文章编号:1001-9014(2004)04-0241-05

MAGNETIC AND MAGNETO-OPTICAL PROPERTIES OF Mn/Sb MULTILAYER FILMS

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Abstract: Mn/Sb multilayer films with different thicknesses were grown on GaAs(100) and glass by ultrahigh vacuum (UHV) evaporation technique and then annealing for a short duration(1 or 20 min). Magnetization measurements revealed strong room-temperature ferromagnetism. And when the thickness of layers was increased from 700Å to 1600Å, the saturation magnetization increased nearly double; and the polar and longitudinal Kerr saturation angles θ_k increased too, but less than two times. It indicates that both the magnetization and Kerr rotation angle depend on the thickness of layers, but are not simply proportional to the thickness of the layers. The saturation magnetization and both the polar and longitudinal Kerr saturation angles can be enhanced with increasing the thickness of the layers. X-ray diffraction(XRD) pattern results show that high-quality crystal structures of thicker Mn/Sb films can be fabricated by UHV evaporation technique with subsequent thermal annealing for a very short duration(about 1 min).

Key words: multilayer films; ferromagnetism; magneto-optical Kerr effect; annealing; X-ray diffraction
CLC number: O482.55 **Documentn code**: A

Mn/Sb 多层膜的磁性和磁光特性

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摘要:用超高真空蒸发技术在GaAs(100)和玻璃衬底上生长不同厚度Mn/Sb多层膜,并经短时间热退火(~1,20min).磁化强度测量显示具有很强的室温铁磁特性.当多层膜厚度从700Å增至1600Å时,饱和强度增加了近一倍,极向和纵向克尔角也增加了,但不到一倍.这表明磁化强度和克尔角两者均依赖于多层摸的厚度,但不是简单的正比于厚度的关系.增加Mn/Sb多层膜的厚度能增强饱和磁化强度和极向和纵向克尔饱和角.X射线衍射谱图结果表明高质量单晶结构的Mn/Sb多层膜能用超高真空蒸发技术生长,对较厚的多层薄膜,热退火的时间可很短(约1min).

关 键 词:多层膜;铁磁性;磁光克尔效应;退火;X射线衍射

Introduction

The growth of ferromagnetic on semiconductors has attracted much attention due to their potential applications in electronic and magneto-optical devices[1], especially in spintronics[2], which gives rise to the pos-

Received date: 2003-07-30, **revised date**: 2004-03-02 **收稿日期**:2003-07-30,**修回日期**:2004-03-02
Foundation item: The project supported by the National Natural Science Foundation of China(19874005)

Biography: CHEN Chen-Jia(1935-), female, Fuzhou Fujian, professor of Peking University, condensed matter physics speciality, research area is semiconductor physics, recently working on optical and magneto-optical properties of diluted magnetic semiconductors, superlattices and quantum wells of semiconductor, and spintronics.

sibility of reading and writing nonvolatile information through magnetism. Ferromagnetic MnSb shows a large magneto-optical Kerr effect (MOKE). Much attention has been paid to the growth of MnSb on various substrates especially on a GaAs semiconductor[3~6]. MnSb multilayer films can be fabricated by UHV evaporation[3], and rf sputtering[4] with subsequent thermal annealing for a long duration (e.g., ~10h), or epitaxial growth by hot-wall epitaxy (HWE)[5], and molecular beam epitaxy (MBE).[6]. Previously we reported that Mn/Sb multilayer films were grown on GaAs and other substrates by an UHV evaporation technique and subsequent annealing for a short duration (20min)[7], where X-ray diffraction and magnetic force microscope patterns showed that a high-quality crystal structure of MnSb was formed. Both polar and longitudinal magneto-optical Kerr rotations were observable for all the annealed films. In this paper we report Mn/Sb multilayer films grown on GsAs and glass substrates with increasing the thickness by UHV evaporation technique and subsequent thermal annealing for a much shorter duration than before.

1 Experiment

Mn/Sb multilayer films were grown on GaAs (100) and glass substrates by using a Balzer's UMS 500P UHV system. The vacuum was approximately 5×10^{-7} Torr and the substrates were kept at 100℃ during deposition. The films were capped with 100Å or 200Å of SiO_2 and then annealed at temperatures of 250 ~450℃ for 1 and 20 min in the gas of N_2. Typical structures are film A: (200Å Sb/300Å Mn/200Å Sb/100Å SiO_2)[7] and film B (200Å Sb/400Å Mn/400Å Sb/400Å Mn/200Å Sb/200Å SiO_2). Magnetization measurements were obtained by using a model 2900 Micro-Mag™ alternating gradient magnetometer (AGM) at room temperature. The diamagnetic background contribution due to substrates was subtracted form the data. XRD analysis was performed by using a Philips 1710 diffractormater equipped with a copper anode operated at 40KV and 35 mA, a graphite curved monochromater on the diffracted beam, and a proportional counter. Both longitudinal and polar Kerr rotations were studied with MOKE system setup[8].

