Transactions of the Materials Research Society of Japan 29[4] 1539-1542 (2004)

Fabrication and magnetoresistance of the diluted magnetic semiconductor (In,Mn)Sb

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Diluted magnetic semiconductor (In,Mn)Sb films were fabricated by doping InSb with Mn, and their magnetic properties and magnetoresistance were investigated. The films were p-type semiconductors that exhibited an anomalous Hall effect and showed carrier-induced magnetism. A sample with 1% Mn concentration had a negative magnetoresistance of 28% at a temperature of 4.2 K.

Key words: diluted magnetic semiconductor, InSb, magnetoresistance, Mn

1.INTRODUCTION

In recent years, materials displaying large magnetoresistance have been extensively investigated with the aim of achieving high-density recording in devices such as hard disk and MRAM. On the other hand, III-V diluted magnetic semiconductors have unique magnetic characteristics. In particular, it has been found that the diluted magnetic semiconductors (In,Mn)As [1] and (Ga,Mn)As [2] become ferromagnetic at low temperature. These materials are made by doping InAs and GaAs - which are important III-V compound semiconductors for electrical device - with Mn as a magnetic element. The ferromagnetism in (In,Mn)As and (Ga,Mn)As originates from carrier-mediated spin exchange between Mn ions, and allows the magnetism to be controlled by changing the carrier density with light irradiation [3][4] or an application of electric field [5]. Although diluted magnetic semiconductors have unique magnetic properties, little has been done for their magnetoresistance. If a large magnetoresistance can be induced in III-V diluted magnetic semiconductors, then it should be possible to produce novel electronic devices with enhanced performance compared to conventional magnetic recording head and MRAM. InSb has the narrowest band gap of all group III–V compound semiconductors, and combines high electron mobility with a large Hall effect and magnetoresistance. This makes it suitable for high-speed devices, high-frequency devices and magnetic sensors. Therefore, with the aim of using diluted magnetic semiconductors in electronic devices that require a high magnetoresistance, we produced various samples of Mn-doped InSb and investigated their magnetic and magnetoresistance properties.

2.FABRICATION OF (In,Mn)Sb FILMS

MBE was used to fabricate (In,Mn)Sb diluted magnetic semiconductor films with structures as shown schematically in Fig. 1. Single-crystal GaAs(001) was used as the substrate. The lattice constants of GaAs and InSb were 5.65 Å and 6.48 Å, respectively. To accommodate this lattice mismatch of 15%, GaAs and GaSb were deposited on the substrates as buffer layers. The lattice constant of GaSb was 6.10 Å, so the lattice mismatches between GaAs and GaSb, and between GaSb and InSb, were 8% and 6%, respectively. The GaAs and GaSb layers were fabricated at substrate temperatures of 580°C and 470°C, and were 300 nm and 500 nm thick, respectively. In order to fabricate sample A, a 200 nm layer of $In_{0.99}Mn_{0.01}Sb$ was deposited on the GaSb/GaAs/GaAs(001) structure at a substrate temperature of 235°C. The Mn concentration was controlled by adjusting the Mn and Sb beam flux.

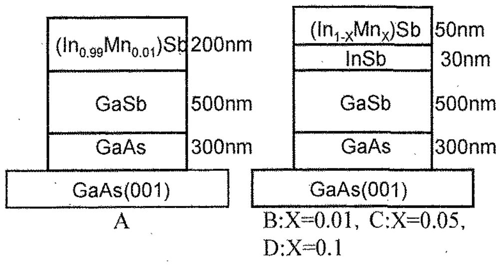

Fig.1 Schematic structures of fabricated (In,Mn)Sb films

Samples B, C and D, with higher Mn concentrations, were then produced. As the mismatch between GaSb and InSb was 6%, a layer of InSb was deposited on the GaSb/GaAs/GaAs(001) structure as a buffer. The InSb layer was 30 nm thick and was deposited at a substrate temperature of 320°C. The Mn concentration of the (In,Mn)Sb layer was successfully increased by reducing the substrate temperature to 150°C.

A SQUID magnetometer was used to measure the magnetic properties of the samples at temperatures ranging from 4.2 K to 300 K, and the magnetoresistance was measured at 4.2 K in an applied magnetic field of 5 T. The transport properties—carrier type, density and mobility—were calculated from measurements of the Hall effect at 300 K in a magnetic field of 0.3 T.

3.RESULTS AND DISCUSSION

3-1. Sample A

Fig. 2 shows the reflection high-energy electron diffraction (RHEED) pattern of sample A measured during fabrication. The presence of a pattern (1x3) of well-defined streaks confirmed that a smooth film had been formed. Fig. 3 shows the secondary ion mass spectrometry (SIMS) profile of the (In,Mn)Sb thin film in the direction perpendicular to the surface. The constituent ratios of In, Mn and Sb were uniform across the thickness of the film, showing that sample A was homogeneous.

