Available online at www.sciencedirect.com
SCIENCE DIRECT®
Journal of Magnetism and Magnetic Materials 300 (2006) e16–e19
Journal of magnetism and magnetic materials
www.elsevier.com/locate/jmmm

Transport and magnetotransport properties of Mn-doped $In_xGa_{1-x}As/GaAs$ quantum well structures

V.A. Kulbachinskii[a,*], R.A. Lunin[a], P.V. Gurin[a], B.A. Aronzon[b], A.B. Davydov[b], V.V. Rylkov[b], Yu.A. Danilov[c], O.V. Vikhrova[c], B.N. Zvonkov[c]

[a]M.V. Lomonosov Moscow State University, Low Temperature Physics Department, 119992 GSP-2, Moscow, Russia
[b]Russian Research Center "Kurchatov Institute", 123182 Moscow, Russia
[c]Physico-Technical Research Institute, University of Nizhny Novgorod, 603950 Nizhny-Novgorod, Russia

Available online 17 November 2005

Abstract

We report on the transport, magnetotransport and magnetic properties of $In_{0.17}Ga_{0.83}As$ quantum well in GaAs δ-doped by Mn. At low temperatures, the anomalous Hall effect was observed which detects the spin-polarized carriers. Negative magnetoresistance was found at low temperatures, which became positive at high temperature.

PACS: 72.20.−i; 75.50.Gg

Keywords: Ferromagnetism; (Ga; Mn)As; Anomalous Hall effect; Magnetoresistance

1. Introduction

The task to get the spin-polarized carriers in the conducting channel is one of the important goals of the new field of microelectronics, namely spintronics. Spintronics, or spin electronics, involves the study of active control and manipulation of spin degrees of freedom in solid-state systems. Spin transport differs from charge transport because spin is a nonconserved quantity in solids due to spin–orbit and hyperfine coupling. Diluted magnetic semiconductors (DMS) are very perspective materials for spintronics. III–V-based low-dimensional DMS (Ga,Mn)As and (In, Mn)As showed carrier-mediated ferromagnetism [1,2]. Mn in such materials plays two roles: (i) it is responsible for magnetic properties and (ii) it is an acceptor. Mainly studies of DMS properties were performed on grown with MBE thin solid films, which are a bulk material.

Contrary to that, numbers of publications on studies of 2D structures are relatively low. We would like to note Ref. [3], where 2D heterostructure GaAs/AlGaAs δ-doped by Mn showed Curie temperature T_c about 172 K, which is higher than that observed in GaMnAs films ($T_c = 160$ K [4]). Currently [5], the highest T_c in GaMnAs is 173 K, which seems to be at least equal to that in δ-doped structures.

In this paper, we focused on transport and magnetotransport properties of $In_xGa_{1-x}As/GaAs$ quantum well δ-doped by Mn with *p*-type 2D conductivity. Such structures are not well investigated but have generated intense interest because they open the prospect of developing devices, which combine, for example, information processing and storage functionalities in one material.

2. Experimental

All samples were prepared with metal-organic compound-hydride epitaxy method. The method of fabrication of these structures has been published previously [6]. Samples contain $In_xGa_{1-x}As$ quantum well ($x \approx 0.17$) with width 10 nm, carbon δ-layer (to provide p-type conductivity in the quantum well) and laser-deposited Mn layer separated by GaAs spacer with width $d = 3$ nm. A schematic diagram of the structure is shown in Fig. 1. Buffer layer and spacer

*Corresponding author. Tel.: +7 095 939 1147; fax: +7 095 932 8876.
E-mail address: kulb@mig.phys.msu.ru (V.A. Kulbachinskii).

0304-8853/$ - see front matter © 2005 Elsevier B.V. All rights reserved.
doi:10.1016/j.jmmm.2005.10.139

