ISSN 1063-7834, Physics of the Solid State, 2016, Vol. 58, No. 11, pp. 2240–2243. © Pleiades Publishing, Ltd., 2016.
Original Russian Text © A.M. Lugovykh, T.B. Charikova, V.I. Okulov, K.D. Moiseev, Yu.A. Kudryavtsev, 2016, published in Fizika Tverdogo Tela, 2016, Vol. 58, No. 11, pp. 2160–2163.

MAGNETISM

Charge Transfer Features and Ferromagnetic Order in Semiconductor Heterostructures δ-Doped with Manganese

A. M. Lugovykh[a], T. B. Charikova[a, b, *], V. I. Okulov[a, b], K. D. Moiseev[c], and Yu. A. Kudryavtsev[d]

[a] *Mikheev Institute of Metal Physics, Ural Branch of the Russian Academy of Sciences, ul. S. Kovalevskoi 18, Yekaterinburg, 620990 Russia*

[b] *Institute of Natural Sciences, Ural Federal University after the first President of Russia B.N. Yeltsin, pr. Lenina 51, Yekaterinburg, 620000 Russia*

[c] *Ioffe Institute, Russian Academy of Sciences, ul. Politekhnicheskaya 26, St. Petersburg, 194021 Russia*

[d] *National Polytechnical Institute, (Cinvestav-IPN), Avenida IPN 2508, Colonia Zacatenco, Mexico City, 07360 Mexico*

**e-mail: charikova@imp.uran.ru*

Abstract—The temperature and field dependences of the specific magnetization and magnetoresistance in heterostructures with a $GaAs/Ga_{0.84}In_{0.16}As/GaAs$ quantum well and a δ-layer of atomic Mn in the barrier layer near the quantum well filled with holes are studied. A change in the resistance and magnetization behavior upon ordering of localized magnetic moments in the cap layer due to a change in the manganese ion distribution topology is detected.

DOI: 10.1134/S1063783416110226

1. INTRODUCTION

In the last decade, great interest has been paid to spintronic devices, which has caused new physical and technological approaches to fabrication of semiconductor magnetic heterostructures. Unique physical properties of semiconductor heterostructures based on $A^{III}B^{V}$ compounds with a transition element impurity demonstrate wider prospects in applications for spintronics than ferromagnetic metals, which is explained by the ferromagnetism controllability in them by electric fields [1–3]. So far, most studies of spin-electronic materials have been associated with the properties of magnetic diluted alloys such as InMnAs, GaMnAs, and GaInMnAsSb [4–6] and heterostructures with a InGaAs/GaAs quantum well and a thin manganese layer inserted in one of the GaAs barriers, fabricated by a combined method of hybrid metal-organic vapor-phase epitaxy (MOVPE) and laser deposition [7]. Molecular-beam epitaxy (MBE) has significant advantages in the growth technology in comparison with other epitaxial methods, which makes it possible to fabricate ferromagnet/semiconductor heterostructures where a magnetic layer with strong doping profile, placed into a semiconductor alloy, is atomically scaled. If the dopant distribution is restricted to one of several atomic monolayers (MLs), the doping profile can be described by the Dirac δ-function. Such a layer can provide a high dopant concentration created in a limited space within the width comparable to the matrix material lattice constant. Recently, it was shown that the introduction of the δ-layer of Mn magnetic impurity into the GaAs matrix near a *p*-type channel with a high carrier concentration, formed at the *p*-GaAs/*p*-AlGaAs heterointerface, provided the ferromagnetic order formation among manganese spins [8]. At the same time, luminescence properties of the spin-oriented system can be detected using heterostructures with a type-I quantum well (QW) instead of a single heterojunction with a 2D hole channel at the heterointerface. In this paper, we consider the transport and magnetic properties of heterostructures grown by MBE, with a single GaAs/InGaAs/GaAs quantum well containing a GaAs barrier layer doped using a δ-layer of atomic manganese, distant from the InGaAs/GaAs heteroboundary.

2. TECHNIQUE FOR FABRICATING HETEROSTRUCTURES AND EXPERIMENTAL METHODS

Heterostructures containing a single $GaAs/Ga_{0.84}In_{0.16}As/GaAs$ quantum well were grown on a single-crystal GaAs(001) substrate by MBE. The QW width was 5 nm. Epitaxial growth was performed in a single technological process in a Riber C21 growth chamber in the temperature range of 250–600°C. Two sample types were chosen for studies. In sample *A*, one of the barrier layers was doped with manganese during growth to a concentration of 10^{21} cm^{-3}, while sample *B* contained a GaAs barrier layer with an inserted atomic Mn layer spaced from the InGaAs/GaAs heteroboundary by 3 nm (Fig. 1). The manganese layer thickness of 1.2 monolayers (MLs) was chosen for reasons of not violating the heterostructure structural quality. Another GaAs barrier layer was doped with Be to provide quantum well filling with holes. As a result, two channels of spin-dependent carriers (the hole-enriched quantum well and the delta-layer of ferromagnetic impurity) arranged close to each other simultaneously exist in the heterostructure.

