Quantum, normal and anomalous Hall effect in 2D ferromagnetic structures: GaAs/InGaAs/GaAs quantum well with remote Mn delta-layer

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Abstract. We study experimentally the electronic transport and magnetism of GaAs/InGaAs/GaAs quantum wells (QW) with remote Mn δ-layer. The 2D energy spectrum of the carriers is revealed by quantum Hall Effect measurements. The ferromagnetic ordering is evidenced by anomalous Hall Effect and direct magnetization measurements. A signature of this state is also observed on the temperature dependence of the sample resistance. The dependence of the Curie temperature, \( T_C \), on manganese content, quantum well depth, and on the spacer thickness between QW and Mn δ-layer shed light on the mechanisms of exchange interaction in such structures.

1. Introduction

Due to fundamental limits for further miniaturization of transistors in microprocessors and memory cells, electronic devices based on new physical principles are demanded. One of the most promising proposal is to transfer and process information not only through the charge but also via the electrons spin. This domain of research is called spintronics. In this context, Dilute Magnetic Semiconductors (DMS), mostly based on A IIIBV-type semiconductors, are currently the object of a widespread attention. However, two-dimensional (2D) structures, which proved to be suitable for electronics, are much less studied in the context of spintronics, and only recently some papers appeared, see for example [1, 2, 3]. For such structures, the possibility to achieve a spatial separation of magnetic dopants and charge carriers seems to be crucial and promising. Having this in mind, we have studied heterostructures GaAs/Mn δ-layer/GaAs/InGaAs/GaAs quantum wells with a remote Mn δ-layer introduced into one of the GaAs layers. The Mn content (Mn layer effective thickness) \( \Delta \text{Mn} \) varied in the range of 0.25 -1.2 ML, the spacer thickness \( \delta \), between the Mn layer and the QW was fixed from 1 to 5 nm, the thickness of the QW was 10 nm and its depth \( U_0 \) in the range from 80 to 160 meV was controlled by In concentration. For detailed description of the structure see [3]. In these samples we observed ferromagnetic (FM) ordering and different manifestations of the spin polarization of the charge carriers.
2. Results and discussion

Unlike previous studies of $A^{III}B^{V}$-type DMS with Mn $\delta$-layers, in our case the Mn layer and the conductive channel (the quantum well filled with charge carriers) are well separated from each other. This results in a relatively high mobility of the carriers, two orders of magnitude higher as compared to the DMS-based structures studied earlier [4, 5]. The hole spectrum is unambiguously 2D, as it is confirmed by the observation of the quantum Hall effect shown in Fig. 1. At low magnetic fields we have observed the anomalous Hall effect (AHE) up to relatively high temperatures (140 K) [3, 6] (see Fig.2) unveiling the spin polarization of the 2D hole gas. The magnetic ordering in the structure under study was also detected by the presence of a hump in the temperature dependence of the electrical resistance $R(T)$ presented in Fig. 3, which is a signature of FM ordering, while samples doped with nonmagnetic acceptor do not show such a hump [3, 6]. The position of this hump is often assumed as Curie temperature $T_c$ [7].

The polarization of photo- and electroluminescence, proving the spin polarization of the carriers, was recently observed in similar structures [8]. Direct magnetization measurements were also performed. At high temperatures, the magnetization curves correspond to a magnetic cluster glass, while at low temperatures and at low Mn content a hysteresis loop was observed [9]. For structures with high Mn content exchange bias was also observed [10]. This is due to spatial disorder of Mn distribution, which results in the existence of antiferromagnetic regions that could pin the magnetic moment of FM areas.

![Fig. 1. Magnetic field dependence of the Hall and longitudinal resistance of the structure with $\Delta$Mn = 0.3 ML and $d = 3$ nm.](image1)

![Fig. 2. Anomalous Hall effect resistance versus magnetic field for samples with Mn content $\Delta$Mn = 0.3 ML and 0.25 ML, measured at $T = 33$ K and $T = 140$ K, correspondently, $d = 3$ nm.](image2)

![Fig. 3. Temperature dependence of resistance for samples with various Mn content $\Delta$Mn = 0.3, 0.4 and 0.5 ML, $d = 3$ nm. The hump on these dependences corresponds to $T_c$.](image3)
In this paper, the possible mechanisms of exchange interaction leading to the FM state in these systems will be discussed. To shed light on these mechanisms, we performed measurements at various Mn concentration, QW depth $U_0$ and spacer thickness $d$. These results, presented in Figs. 4 and 5, suggest the occurrence of two mechanisms contributing to the spin polarization of carriers in the QW. The first is related to the indirect exchange between carriers in the QW and Mn ions in $\delta$-layer [11]. According to the second mechanism the magnetization of Mn $\delta$-layer is due to holes inside it and the interaction between FM ordered Mn $\delta$-layer and the carriers in the QW leads to carrier spin polarization [12].

The first model assumes that holes wave function has a tail which is extending out of the QW that could overlap with the Mn atoms in the Mn $\delta$-layer. So exchange between Mn atoms could be mediated by free carriers (localized in the QW) as in the RKKY model, this mechanism provides in turns a way for the polarization of the mobile holes. However, the interaction between carriers and magnetic atoms is weaker than in the RKKY scenario, because the amplitude of the wave function tail decays exponentially outside the QW. On the other hand the mean free path of carriers in our structures is much longer than in bulk due to the high mobility value that helps for exchange.