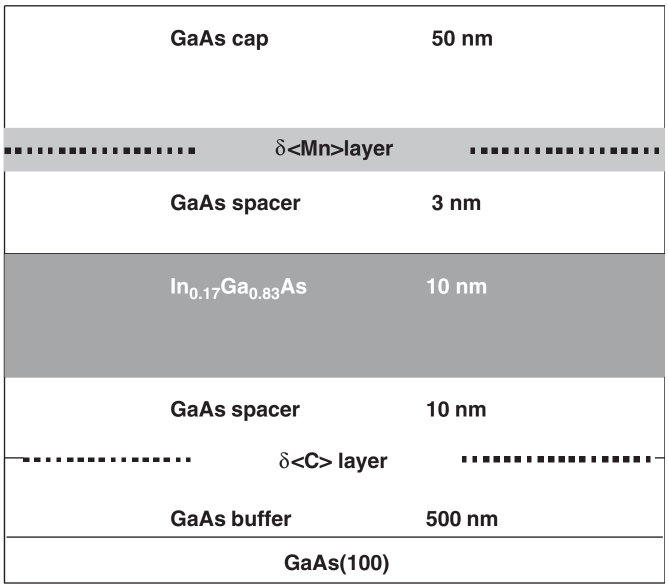

Fig. 1. Schematic diagram of the structure.

Table 1
Fraction of Mn, Hall density p, Hall mobility μ at $T = 300\,\mathrm{K}$

Sample number	Mn fraction (a.u.)	p, $10^{12}\,\mathrm{cm}^{-2}$	μ, $\mathrm{cm}^2/\mathrm{V\,s}$
415	0.0	1.8	320
419	1.0	3.4	230
420	2.0	5.6	170
417	2.8	6.7	160
421	4.0	7.9	140

were grown at $T = 600\,°\mathrm{C}$, while the deposition of Mn was carried out at $T = 450\,°\mathrm{C}$.

The Mn concentration controlled by duration time of Mn laser deposition ranged in the interval 6–24 s, resulting in Mn layer deposition up to 1 ML. Thus Mn concentration was different in the samples. Dependence of resistance on temperature was measured from 300 K down to 4.2 K, magnetoresistance and Hall effect for $4.2 \leqslant T \leqslant 77\,\mathrm{K}$ in magnetic fields up to 6 T. Samples were fabricated by photolithography as double Hall bridges with length $L = 1.4\,\mathrm{mm}$ and width of the channel $W = 0.23\,\mathrm{mm}$. Some parameters of the samples are listed in Table 1.

3. Results and discussions

At $T > 77\,\mathrm{K}$, all structures except the sample 415 without Mn δ-layer showed the metallic type of the temperature dependence of resistance R_{xx} (Fig. 2).

At $T < 77\,\mathrm{K}$, the character of $R(T)$ depends on Mn concentration. In the temperature interval 15–30 K there is a kink, which is a characteristic of the ferromagnetic transition [1,7]. At $T < T_c$ the spin flip scattering disappears [8], mobility increases and resistance decreases. This effect

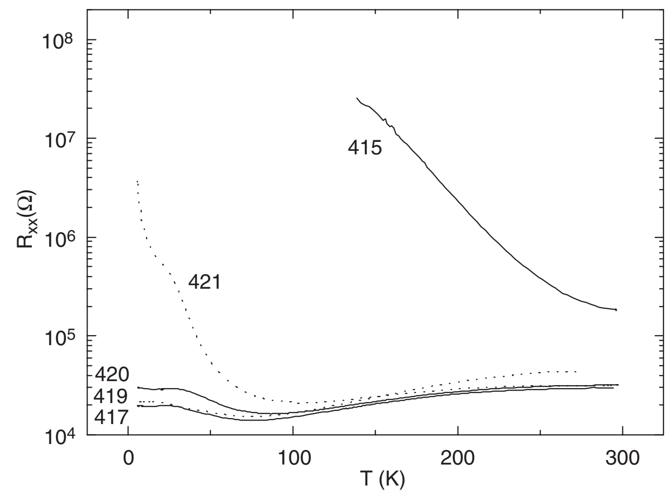

Fig. 2. Temperature dependence of resistance for all samples.

results in a kink for an activation type of the experimental dependence of $R_{xx}(T)$ as we have observed.

One of the methods to detect the spin-polarized carriers is the anomalous Hall effect. It is known that in magnetic materials the Hall field E_H is formed from two components, see e.g. Ref. [9]

$$E_H = R_0 B j_x + R_a \mu_0 M j_x,$$

where B is magnetic induction, M is magnetization, j_x is current density, R_0 is a normal Hall effect coefficient caused by action of Lorentz force, and R_a is coefficient of anomalous Hall effect due to asymmetry of scattering of spin-polarized carriers due to spin–orbital interaction.