The temperature and field dependences of the resistivity were measured under direct current by the four-probe method in the temperature range $T = 1.8$–300 K using a setup for measuring galvanomagnetic effects at the laboratory of semiconductors and semimetals and a PPMS-9 setup at the shared service center "Testing Center of Nanotechnologies and Promising Materials" (Institute of Metal Physics). Contacts for all samples were prepared by wet etching using a photolithographic alignment setup. The field and temperature dependences of the specific magnetization were studied in the temperature range $T = 1.8$–300 K in magnetic fields to $H = \pm 50$ kOe using a SQUID magnetometer at the shared service center "Testing Center of Nanotechnologies and Promising Materials."

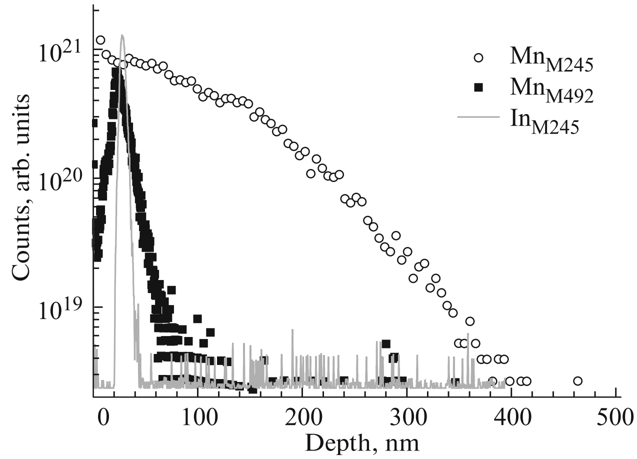

Fig. 1. Experimental manganese distribution profiles in sample *A* (open circles) and sample *B* (closed squares) in the epitaxial growth direction, measured by secondary ion mass spectrometry (SIMS) using a Cameca ims-6f ion microprobe. The gray solid curve is the indium distribution profile, i.e., the GaAs/InGaAs/GaAs quantum well profile. The horizontal axis zero corresponds to the air/sample surface interface.

3. EXPERIMENTAL RESULTS AND DISCUSSION

When introducing manganese into the GaAs barrier layer immediately during the epitaxial growth, impurity atoms are statistically distributed in the deposited layer bulk; furthermore, they penetrate deep into the semiconductor matrix to a significant distance due to diffusion (see Fig. 1, sample *A*). At the initial doping level of ~8×10^{20} cm^{-3} in the cap barrier, the impurity concentration of 6×10^{20} cm^{-3} is retained in the quantum well neighborhood (to 50 nm). As a result, the quantum well is in the GaAs semiconductor matrix doped with manganese. In the case of the atomic Mn δ-layer introduction into the GaAs barrier layer (sample *B*), the magnetic impurity is localized in a narrow space comparable with the matrix lattice constant, and its diffusion to the heterostructure depth is essentially bounded. Distribution "tails" in the SIMS profiles, caused most likely by the knock-on effect [9], i.e., manganese atom penetration into the quantum well, can be excluded at the 3-nm GaAs buffer layer separating the Mn δ-layer from the GaAs/InGaAs/GaAs quantum well. Thus, two systems with semimetallic conductivity, connected in parallel by current, were formed in sample *B*, and the heterostructure under study exhibits metallic conductivity (Fig. 2). In this case, the two-dimensional quantum well is the main current flow path.