2 Results and discussion

2.1 Ferromagnetism and magneto-optical Kerr effect

Magnetization hysteresis loops, which were obtained by AGM at room temperature for unannealed and annealed films of GaAs and glass substrates with $H\perp$ and $H//$ to the plane, show ferromagnetic characteristics. The results indicate that there was strong interdiffusion between Mn and Sb layers. After annealing, all the films show that saturation magnetization M_s is increased and coercively H_c is decreased. The magnetizations of MnSb films on these two different substrates do not display any obvious differences. Maybe this is due to the fact that the interface between the film and substrate only has little influence under our experimental conditions. As a typical result, we show the magnetization (M) hysteresis loops with $H\perp$ and $H//$ to the plane on glass for film B (200Å Sb/400Å Mn/400Å Sb/400Å Mn // 200Å Sb/200Å SiO_2) annealed at 350℃ for 20 min in Fig. 1. The magnetization hysteresis loops of film B show very obvious geometrical anisotropy with $H\perp$ and $H//$ to the plane, which is very similar to film A[7]. This means that the easy axis of the films is parallel to the plane. Typical magnetization hysteresis with H parallel to the plane on glass substrate at room temperature for film A (200Å Sb/300Å Mn/200Å Sb/100Å SiO_2) and film B (200Å Sb/400Å Mn/400Å Sb/400Å Mn/200Å Sb/200Å SiO_2) are shown in Fig. 2(a), and (b). We note that film B

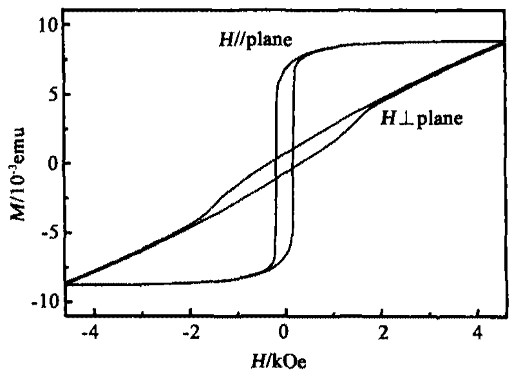

Fig. 1 Magnetization hysteresis loops obtained at room temperature with magnetic field $H\perp$ and $H//$ to the film plane for film B on glass annealed at 350℃ for 20min.
图1 室温下多层膜B的磁滞回线图，$H\perp$和$H//$表示磁场垂直和平行膜层平面；多层膜生长在玻璃衬底上，在350℃下退火20min

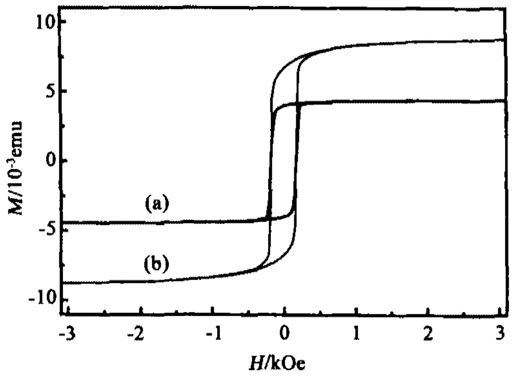

Fig. 2 Magnetization hysteresis loops obtained at room temperature with magnetic field $H//$ to the film plane for (a) film A and (b) film B on glass annealed at 350℃ for 20 min

图2 (a)和(b)分别为室温下多层膜 A 和多层膜 B 的磁滞回线图. 磁场方向($H//$)与膜层平面平行;多层膜 A 和 B 生长在玻璃衬底上,在 350℃下退火 20min

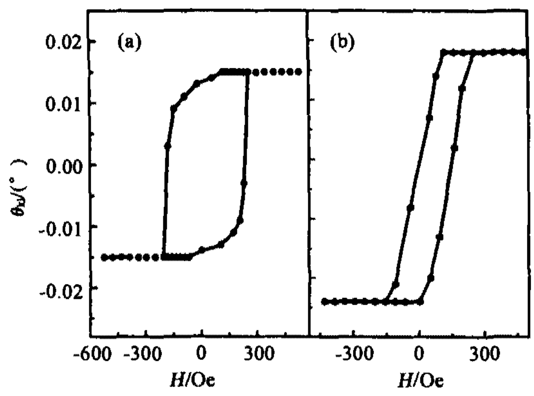

Fig. 3 Longitudinal Kerr angles θ_{kl} at room temperature for (a) film A and (b) film B on glass substrate annealed at 350℃ for 20 min.