In investigated structures anomalous Hall effect appears at the same temperature, as a kink in the temperature dependence of resistance. The temperature at which anomalous Hall effect was observed is slightly above a supposed Curie temperature (areas of a kink in the temperature dependence of resistance). The similar results were observed in other research groups and for other materials, in particular for single-phase solid solution $Ga_{1-x}Mn_xAs$. It was shown in Ref. [10] that the anomalous Hall effect can be observed not only at low temperatures at the ferromagnetic state, but also above the Curie temperature, in a paramagnetic state. It is natural that in the latter case anomalous Hall effect is manifested very weak, because the magnetic susceptibility of a semiconductor matrix defining magnetization of the sample decreases with increasing temperature [10].

Contribution of the anomalous Hall effect to the Hall voltage has been observed in samples with high Mn concentration. We shall note, however, that anomalous Hall effect is visible only in samples with activation dependence of conductivity on temperature. The magnetic field dependence of the Hall resistance shown in Fig. 3 is similar to the anomalous Hall effect in Mn-containing layers based on GaSb and GaAs [10,11], in which the contribution from anomalous Hall effect is observed. We

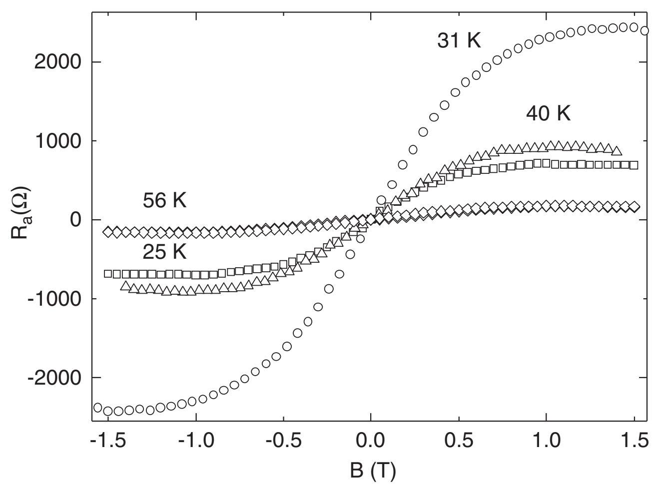

Fig. 3. Anomalous Hall effect for sample 421 at different temperatures.

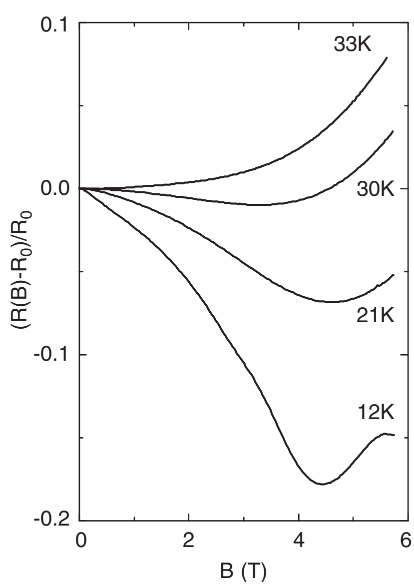

Fig. 4. Relative magnetoresistance of sample 419 at different temperatures. R_0 is resistance in zero magnetic field.

would like to note, however, that the structures studied in Refs. [11,12] have the manganese concentration, which essentially exceeds the critical value corresponding to the metal–insulator transition. In our case the situation is different. Anomalous Hall effect is observed simultaneously with an activation type of the temperature dependence of conductivity. Let us also note that signs of the normal Hall effect and the anomalous Hall effect coincide (positive), as well as in the case of samples $Ga_{1-x}Mn_xAs$ with much higher concentration of Mn [12].

Magnetoresistance in all Mn-doped samples is changed from negative to positive when temperature increases. As an example, magnetoresistance of sample 419 is shown in Fig. 4.

In the temperature interval 4.2–30 K negative magnetoresistance is observed, transferring to the positive magnetoresistance in magnetic field $B > 4$ T. At temperatures above 30 K, only positive magnetoresistance is observed up to 6 T. Complicated dependence of magnetoresistance on magnetic field may be explained by both quantum corrections to conductivity and the spin-dependent scattering of carriers.

The quantum interference phenomena play an essential role in the investigated structures. They were observed in the temperature dependence of conductivity. They specify an essential role of the disorder in the formation of transport properties of the structures. The role of the magnetic disorder or spin-dependent scattering seems essential because the kink in the temperature dependence of resistance (see Fig. 2) and the anomalous Hall effect (see Fig. 3) were observed.