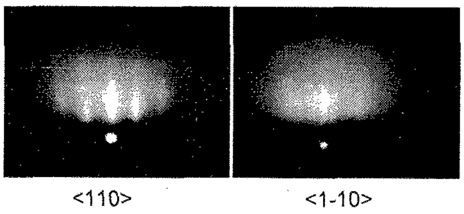

Fig.2 RHEED patterns of Sample A ($In_{0.99}Mn_{0.01}$)Sb

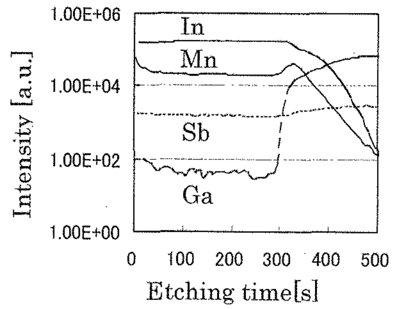

Fig.3 SIMS profile of Sample A ($In_{0.99}Mn_{0.01}$)Sb

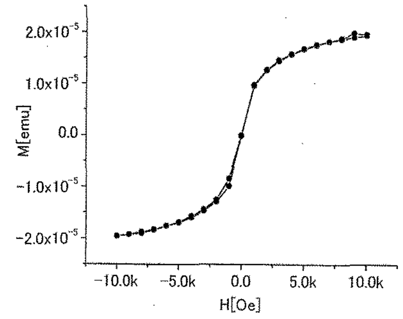

Fig.4 M-H loop of Sample A ($In_{0.99}Mn_{0.01}$)Sb at 4.2K

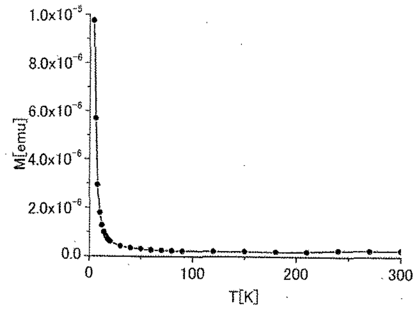

Fig.5 Temperature dependence of magnetization of Sample A ($In_{0.99}Mn_{0.01}$)Sb

Next, we measured the magnetic properties of sample A. Fig. 4 shows the magnetization versus applied field loop measured at 4.2 K, and Fig. 5 shows the temperature dependence of the magnetization between 4.2 K and 300 K. It is clear from Fig. 4 that sample A was paramagnetic at 4.2 K, and Fig. 5 shows that it became non-magnetic at 10 K and above. The direction of the magnetic anisotropy of the sample was in-plane.

Table1 Transfer properties of Sample A

Carrier type	P
Carrier density[cm^{-3}]	1.80×10^{20}
Mobility[cm/V^2S]	56.0
Hall efficient[Ω/T]	0.173

