 nm MnSb thin film](image-url)
single phase with bulk NiAs crystal structure. Further, among the films deposited, the 230 nm film probably is the best epitaxial MnSb film as it has the smallest full width at half maximum value.

Figure 2 shows the lattice spacing \( c \) and atomic composition of the MnSb film as a function of film thickness. The variety of the manganese antimonide phases may be the cause of the difficulty in the epitaxial growth of Mn\(_{1+x}\)Sb [11], giving rise to composition fluctuations especially for very thin films even under the same growth conditions. The atomic composition of the films was determined by X-ray photoemission spectroscopy (XPS) to be 57.8, 55.7 and 53.9 at% Mn for the 80, 155 and 230 nm films, respectively. Sapphire has a rhombohedral crystal structure with \( a = 0.5128 \) nm and \( \beta = 55^\circ22' \). Thus, the MnSb hexagonal lattice with \( a' = 0.4128 \) nm and \( c = 0.5789 \) nm has to undergo significant deformation in order to match the substrate lattice. Consequently, the film is under stress, at least near the film–substrate interface. As \( c \) increases with film thickness, it can be argued, assuming a constant volume approximation, that the hexagonal area near the interface is larger than being away from it, suggesting the presence of biaxial tensile strains at the film–substrate interface. The strain takes its largest value at the interface, so that little relief is possible when films are very thin.

The associated changes in magnetic and anisotropy properties of the MnSb films due to small variation in composition have already been discussed in many previous papers. For example, Okita and Makino [13] reported that the Curie temperature depends strongly on the composition \( x \) of Mn\(_{1-x}\)Sn in the range of 0.08 to –0.27. Furthermore, Okita and Makino [13] and Bai and Rao [14] showed that the sign of the magneto-crystalline anisotropy constant, namely the easy magnetization axis, changes depending on the composition and temperature. Our finding is also consistent with another report [15] where the crystallographic parameter \( c \) decreases linearly as the Mn concentration increases from the stoichiometric composition.

Hysteresis loops measured at room temperature (293 K) for the three films are shown in Fig. 3, where the field was applied parallel to the film plane. Figure 4 shows the hysteresis loops of the 230 nm film. The results showed that the saturation magnetization \( M_s \) and the coercivity \( H_c \) are dependent on film thickness: with increasing film
thickness, $H_c$ decreases while $M_s$ increases. The former may result from structurally related phenomena that affect the nucleation and movement of magnetic domain walls while the latter is likely a result of the deviation from stoichiometric composition.

Figure 5 shows an approximate linear dependence of the saturation magnetization $M_s$ and coercivity $H_c$ on the Mn concentration. It is thus concluded that $H_c$ and $M_s$ have relationship not only with the film thickness but also with the composition of the films.

Magneto-optical properties of the films were studied by our home-made MOKE system. The MOKE was measured at room temperature for the films using 632.8 nm laser with incidence angles of 45° and 60° for the longitudinal and polar directions, respectively. The magnetic field was applied from $-318$ to $318$ kA/m with a sweep frequency of 0.01 Hz and the Kerr rotation data were collected by a computer.
Figures 6a and b show the curves of the Kerr rotation with the field applied parallel and perpendicular to the film plane, respectively. For field parallel to film plane, it was found that the Kerr rotation angle reaches saturation at relatively low field. For perpendicular field, however, the saturation limit is not reached even at maximum available field. A comparison with the results obtained by VSM reveals that the general shape of the Kerr rotation curve is strikingly similar to that of the magnetic hysteresis loop. This suggests that the MOKE curve can also reflect the magnetization characteristics of the film.

The maximum Kerr rotation angle was found to increase with film thickness. Figures 6a and b clearly show that the thickest film exhibits the largest Kerr rotation angle. In Fig. 6a, where \textbf{H} is parallel to the film plane, the Kerr rotation angles are 0.26°, 0.29° and 0.31° for 80, 155 and 230 nm films, respectively. In Fig. 6b (\textbf{H} \perp film plane), the Kerr rotation angles are 0.22° (80 nm), 0.25° (155 nm) and 0.3° (230 nm).

Fig. 5. Composition dependence of coercivity $H_c$ and saturation magnetization $M_s$. The results suggest an approximate linear dependence.

Fig. 6. Thickness dependence of the Kerr rotation angle for fields applied a) parallel and b) perpendicular to the film plane.
In very thin films, the strain at the film–substrate interface can have a significant effect on the Kerr rotation angle. The deformation of the film can disorder its spin orientations, resulting in a decrease in its overall magnetization. Since only the component of magnetization parallel to the direction of propagation of the light is effective in rotating the plane of polarization, the Kerr angle is thus expected to decrease. The varying atomic composition of the film [16] may also provide another possible reason for the thickness dependence of the Kerr angle. In our present study, as the film gets thinner, the observed deviation from the stoichiometric composition may lead to a significant reduction of the Kerr effect.

4. Conclusion

Ferromagnetic MnSb thin films have been successfully grown on sapphire substrates by hot-wall epitaxy technique. The growth plane of MnSb is (002). The lattice spacing of the film has to be deformed in order to match the lattice of the substrate with a hexagonal crystal structure.

It is concluded that a thinner film yields larger $H_c$ values, whereas a thicker film exhibits a larger $M_s$ value. A large Kerr rotation angle was also obtained for field applied both parallel and perpendicular to the film plane. The MOKE curve represents the magnetization property of the film. The Kerr rotation angle increases with film thickness, and the composition of the film has an effect on the Kerr signal.

References