In our opinion, the observed experimental facts testify that the presence of the fluctuation potential in the 2D channel (quantum well) of the structures, caused by nonuniform distribution of the Mn ions, plays a significant role in the transport and magnetotransport phenomena in the investigated structures. As Mn is an acceptor, and carriers in the channel are holes, maximal local concentration of Mn corresponds to the minimum of a potential relief. In this case carriers in the channel move not in a uniform 2D layer, but in the areas of a maximal hole concentration corresponding to the maximal concentration of Mn in which a maximal concentration of the magnetic moment (ions of Mn) is realized. Thus, the increase in concentration of Mn leads to strengthening of the magnetic properties and in the formation of the areas with a higher hole concentration in the quantum well. The disorder and the amplitude of fluctuation potential are increased. As a result, the anomalous Hall effect is observed. There are two main reasons for this: (i) increase of the concentration of magnetic ions (Mn) in general; (ii) increase in local concentration of Mn is the most preferable for current areas.

4. Conclusion

In conclusion, we demonstrated the opportunity to observe effects due to spin polarization of carriers caused by magnetic disorder in the conducting channel in 2D semiconductor structures based on InGaAs quantum well δ-doped by Mn.

Acknowledgements

The work was supported by RFBR, Grants 04-02-19964a, 05-02-16624a, 05-02-17021a and 05-02-17029a.

References

[1] H. Ohno, Science 291 (2001) 840.
[2] H. Ohno, Science 281 (1998) 951.
[3] A.M. Nazmul, S. Sugahara, M. Tanaka, Phys. Rev. B 67 (2003) 241308.

[4] K.W. Edmonds, P. Bogusławski, K.Y. Wang, R.P. Campion, S.N. Novikov, N.R.S. Farley, B.L. Gallagher, C.T. Foxon, M. Sawicki, T. Dietl, M. Buongiorno Nardelli, J. Bernholc, Phys. Rev. Lett. 92 (2004) 037201.
[5] K.Y. Wang, R.P. Campion, K.W. Edmonds, M. Sawicki, T. Dietl1, C.T. Foxon, B.L. Gallagher, Cond-mat/0411475, November 2004.
[6] Yu.V. Vasil'eva, Yu.A. Danilov, AntA. Ershov, B.N. Zvonkov, E.A. Uskova, A.B. Davydov, B.A. Aronzon, S.V. Gudenko, V.V. Ryl'kov, A.B. Granovsky, E.A. Gan'shina, N.S. Perov, A.N. Vinogradov, FTP 39 (2005) 87;
Yu.V. Vasilieva, Yu.N. Danilov, S. AntA. Ershov, B.N. Zvonkov, E.A. Uskova, A.B. Davydov, B.A. Aronzon, S.V. Gudenko, V.V. Rul'kov, A.B. Granovskiy, E.A. Gan'shina, N.S. Perov, E.N. Vinogradov, Semiconductors 39 (2005) 77.
[7] V.A. Kulbachinskii, A.Yu. Kaminskii, K. Kindo, E. Narumi, K. Suga, P. Lostak, G. Svanda, Pisma ZETF 73 (2001) 396;
V.A. Kulbachinskii, A.Yu. Kaminskii, K. Kindo, E. Narumi, K. Suga, P. Lostak, G. Svanda, JETP Lett. 73 (2001) 352.
[8] M.N. Baibich, J.M. Broto, A. Fert, Nguyen Van Dau, F. Petroff, P. Eitenne, G. Crenzet, A. Friederich, J. Chazelas, Phys. Rev. Lett. 61 (1988) 2472.
[9] C.L. Chien, C.R. Westgate, in: The Hall Effect and its Applications, Plenum Press, New York, 1980
A.V. Vedyaev, A.B. Granovskiy, J.A. Kotel'nikova, Kinetic phenomena in disordered ferromagnetic alloys, Moscow, MSU, 1992 (in Russian).
[10] H. Ohno, F. Matsukura, Solid State Commun. 117 (2001) 179.
[11] X. Chen, M. Na, M. Cheon, S. Wang, H. Luo, B.D. McCombe, X. Liu, Y. Sasaki, T. Wojtowicz, J.K. Furdyna, S.J. Potashnik, P. Schiffer, Appl. Phys. Lett. 81 (2002) 511.
[12] K.W. Edmonds, R.P. Campion, K.-Y. Wang, A.C. Neumann, B.L. Gallagher, C.T. Foxon, P.C. Main, J. Appl. Phys. 93 (2003) 6787.