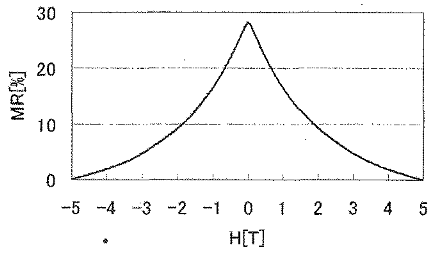

Fig.6 MR loop of Sample A at 4.2K

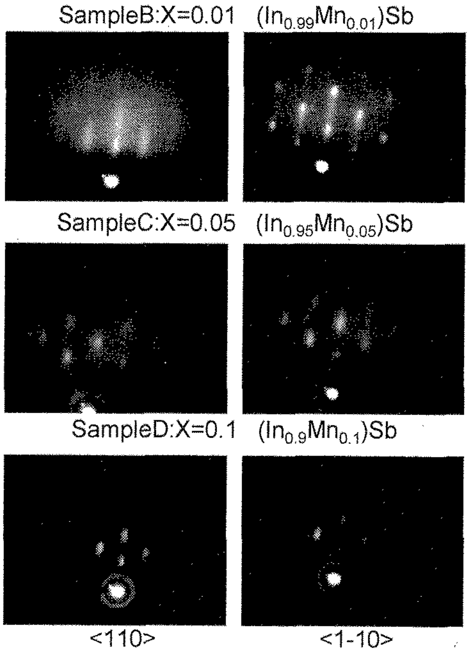

Fig.7 RHEED patterns of Sample B,C, and D

Studies of other diluted magnetic semiconductors have shown that (In,Mn)As is a perpendicular magnetic film[1] because it is subjected to tensile stress, whereas (Ga,Mn)As is an in-plane magnetic film[2] because it is subjected to compressive stress. As (In,Mn)Sb had a larger lattice constant than GaSb, the (In,Mn)Sb film was subjected to compressive stress, which is thought to explain why it formed an in-plane magnetic film. Table 1 shows the transport properties calculated from the results of Hall-effect measurements at 300 K. Undoped InSb is an n-type semiconductor, but it changed to p-type on doping with Mn. (In,Mn)As and (Ga,Mn)As are also known to be p-type semiconductors, which is characteristic of diluted magnetic semiconductors. The carrier density of the holes was 1.8×10^{20} cm^{-3}, and their mobility was 56 cm^2/Vs. Fig. 6 shows the magnetoresistance (MR) curve at 4.2 K. In a magnetic field of 5 T, the sample exhibited a negative magnetoresistance of 28%. By contrast, undoped InSb had a large positive magnetoresistance. Therefore, the negative magnetoresistance originated from carrier-induced magnetism as a result of doping with the magnetic element Mn.