This mechanism could explain the nonmonotonous dependence of $T_C(U_0)$ determined as the temperature at which $R(T)$ has a hump, see Fig. 4. Holes in the QW are transferred from Mn acceptors. So if the QW is not deep enough the hole subband could be located below the acceptor level and no free holes could contribute to the magnetic exchange. With increasing $U_0$ free holes concentration in QW increases also and becomes large enough to give rise to the above depicted exchange interaction. Further increase of $U_0$ results in diminishing of the wave function tail amplitude outside the QW. That leads to decrease of the interaction between carriers and magnetic atoms and lowering of $T_C(U_0)$ at high enough $U_0$ values. This mechanism may be relevant for small thicknesses of spacer and should depend on its thickness. In support of this is the graph shown in Fig. 5, which clearly shows that the Curie temperature is a decreasing function of the spacer thickness.

However the dependence $T_C(d)$ presented at Fig. 5 is very weak, while the above mechanisms assumes the exponential behavior of Curie temperature versus spacer thickness. So another mechanism of the FM ordering and spin polarization of the carriers in the system should be suggested to explain this dependence. It was proposed in Ref. [12]. Due to diffusion, the Mn $\delta$-layer is blurred and spread into
GaAs layers (spacer and cover) up to a thickness of 2-3 nm, but as demonstrated by X-ray measurements, does not overlap with the QW [3]. So the Mn \( \delta \)-layer could be considered as a thin GaMnAs DMS layer. According to [12] it is sufficient for the occurrence of itinerant FM ordering in this layer. This mechanism of the ferromagnetic ordering does not need carriers from QW and \( T_C \) should not depend on \( d \). As already stated, carriers in the QW come from Mn atoms located in the \( \delta \)-layer and act as acceptors. The transition to FM state results in the lowering of the Fermi energy in the layer and so some carriers should be transferred from the QW back to acceptors, according to the new Fermi level position. That was observed and shown in Fig. 6 also proving the contribution of this mechanism of FM ordering. Tails of wave functions related to the FM state in the Mn layer could penetrate to QW causing the holes spin–polarization [12]. The large temperature range where hole concentration \( p \) is \( T \) dependant is related to the nonuniform spatial distribution of Mn. At high enough temperature the Mn layer is paramagnetic. When temperature decreases the phase separation occurs in this layer. It is divided in ferromagnetic and paramagnetic regions. The Curie temperature in each of FM regions (FM puddles) has its local value \( T_{C,loc} \) and these values are different for various puddles. As it was mentioned above the hole concentration in QW regions corresponding to the FM puddles drops down at the related \( T_{C,loc} \). The averaged hole concentration diminishes also. As the temperature diminishes the interaction between FM droplets increases and their size increases so they overlap and the long range FM state is forming at \( T = T_C \). So the hole concentration should go down in the temperature range between \( T_{C,loc} \) maximum and the \( T_C \) value. In accordance with this model \( p(T) \) flattens at \( T = T_C \) as it is seen in Fig. 6.

The amplitude of the \( T_C \) maximum at the nonmonotonous \( T_C(U_0) \) dependence related to the first mechanism is about 15 K, while residual \( T_C \) values at the smallest \( U_0 \) and at the widest spacer are also in the range 15 – 20 K. So taking into account that the error of \( T_C \) measurements is about 2 K we conclude that both mechanisms provide a considerable contribution to the ferromagnetic ordering and to the holes spin polarization in our samples.

Our experimental results point out the intrinsic nature of the anomalous Hall effect (AHE) in 2D DMS, which is related to the renormalization of carrier group velocity under the influence of the spin-orbit interaction. The main reason for this statement is the observation of the change of the AHE sign with lowering temperature, as shown in Fig. 7. The AHE magnitude is in a good agreement with the theoretical estimations for 2D structures, taking into account the intrinsic mechanism of AHE [13]. In the whole temperature range, we observed \( \rho_{xy}^a \propto \rho_{xx}^2 \) which is relevant for two AHE mechanisms: side-jump and intrinsic [14] (\( \rho_{xy}^a \) and \( \rho_{xx} \) are

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**Fig. 6.** The carrier concentration obtained from the normal Hall effect versus temperature for sample with Mn content 0.3 ML and \( d = 3 \) nm.

**Fig. 7.** Anomalous Hall effect resistance versus temperature measured for sample with \( \Delta \)Mn = 0.3 ML, \( d = 3 \) nm at fields 3 T, 1 T and 0.3 T.
the anomalous Hall and longitudinal resistivities). The change of the AHE sign may only be explained if one assumes two different mechanisms contributing to the AHE at low and high temperatures. So one of these mechanisms is intrinsic which plays the main role at low temperatures, when the scattering and so side-jump is less effective.

**Conclusion**

We have studied the electronic transport and magnetism in semiconductor heterostructures GaAs/InGaAs/GaAs quantum wells with a remote Mn δ-layer. In these structures, we observed the FM state and the quantum Hall effect. The FM state was detected by the presence of a broad maximum of the resistivity vs. temperature, anomalous Hall Effect and magnetization measurements. The measured $T_c$ dependencies on the QW depth and the spacer thickness between QW and Mn δ-layer lead to conclusion that there are two mechanisms contributing to the FM state and holes spin polarization. According one of them the FM ordering in the Mn δ-layer is due to exchange between Mn ions through carriers in QW as a result of penetration of the "tails" of the carrier wave functions into Mn layer. Second mechanism is based on assumption that the actual Mn δ-layer could be represented as a thin GaMnAs layer due to diffusion of Mn atoms into surrounding GaAs blankets. So FM ordering could occur in this layer by itself without help of holes from QW, while the spin-polarization of carriers in QW is caused by a penetration into QW tails of wave functions related to the FM state in the Mn layer. It is logical to assume that in the studied structures FM transition occurs due to both mechanisms, which are complementary to each other and provide a considerable contribution.

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