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Journal of Crystal Growth 279 (2005) 272–275
JOURNAL OF CRYSTAL GROWTH
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$Ga_{1-x}Mn_xSb$ grown on GaSb with mass-analyzed low-energy dual ion beam deposition

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Received 15 November 2004; accepted 16 February 2005
Available online 8 April 2005
Communicated by M. Schieber

Abstract

The $Ga_{1-x}Mn_xSb$ samples were fabricated by the implantation of Mn ions into GaSb (1 0 0) substrate with mass-analyzed low-energy dual ion beam deposition system, and post-annealing. Auger electron spectroscopy depth profile of the $Ga_{1-x}Mn_xSb$ samples showed that the Mn ions were successfully implanted into GaSb substrate. Clear double-crystal X-ray diffraction patterns of the $Ga_{1-x}Mn_xSb$ samples indicate that the $Ga_{1-x}Mn_xSb$ epilayers have the zinc-blende structure without detectable second phase. Magnetic hysteresis-loop of the $Ga_{1-x}Mn_xSb$ epilayers were obtained at room temperature (293 K) with alternating gradient magnetometry.

PACS: 61.72.Vv; 61.82.Fk; 75.50.Pp; 81.05.Zx; 81.15.Jj

Keywords: A1. X-ray diffraction; A3. Ion beam epitaxy; B2. Semiconducting ternary compounds

1. Introduction

Semiconductors and magnetic materials are two very important materials in the field of modern information technology and two large fields of solid state physics. Semiconductor devices take advantage of the charge of electron to process information, whereas magnetic devices take advantage of the spin of electron to record information. Diluted magnetic semiconductors (DMSs) are semiconductors with a fraction of their host lattice replaced by transition metal elements or rare earths. Combining the interesting properties of both magnetic materials and semiconductors, DMSs are expected to play an important role in interdisciplinary materials science and electronics.

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doi:10.1016/j.jcrysgro.2005.02.038

Since the first low-temperature molecular-beam epitaxial growth of III–V based DMS (In,Mn)As [1] and subsequent discovery of ferromagnetism in (In,Mn)As [2] and (Ga,Mn)As [3,4], III–V based DMSs have been extensively studied. The natural property of much lower acceptor level of Mn in GaSb than that in GaAs, doping of GaSb by Mn offers yet another opportunity to investigate the chemical trends of the interaction between transition metal ions and carriers without the use of additional doping [5,6]. While ferromagnetic (In, Mn)As and (Ga,Mn)As exhibit well-defined hysteresis loops, such clear behavior has been elusive in (Ga,Mn)Sb random alloys in which hysteresis loops are very small [7–9]. Furthermore, the Curie temperature T_c is very low (25 K) and has to be improved for practical applications.

In this article, the structure and magnetic properties of room-temperature ferromagnetic semiconductor $Ga_{1-x}Mn_xSb$ prepared by mass-analyzed low-energy dual ion beam implantation apparatus are shown.

2. Material preparation

$Ga_{1-x}Mn_xSb$ samples were prepared by mass-analyzed low-energy dual ion beam implantation apparatus which consists of ion beam systems and vacuum systems. One of its advantages is to purify ions by its magnetic analyzer, with which manganese can be purified as pure as isotope.

First, the Mn ions were uniformly implanted on GaSb (0 0 1) wafers with Mn ion energy of 1000 eV and a dose of 7.5×10^{17} Mn^+/cm^2 at 473 K. Then, the Mn ions with energy of 100 eV and a dose of 3×10^{17} Mn^+/cm^2 were deposited on the surface of the wafer, which formed a thin layer on the $Ga_{1-x}Mn_xSb$ samples. All GaSb substrates were etched and cleaned before the implantation of Mn ions. The purity of Mn used in the growth of $Ga_{1-x}Mn_xSb$ samples was 99.98%. Mn did not need to be etched and cleaned because of the purifying function of the mass-analyzed ion beam implantation apparatus itself. In order to remove the absorbed impurities of the surface of the GaSb substrates, all substrates were bombarded by Argon ion for 10 min before the implantation of Mn ions. After the Mn-ions implantation and deposition, the samples were annealed at 673 K in an argon ambience for 30 min. The thin layer of manganese on the surface of the $Ga_{1-x}Mn_xSb$ samples can prevent the implanted manganese ions from diffusing out of the surface of the wafer, and can keep the content of Mn at a high level near the surface of $Ga_{1-x}Mn_xSb$ samples while annealing.