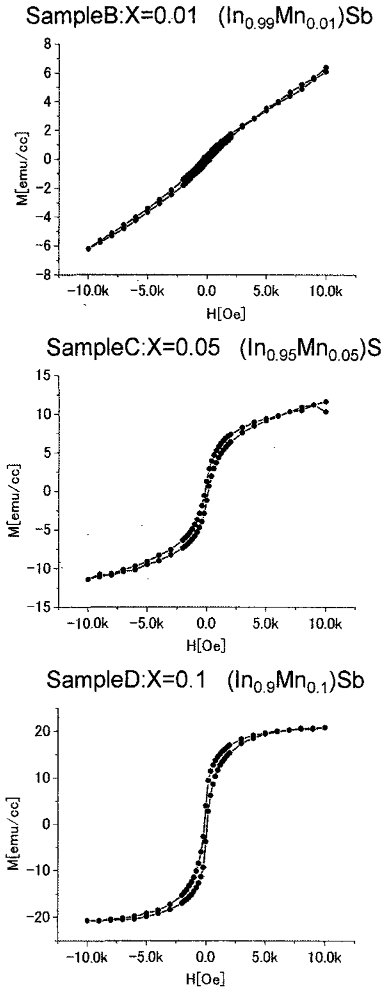

Fig.8 M-H loops of Sample B,C, and D at 4.2K

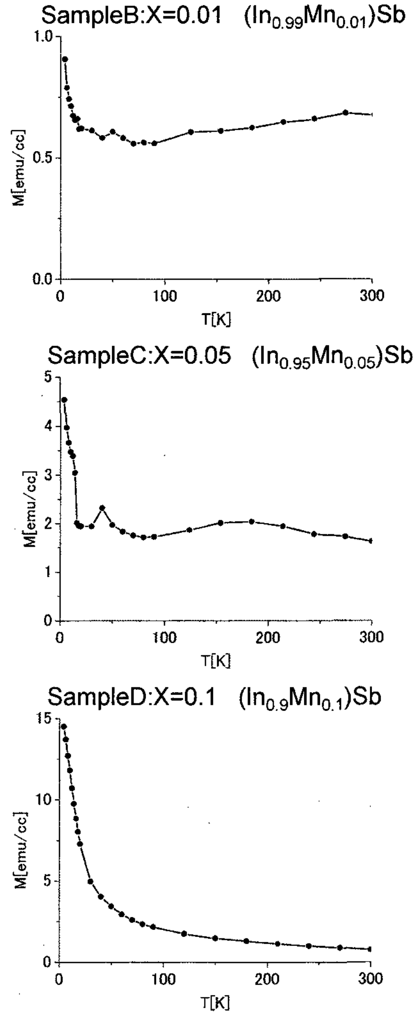

Fig.9 Temperature dependence of magnetization of Sample B,C, and D

3-2 Samples B, C and D

Samples B, C and D were fabricated with higher Mn concentrations. Their RHEED patterns are shown in Fig. 7. These patterns initially showed streaks, which gradually turned into spots as the deposition process progressed, but did not form halos. Fig. 8 shows the M-H loops measured at 4.2 K, and Fig. 9 shows the temperature dependence of the magnetization between 4.2 K and 300 K. Fig. 8 reveals that sample B with 1% Mn was paramagnetic, whereas the M-H loop of sample D with 10% Mn exhibited hysteresis, indicating that sample D was ferromagnetic. Fig. 9 shows that the magnetization of sample D was non-zero even at 300 K, probably as a result of the formation of ferromagnetic impurities such as MnSb. However, the sharp rise in magnetization at low temperatures was caused by carriers introduced through the addition of Mn. Table 2 shows the transport properties obtained from the results of the Hall-effect measurements at 300 K. Similar to sample A, all of these samples were p-type semiconductors. However, the carrier densities were of the order of 10^{19} cm^{-3}, which was an order of magnitude lower than that of sample A. Also, the largest carrier density was obtained with an Mn content of 5%. This was probably because the InSb buffer layer was an n-type semiconductor, and the conduction of the p-type (In,Mn)Sb layer was superimposed on the conduction of the n-type InSb layer. In Fig. 9, the carriers introduced by Mn-doping are responsible for the sharp rise in magnetization observed at low temperature. Although samples B and C had non-zero magnetization at 300 K, this is because the magnetization of the substrate is superimposed on that of InMnSb. For sample D, the magnetization continued to decrease gradually as the measurement temperature increased, probably due to the presence of ferromagnetic impurity compounds such as MnSb. The magnetization and carrier density at 300K were greatest for sample C. This is because the number of Mn hole carriers increases, the magnetization becomes stronger and the MR ratio is also enhanced as the Mn concentration increases from 1% to 5%. However, at a concentration of 10% there is an excess of Mn and impurity compounds such as MnSb are formed. Fig. 10 shows the MR curves at 4.2 K. With an Mn content of 1% the magnetoresistance was positive. However, a slight increase was observed in the vicinity of zero magnetic field, and the curve appeared to be formed from the combination of a positive and a negative magnetoresistance component. In similar fashion to the carrier density as described above, this was probably due to the large, positive magnetoresistance possessed by the InSb buffer layer being superimposed on that of InMnSb. By taking into account the positive magnetoresistance of the InSb layer, it is estimated that the MR ratios of InMnSb layers with

Mn concentrations of 5% and 10% are greater than 15% and 10%, respectively. However, in order to obtain the true MR ratio it will be necessary to develop a method for fabricating a high quality (In,Mn)Sb layer without an InSb buffer layer.

Table2 Transfer properties of $(In_{1-X}Mn_X)Sb$ films

Sample Name	B	C	D
Mn concentration X	0.01	0.05	0.1
Carrier type	P	P	P
Carrier density[$10^{19}cm^{-3}$]	2.39	5.22	3.34
Mobility[cm/V^2S]	51.6	88.2	98.0
Hall efficient[Ω/T]	5.38	2.39	3.74

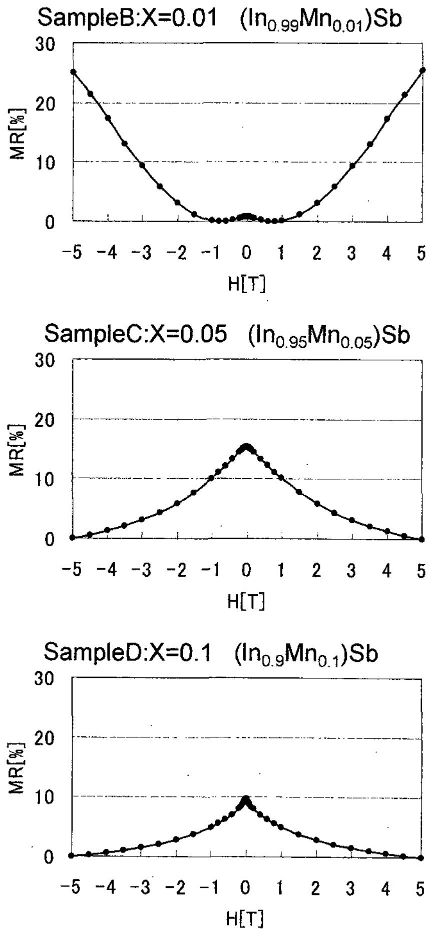

Fig.10 MR loops of Sample B,C and D at 4.2K

4.CONCLUSION

Diluted magnetic semiconductor (In,Mn)Sb films were fabricated, and their magnetic properties and magnetoresistance are summarized below.

The structure $(In_{0.99}Mn_{0.01})Sb/GaSb/GaAs/GaAs(001)$, with no InSb buffer layer, constituted an in-plane magnetic film that exhibited carrier-induced paramagnetism at temperatures of 10 K and below. This structure had a negative MR ratio of 28% at 4.2 K in an applied magnetic field of 5 T. The magnetoresistance originated from the carrier-induced magnetization that was caused by doping with Mn. To increase the Mn concentration, the substrate temperature had to be reduced to 150°C, and an InSb buffer layer was deposited between the (In,Mn)Sb and GaSb layers. These samples also exhibited carrier-induced magnetism. Over the range of Mn concentrations from 1% to 5%, the magnetization, carrier density and MR ratio increased with Mn concentration, but the corresponding values were lower in the samples with an Mn concentration of 10% due to the formation of impurity compounds such as MnSb. The maximum MR ratio measured for these samples was only 15% due to the electrical conductivity of the InSb layer being superimposed on the results for (In,Mn)Sb. In order to ascertain the true MR ratio of the (In,Mn)Sb layer it will be necessary to develop a method for the production of high quality (In,Mn)Sb layers without InSb buffer layers.

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(Received October 8, 2003; Accepted March 31, 2004)