图3 (a)和(b)分别为室温下多层膜 A 和多层膜 B 的纵向克尔角. 多层膜 A 和 B 生长在玻璃衬底上,在 350℃下退火 20min

with a thickness of 1600Å is more than double of the thickness of film A(700Å). The saturation magnetization M_s of film B(88×10^{-3}emu) is nearly double that of film A(44.1×10^{-3}emu), and the magnitude of coercivity H_c is about the same (177 Oe for film A and 148 Oe for film B). The result shows that magnetization depends on the thickness of film. A thicker film exhibits a larger saturation magnetization value in our thickness region. As is known, Mn is antiferromgnetic and Sb is nonmagnetic, so the saturation magnetization result indicates that there was a very strong inter-diffusion between Mn and Sb layers. A ferromagnetic MnSb is formed with the thickness from 700Å to 1600Å. (The fact is that the saturation magnetization also strongly depends on stoichiometry of MnSb and decreases rapidly with the decrease of Sb content, becoming zero at the Mn_2Sb. The decrease of magnetization with excess Mn in MnSb is explained by assuming that the excess Mn atoms occupy the B site, and these magnetic moments are anti-parallel to those of Mn in A site.)

The polar and longitudinal Kerr rotation angles (θ_k) of the films as a function of the applied magnetic field were measured at room temperature by using a He-Ne laser of 632.8nm wavelength with magneto-optical modulation method[8]. It is worth noting that the Kerr rotation angles of the Mn/Sb films on GaAs and glass substrates do not display any obvious differences, which is similar to the magnetization, because the interface between the film and substrate has little influence. Typical results of θ_{kl} for film A and film B on glass substrate annealed at 350℃ for 20 min are shown in Fig. 3. (a) and (b), respectively. The polar and longitudinal Kerr saturation angles θ_k for film A are 0.12° and 0.015° and for film B are 0.19° and 0.024°. In our experiments, the remarkable difference in the magnitude of polar and longitudinal Kerr angles θ_k is due to the small incident angle(~10°). According to the generalized analytic formulae of magneto-optical Kerr effects for both the optically thick and the ultrathin films[9], Kerr rotation angle θ_k for optically thick film limit is independent of the thickness of layers, whereas for the ultrathin film limit it is proportional to the thickness of layers. Both optically thick and ultrathin films cases cannot fit to our Mn/Sb films. Our experimental results show that Kerr rotation angle θ_k is dependent on the thickness of film but not simply proportional to the thickness of film. It indicates that both the polar and longitudinal Kerr rotation angles can be enhanced with the increasing of film thickness.

Han et al reported that the MOKE hysteresis loop could be obtained only for MnSb on sapphire while there is no observable Kerr rotation on GaAs substrate[5]. However, both the polar and longitudinal Kerr rotations are observable in our results. It is also worth noting that the longitudinal Kerr angle cannot be observed in unannealed films on different substrates. It is due to crystal structure quality and inhomogeneous magnetic distribution in unannealed samples. Yoshioka et al[3] reported that θ_k strongly depends on the composition of $Mn_{1-x}Sb_x$, and deviation from the standard 1: 1 may cause the decrease of θ_k.

2.2 Structural properties

MnSb is a ferromagnetic compound with a rather high Curie temperature of 314℃ and has a hexagonal NiAs crystal structure with lattice constants of a = 0.4128nm and c = 0.5789nm. Our previous XRD results showed that the best annealing temperature for film A on GaAs and glass is 350℃ for a short duration (20 min)[10]. For film B on GaAs and glass substrates, our results also show that the best annealing temperature is 350℃. Fig.4(a) shows a typical XRD pattern for film B on glass substrate as deposited. There is only a very weak peak corresponding to MnSb (00.2). Fig.4(b) shows a XRD pattern for film A on glass annealed at 350℃ for 20min. A biggest sharp peak at ~30.9° and a minor peak at 64.4°, which is corresponding to MnSb(00.2) and MnSb(00.4), respectively, are obtained after annealing, (also including a small peak at 29.3°, which is related to structure MnSb(10.1)). Fig.4(c) shows a XRD pattern for Film B on glass annealed at 350℃ for 20 min.

