Ferromagnetism and magnetotransport in GaAs structures with InAs quantum dot layer or In\textsubscript{x}Ga\textsubscript{1-x}As quantum well delta-doped with Mn and C

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Abstract. In the present study we investigated the influence of Mn delta-doping on magnetic and galvanomagnetic properties of GaAs structures with InAs quantum dot layer or GaAs/In\textsubscript{x}Ga\textsubscript{1-x}As/GaAs quantum well. All samples were prepared with the combined method of MOC-hydride epitaxy and laser deposition of Mn. The ferromagnetic phase up to 400 K was detected by SQUID magnetometer. All samples had \textit{p}\textsuperscript{-}type conductivity and high mobility of holes. In the temperature interval 4.2 – 35 K negative magnetoresistance is observed, transferring to the positive magnetoresistance at T>35 K. Anomalous Hall-effect was observed in the temperature interval 20–80 K.

1. Introduction
Mn-doped GaAs is an attractive diluted magnetic semiconductor (DMS) for a new spin-based electronics. It has been shown that the Curie temperature ($T_c$) in Ga\textsubscript{1-x}Mn\textsubscript{x}As can be raised by increasing the hole concentration as well as Mn concentration [1]. Although Mn acts as an acceptor in GaAs, the hole activation ratio is much less than unity and the hole concentration tends to saturate due to the compensation of Mn acceptors by the defects. Therefore, some additional doping of acceptor impurity is needed to achieve a high hole concentration. One of the method is the molecular beam epitaxy growth of the GaAs based heterostructures. Such procedure leads to the value of $T_c=250$ K [2].

In the present study we investigated the influence of Mn delta-doping on magnetic and galvanomagnetic properties of GaAs structures with InAs quantum dot layer or GaAs/In\textsubscript{x}Ga\textsubscript{1-x}As/GaAs quantum well.

2. Samples and experimental
All samples were prepared with the combined method of MOC-hydride epitaxy and laser deposition. Samples were grown on GaAs (100) substrate and contain carbon δ-layer (to provide enhanced $p$-type conductivity in the quantum dot (QD) layer or quantum well (QW)), then InAs QD layer or QW and laser-deposited Mn layer separated by GaAs spacers with width $d=10$ nm. In In\textsubscript{x}Ga\textsubscript{1-x}As quantum well ($x=0.17$) with width 10 nm, laser-deposited Mn layer was separated by $d=3$ nm GaAs spacer. The Mn
concentration controlled by duration time of Mn laser-deposition. Thus Mn concentration was different in the samples. Temperature dependence of resistance was measured in the temperature interval of $4.2\leq T\leq 77$ K in magnetic fields up to 6 T. Some parameters of the samples with quantum dot layer are listed in table 1 and with quantum well in table 2. For measurements of the magnetization in the temperature interval $4.2\leq T\leq 400$K in magnetic fields up to 7T, a SQUID magnetometer was used. The measurements were performed by applying

### Table 1. Concentration of Mn, Hall density $p$, Hall mobility $\mu$ at $T=300$ K and 4.2 K for QD structures.

| N  | Mn (cm$^{-3}$) | $p(300K)$, $10^{12}$ cm$^{-2}$ | $\mu(300K)$, cm$^2$/Vs | $p(4.2 K)$, $10^{12}$ cm$^{-2}$ | $\mu(4.2 K)$, cm$^2$/Vs |
|----|---------------|-------------------------------|------------------------|-------------------------------|------------------------|
| 612| 0             | 0.3                           | 200                    | -                            | -                      |
| 615| $2.3\times10^{13}$ | 1.7                           | 450                    | 1.8                           | 2580                   |
| 616| $1.7\times10^{14}$ | 3.7                           | 285                    | 1.5                           | 3270                   |
| 617| $3.4\times10^{14}$ | 4.0                           | 330                    | 1.6                           | 490                    |

### Table 2. Concentration of Mn, Hall density $p$, Hall mobility $\mu$ at different temperatures for QW structures.

| N  | Mn (cm$^{-3}$) | $p(300K)$, $10^{12}$ cm$^{-2}$ | $\mu(300K)$, cm$^2$/Vs | $p(4.2 K)$, $10^{12}$ cm$^{-2}$ | $\mu(4.2 K)$, cm$^2$/Vs |
|----|---------------|-------------------------------|------------------------|-------------------------------|------------------------|
| 415| 0             | 1.8                           | 300                    | -                            | -                      |
| 419| $3.4\times10^{14}$ | 3.4                           | 450                    | 0.35 (4.2 K)                 | 4670 (4.2 K)           |
| 418| $4.4\times10^{14}$ | 1.0                           | 700                    | 0.37 (4.2 K)                 | 5200 (4.2 K)           |
| 420| $6.6\times10^{14}$ | 5.6                           | 190                    | 1.2 (77 K)                   | 1930 (77 K)            |
| 417| $1.0\times10^{15}$ | 6.7                           | 160                    | 1.4 (77 K)                   | 1920 (77 K)            |
| 421| $1.3\times10^{15}$ | 7.9                           | 150                    | 0.58 (16 K)                  | 100 (16 K)             |