A deviation from linearity is observed (Fig. 2a) in the dependence $R_{XX}(H)$ in a magnetic field H = 3.7 kOe at $T = 1.8$ K, which confirms the assumption about magnetic ordering and leads to an increase in the longitudinal conductance in low magnetic fields. In the dependences of the Hall resistance $R_{XY}(H)$, we observe only the linear field dependence and a decrease in the resistance in magnitude with increasing temperature (Fig. 2b). An analysis of $R_{XX}(H)$ and $R_{XY}(H)$ made it possible to determine the field dependences of the hole mobility in the GaAs : Be/$Ga_{0.84}In_{0.16}As$/GaAs/δ-Mn/GaAs heterostructure with δ-layer 1.2 ML thick. It was found that the hole mobility and concentration in the temperature range $T = 1.8$–77 K are almost unchanged as the magnetic field varies to $H = 50$ kOe. In the field $H = 50$ kOe, the hole concentration was $p \approx 7 \times 10^{13}$ cm^{-2}, and the mobility was $\mu \approx 65$ cm^2/V s. For comparison, in the GaAs/$Ga_{0.84}In_{0.16}As$/Ga(Mn)As heterostructure, the hole concentration at $T = 100$ K was $p \approx 1.6 \times 10^{11}$ cm^{-2}, which is one hundred times lower than that of the heterostructure with a manganese δ-layer. Hence, localization of impurity atoms distributed in the GaAs matrix bulk in the range of several nanometers makes it possible to increase the hole concentration by two orders of magnitude.

As was shown previously, the ferromagnetic order cannot be implemented in heterostructures doped with Mn δ-layers due to the absence of a sufficient concentration in the hole system [10]. The appearance of the two-dimensional *p*-type channel due to quantum well filling with holes from the GaAs barrier

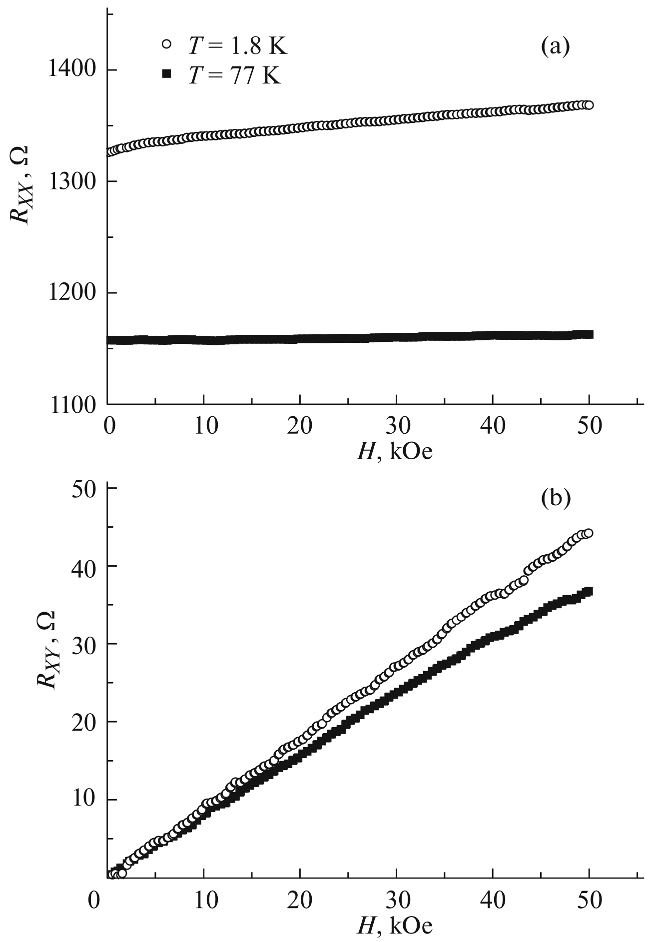

Fig. 2. Dependences of the (a) longitudinal and (b) Hall resistances on the external magnetic field of the GaAs : Be/$Ga_{0.84}In_{0.16}As$/GaAs/δ-Mn/GaAs heterostructure with a δ-layer 1.2 ML thick at $T = 1.8$ K (open circles) and $T = 77$ K (closed squares).

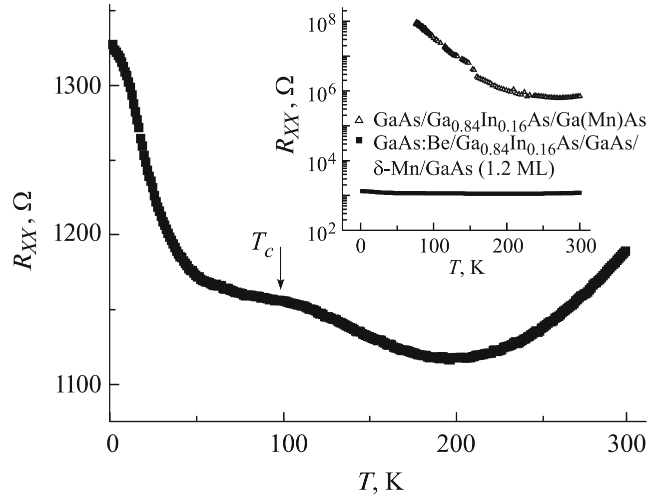

Fig. 3. Temperature dependence of the longitudinal resistance in the GaAs/$Ga_{0.84}In_{0.16}$As/GaAs/δ-Mn/GaAs heterostructure doped with a manganese δ-layer 1.2 ML thick. The inset shows the dependences $R_{XX}(T)$ for heterostructures with a Ga(Mn)As layer (open triangles) and a manganese δ-layer (closed squares).

doped with nonmagnetic Be impurity will make it possible to form the ferromagnetic order due to overlapping wave functions of the two-dimensional hole gas and the spin-oriented system of the atomic manganese δ-layer.