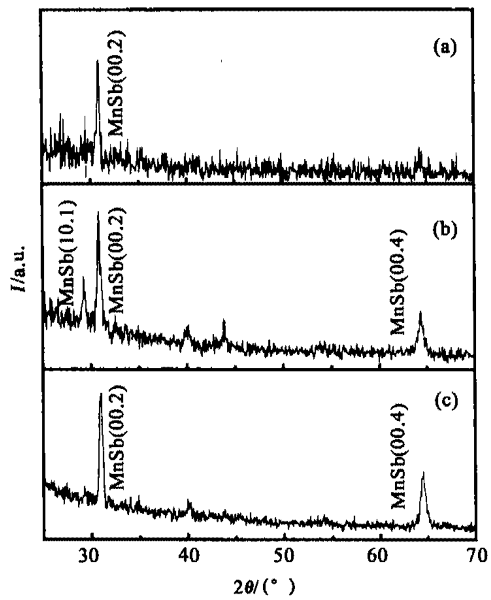

Fig.4 XRD pattern on glass substrate: (a) film B, unannealed, (b) film A, annealed at 350℃ for 20 min, and (c) film B, annealed at 350℃ for 20 min

图4 X射线衍射谱图:(a)未经退火的多层膜B的谱图(b)在350℃下退火20min的多层膜A的谱图(c)在350℃下退火20min的多层膜B的谱图

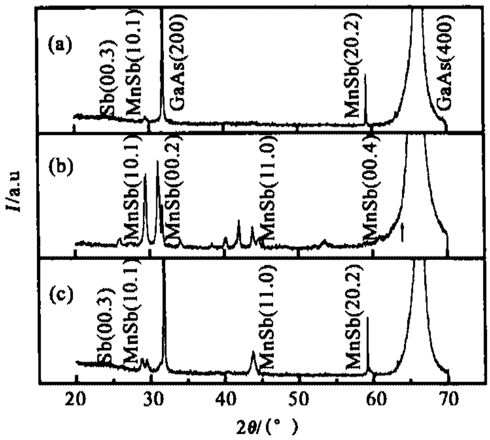

Fig.5 (a) XRD pattern for unannealed film B on GaAs (100) substrate (b) XRD pattern for film B on GaAs(100) substrate annealed at 350℃ for 1 min (c) XRD pattern for film B on GaAs(100) substrate annealed at 350℃ for 20 min.

图5 (a)生长在GaAs(100)衬底上,未经退火的多层膜B的X射线衍射谱图(b)生长在GaAs(100)衬底上,在350℃下退火1min的多层膜B的X射线衍射谱图(c)生长在GaAs(100)衬底上,在350℃下退火20min的多层膜B的X射线衍射谱图

MnSb(00.2) and MnSb(00.4) structures are exhibited clearly.

We reduced the annealing time to 1 min and compared it with 20 min for the film B on GaAs(100) substrate. The magnetization and the Kerr rotation angles measurements do not exhibit differences for these two samples. Fig. 5(a) shows a typical XRD pattern for film B on GaAs(100). Besides the two main peaks corresponding to GaAs substrate, there is a broad peak related to Sb(00.3), and only a sharp peak at 59.8° and a minar peak at 29.3° corresponding to MnSb(20.2) and MnSb(10.1), respectively. Fig.5(b) shows a XRD pattern for film B on GaAs annealed at 350℃ for 1 min. The biggest sharp peak at 30.9° and many peaks at 29.3°, 44.5°, and 64.4° are obtained after annealing. These peaks correspond to MnSb(00.2), MnSb(10.1), MnSb(11.0), and MnSb(00.4), respectively. We note that the broad peak Sb (00.3) disappeared. Fig.5(c) shows a XRD pattern for film B on GaAs annealed at 350℃ for 20min. The main peaks MnSb(00.2) and MnSb(00.4) disappeared and the broad Sb(00.3) peak re-appeared. Thus the CRD results show that the best annealing temperature for film B on the GaAs substrate is 350℃ for 1min.

We note that the substrates are kept in the temperature of 100℃ under our experimental conditions. It means that thicker Mn/Sb multilayer films can be fabricated by UHV evaporation technique with subsequent thermal annealing by using a very short duration (~1min) instead of 20min. duration. These results show that high-quality crystal structures of Mn/Sb can be fabricated by UHV evaporation technique with subsequent annealing for a short duration.

3 Conclusion

Mn/Sb multilayer films with different thicknesses were grown on GaAs(100) and glass by ultrahigh vacuum(UHV) evaporation technique and then annealing for a short duration (1 or 20 min). Magnetization measurements revealed strong room temperature ferromagnetism. When the thickness of layers was increased from 700Å to 1600Å, the saturation magnetization increased nearly double; and the polar and longitudinal Kerr saturation angles θ_k increased too but less than two times. It indicates that both the magnetization and Kerr rotation angle depend on the thickness of layers but are not simply proportional to the thickness of layers. The saturation magnetization and both the polar and longitudinal Kerr saturation angles can be enhanced with increasing the thickness of layers. X-ray diffraction (XRD) pattern results show that high-quality crystal structures of thicker Mn/Sb films can be fabricated by UHV evaporation technique with subsequent thermal annealing for a very short duration(about 1 min).

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