3. Measurement and analyses

In order to investigate the distribution of Mn ions along the depth, the structure and the magnetic properties of the $Ga_{1-x}Mn_xSb$ epilayers, auger electron spectroscopy (AES), double-crystal X-ray diffraction (DCXRD) and alternating gradient magnetometry (AGM) were employed.

3.1. Compositional analyses

AES was employed for analyzing the surface composition of the $Ga_{1-x}Mn_xSb$ epilayers and their compositional variation along the depth. The AES system used in this experiment is PHI-610/SAM. The AES spectra in Fig. 1 shows that there are manganese, gallium, antimony, carbon and oxygen at the surface of $Ga_{1-x}Mn_xSb$ epilayer. The carbon disappears inside the samples. Fig. 2 is the AES depth profile of the $Ga_{1-x}Mn_xSb$ sample. Although the oxygen is very high at the surface of

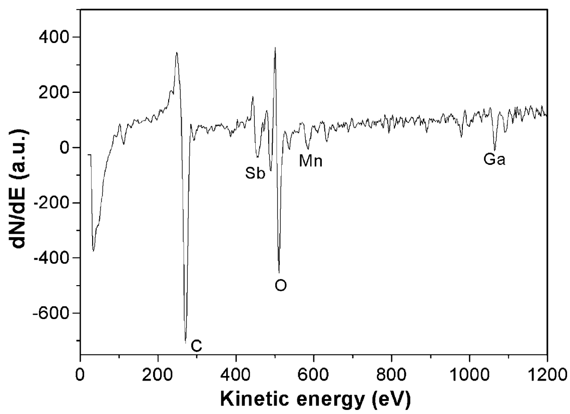

Fig. 1. Auger electron spectroscopy spectra at the surface of $Ga_{1-x}Mn_xSb$ epilayer.

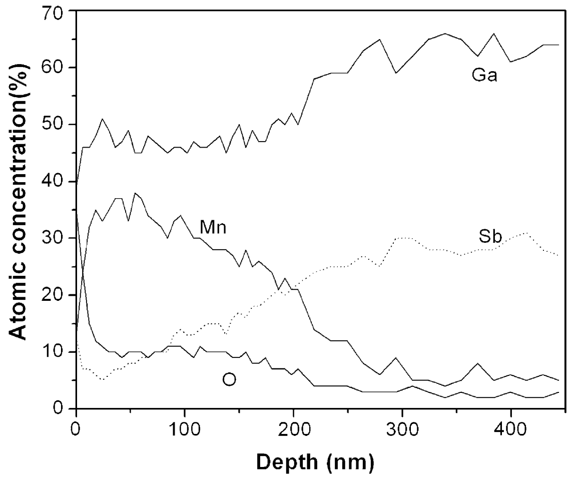

Fig. 2. Auger electron spectroscopy depth profile of $Ga_{1-x}Mn_xSb$ sample.

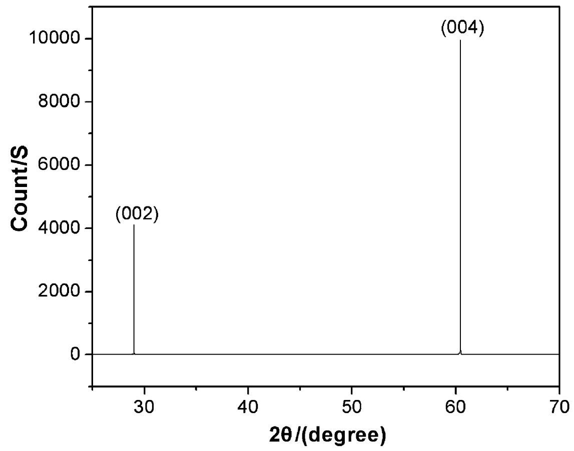

Fig. 3. Double crystal X-ray diffraction spectra of the $Ga_{1-x}Mn_xSb$ sample.

$Ga_{1-x}Mn_xSb$ epilayer, it decreases rapidly along the depth, which was introduced by oxidation of manganese and GaSb after the sample was taken out of the growth chamber.