For the heterostructures under study, a change in the temperature dependence of the longitudinal resistance was observed. For the GaAs/$Ga_{0.84}In_{0.16}$As/Ga(Mn)As heterostructure there is, there is the activation dependence $R(T) \sim \exp(\Delta E/kT)$ with an activation energy $\Delta E \approx 50$ meV in the temperature range $T = 77$–300 K (see the inset in Fig. 3); for the GaAs/$Ga_{0.84}In_{0.16}$As/GaAs/δ-Mn/GaAs heterostructure, the metal behavior with a local maximum in the temperature range $T = 100$–120 K was observed. The linear decrease in the resistance with decreasing temperature in the range $T =$ 200–300 K was followed by a further increase in the resistance in the range $T \approx (1.8$–$30)$ K, proportional to the dependence $R \sim \ln T$, i.e., weak localization in the quantum well was observed (Fig. 3). The feature in the behavior of the longitudinal resistance in the temperature range $T = (100$–$120)$ K is probably associated with the magnetic subsystem transformation and defines the Curie temperature $T_C \sim 100$ K. The value of T_C was confirmed by magnetization measurements. In [7], the results of the study of the photoluminescence spectra and the magnetic-field dependences of the Hall effect in heteronanostructures with a InGaAs/GaAs quantum well point to the appearance of ferromagnetic properties at temperatures below 20–25 K.

The change in the longitudinal resistance behavior with varying temperature in heterostructures based on GaAs with various manganese contents was previously discussed in [11, 12], where the transition from the semiconductor dependence $R_{XX}(T)$ to the metal-type dependence was also observed upon varying the manganese doping level.

Figure 4 shows the magnetic-field dependences of the specific magnetization after considering the diamagnetic contribution of the substrate to the total specific magnetization $\sigma(H)$ of samples. For the GaAs/$Ga_{0.84}In_{0.16}$As/Ga(Mn)As heterostructure with a manganese-doped GaAs cap layer, the specific magnetization hysteresis loop exists at the temperature $T = 5$ K in the field range $H = \pm 1.5$ kOe (Fig. 4a). The specific magnetization reaches $\sigma \approx 6.4 \times 10^{-4}$ emu/g in the external magnetic field $H = \pm 10$ kOe applied along the easy magnetic axis, which we showed in [13]. The hysteresis loop clearly shows the ferromagnetic order formation, which is controlled by the influence

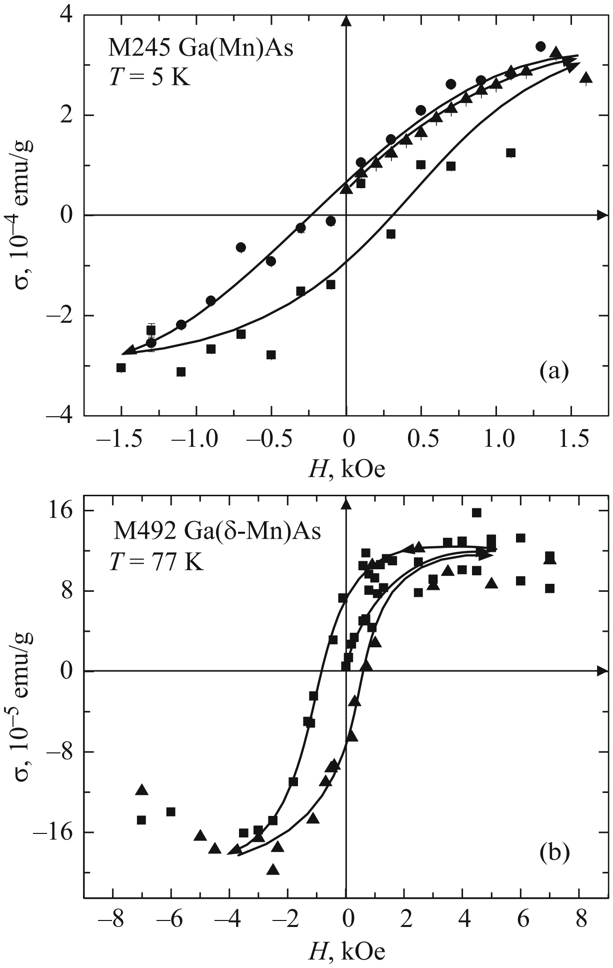

Fig. 4. Magnetic-field dependences of the specific magnetization for (a) the $GaAs/Ga_{0.84}In_{0.16}As/Ga(Mn)As$ heterostructure and for (b) the GaAs : $Be/Ga_{0.84}In_{0.16}As/GaAs/(\delta\text{-}Mn/GaAs$ heterostructure with a δ-layer 1.2 ML thick.

of the negative magnetoresistance that is proportional to the Hall resistivity. For the selectively doped GaAs : $Be/Ga_{0.84}In_{0.16}As/GaAs/\delta\text{-}Mn/GaAs$ heterostructure, it became possible to achieve the ferromagnetic order manifestation at higher temperatures to $T =$ 77 K, and the specific magnetization was $\sigma \approx 1.3 \times 10^{-4}$ emu/g in the field $H = \pm 4$ kOe (Fig. 4b). The results obtained suggest that the presence of localized ions in the delta-shaped distribution profile and selective p-type doping stimulate ferromagnetism in the GaAs semiconductor matrix.

4. CONCLUSIONS

The use of δ-doping based on manganese alloys allowed us to reveal unique features in magnetotransport properties of III–V semiconductor heterostructures, i.e., the fact that ordering of localized magnetic moments in the GaAs cap layer lead to a change in the resistance behavior, i.e., the semiconductor–metal transition and ferromagnetic ordering in weak magnetic fields, due to a change in the manganese ion distribution topology.

ACKNOWLEDGMENTS

The authors are grateful to M. Lopez-Lopez (National Polytechnic Institute, Cinvestav, Mexico) for heterostructures put at their disposal and A.F. Gubkin (Institute of Metal Physics, Yekaterinburg, Russia) for assistance in measurements of magnetic properties with an MPMS-XL-5 setup.

This study was performed within the federal target program "Electron" no. 01201463326 was supported in part by the basic research program of the Institute of Metal Physics, Ural Branch of the Russian Academy of Sciences, Yekaterinburg (grant no. 15-7-2-32) and the Russian Foundation for Basic Research (project no. 15-02-08909).

REFERENCES

1. J. K. Furdyna, J. Appl. Phys. **64**, R29 (1988).
2. H. Ohno, A. Shen, F. Matsukura, A. Oiwa, A. Endo, S. Katsumoto, and Y. Iye, Appl. Phys. Lett. **69**, 363 (1996).
3. T. Dietl, H. Ohno, and F. Matsukura, IEEE Trans. Electron. Devices **54**, 945 (2007).
4. A. J. Blattner, J. Lensch, and B. W. Wessels, J. Electron. Mater. **30**, 1408 (2001).
5. H. Ohno, J. Magn. Magn. Mater. **200**, 110 (1999).
6. K. D. Moiseev, V. P. Lesnikov, V. V. Podol'skii, Yu. Kudryavtsev, O. Kudryavtseva, A. Escobosa, and V. Sanchez-Resendiz, Semiconductors **45** (6), 771 (2011).
7. B. N. Zvonkov, O. V. Vikhrova, Yu. A. Danilov, Yu. N. Drozdov, A. V. Kudrin, and M. V. Sapozhnikov, Phys. Solid State **52** (11), 2267 (2010).
8. A. M. Nazmul, S. Sugahara, and M. Tanaka, Phys. Rev. B: Condens. Matter **67**, 241308R (2003).
9. E. F. Schubert, J. M. Kuo, R. F. Kopf, H. S. Luftman, L. C. Hopkins, and N. J. Sauer, J. Appl. Phys. **67**, 1969 (1990).
10. A. M. Nazmul, S. Sugahara, and M. Tanaka, Appl. Phys. Lett. **80**, 3120 (2002).
11. V. Tripathi, K. Dhorhak, B. A. Aronzon, V. V. Rylkov, A. B. Davydov, B. Raquet, M. Goiran, and K. I. Kugel, Phys. Rev. B: Condens. Matter **84**, 075305 (2011).
12. F. Matsukura, H. Ohno, A. Shen, and Y. Sugawara, Phys. Rev. B: Condens. Matter **57**, R2037 (1998).
13. T. Charikova, V. Okulov, A. Gubkin, A. Lugovikh, K. Moiseev, V. Nevedomsky, Yu. Kudriavstev, S. Gallardo, and M. Lopez, Low Temp. Phys. **41** (2), 157 (2015).

Translated by A. Kazantsev