3.2. Structural analyses

The DCXRD system used in this experiment is Philips X'pert-MRD (X'pert Materials Research Diffractometer System) with a multipurpose sample stage. The wavelength of X-ray radiated from the Cu Kα is 0.1540562 nm. The DCXRD spectra of the samples were measured with $2\theta-\theta$ scan. Fig. 3 shows the DCXRD patterns of the $Ga_{1-x}Mn_xSb$ sample. The two diffraction peaks are corresponding (0 0 2) and (0 0 4) planes of the cubic crystalline $Ga_{1-x}Mn_xSb$, respectively. It indicates that the $Ga_{1-x}Mn_xSb$ epilayer has the zinc-blende structure without detectable second phase.

3.3. Magnetic properties analyses

The magnetic properties of the $Ga_{1-x}Mn_xSb$ samples were studied using AGM. The measurements were carried out at room temperature (293 K). Fig. 4 presents the *M–H* curves (field dependence of magnetization) of $Ga_{1-x}Mn_xSb$ samples. The magnetic field was applied parallel to the sample plane. The diamagnetic contributions from the substrate have been subtracted out of the data. Clear hysteresis loop of the $Ga_{1-x}Mn_xSb$ sample was obtained. The saturation magnetization and residual magnetization, respectively, are 5.12×10^{-6} and 3.34×10^{-6} emu. The coercive force of $Ga_{1-x}Mn_xSb$ is 667.0 Oe. The clear hysteresis-loops indicate that the $Ga_{1-x}Mn_xSb$ sample is ferromagnetic at room temperature.

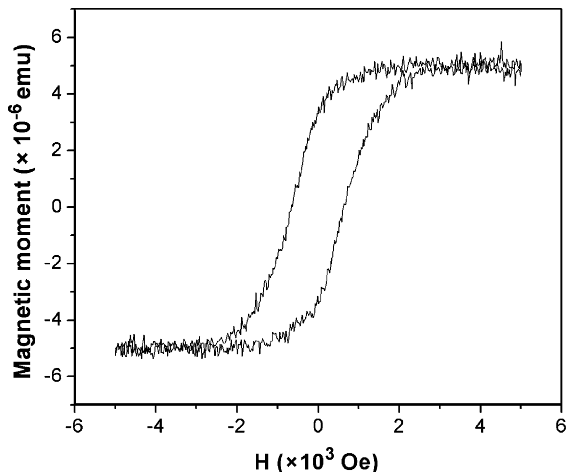

Fig. 4. Typical magnetic hysteresis loop of the $Ga_{1-x}Mn_xSb$ sample measured by AGM. Magnetic field was applied parallel to the sample plane.

4. Summary

Room-temperature ferromagnetic semiconductor $Ga_{1-x}Mn_xSb$ samples were prepared by implanting Mn ions into GaSb wafers in mass-analyzed low-energy dual ion beam implantation system. DCXRD analyses show that the $Ga_{1-x}Mn_xSb$ samples are thermally stable zinc-blende structure without detectable second phase. Clear magnetic hysteresis-loop of the $Ga_{1-x}Mn_xSb$ obtained at room temperature (293 K) with coercivity of about 667.0 Oe indicates that these $Ga_{1-x}Mn_xSb$ single crystals are room-temperature ferromagnetic.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (Grant nos. 60176001, 60390072) and Special Funds for Major State Basic Research Projects of China (Grant no. 2002CB311905).

References

[1] H. Munekata, H. Ohno, S. Von Monlar, A. Segmuller, L.L. Chang, L. Esaki, Phys. Rev. Lett. 63 (1989) 1849.
[2] H. Ohno, H. Munekata, T. Penney, S. VonMolnar, L.L. Chang, Phys. Rev. Lett. 68 (1992) 2664.
[3] H. Ohno, A. Shen, F. Matsukura, A. Oiwa, A. Endo, S. Katsumoto, Y. Iye, Appl. Phys. Lett. 69 (1996) 363.
[4] H. Ohno, Science 281 (1998) 951.
[5] V. Sestakova, P. Hubik, B. Stepanek, J. Kristofik, J. Crystal Growth 132 (1993) 345.
[6] L.P. Krukovskaya, I.F. Mironov, A.N. Titkov, Fiz. Tekh. Poliprovpdn 12 (1978) 689.
[7] F. Matsukura, E. Abe, H. Ohno, J. Appl. Phys. 87 (9) (2000) 6442.
[8] E. Abe, F. Matsukura, H. Yasuda, Y. Ohno, H. Ohno, Physica E 7 (2000) 981.
[9] F. Matsukura, E. Abe, Y. Ohno, H. Ohno, Appl. Surf. Sci. 159–160 (2000) 265.