magnetic field parallel to the surface of samples. Temperature dependences of resistance have been measured in the temperature range $4.2\leq T\leq 300$ K. Magnetoresistance and Hall effect have been measured by a conventional four probe technique in the temperature range $4.2\leq T\leq 300$ K in magnetic field $B$ up to 6 T applied perpendicular to the sample surface.

For measurements of the magnetization in the temperature interval $4.2\leq T\leq 77$K in magnetic fields up to 7T, a SQUID magnetometer was used. The measurements were performed by applying the magnetic field parallel to the surface of samples. Temperature dependences of resistance have been measured in the temperature range $4.2\leq T\leq 300$ K.

### 3. Results and discussion

#### 3.1. Transport properties and magnetism. All samples had $p$-type conductivity. When temperature decreased sheet resistivity $R_s$ samples increased (fig. 1). In the temperature range between 50 and 110K a kink is visible in $R_s(T)$, which is a characteristic of the ferromagnetic transition [3]. At $T<T_c$ the spin flip scattering disappears, mobility increases and resistance decreases. This effect results in a kink for an activation type of the experimental dependence of $R_s(T)$ as we have observed.

All samples showed ferromagnetism, as indicated by hysteresis loop in the magnetization (all samples studied showed qualitatively similar magnetic behavior). The hysteresis loops show clear temperature dependence over the entire range of temperatures studied for QW samples, as can be seen in fig. 2 for sample 419. There are different magnetic phases in the samples, one with $T_c$ about 70 K, others with $T_c$ above room temperature. The first value of $T_c$ is very typical for hole mediated
ferromagnetism in Ga_{1-x}Mn_xAs solid solutions. It is useful note that in samples with high Mn content concentration of holes depends on \( T \) and decreases as \( T \) decreases. Next magnetic phase is due to formation of MnAs clusters. The Curie temperature for bulk MnAs is about 315 K. Above this temperature ferromagnetism survived due to Ga_{1-x}Mn_x clusters. \( T_c \) for such clusters depends on Mn content and may be as high as 600 K for \( x=0.6 \) [4]. In the investigated samples hole mediated long range magnetic order of magnetic ions of Mn coexists with ferromagnetic clusters MnAs and Mn_xGa_{1-x}. Long range order is suppressed at \( T \approx 50–100K \), that is at \( T=T_c \), typical for uniform solid solution of Ga_{1-x}Mn_xAs. Measurements indicate the presence of buried MnAs nanoclusters with a structural phase transition around 315 K, in accord with the first order magneto-structural phase transition of bulk MnAs. The buried nanoclusters are formed at a depth of about 150 nm below the sample surface.

3.2. **Anomalous Hall effect and magnetoresistance.** One of the methods to detect the spin-polarized carriers is the anomalous Hall effect (AHE). The magnetic-field dependences of the Hall resistance \( R_{xy} \) for QD sample 617 obtained at different temperatures are presented in Fig. 3. An evident contribution of the AHE is observed in the temperature interval \( 20 \leq T \leq 80 \text{ K} \). To estimate the relative contribution of the AHE component, we extrapolated the \( R_{xy}(B) \) curves at \( B > 1 \text{ T} \) by a linear dependence, thus having separated out the contribution of the conventional Hall effect, and then subtracted it from the \( R_{xy}(B) \) curve to obtain the AHE component under quasi-saturation conditions of \( R_{AS} \) (at \( B > 1 \text{ T} \)). For Ga_{1-x}Mn_xAs the AHE would increase to the Curie temperature (the maximum in the temperature dependence of \( R_{xy} \) (see [3, 10]) with decreasing temperature, tending then to saturation. In our case, the AHE contribution sharply decreases at \( T < 30 \text{ K} \); at \( T \sim 17 \text{ K} \), the Hall effect is already linear with respect to the field, and the Hall resistance \( R_{xy} \sim 1.2 \times 10^3 \Omega \) in the field \( B \sim 1.5 \text{ T} \). The similar result
was observed for QW samples. The apparent absence of the manifestations of ferromagnetism in samples according to the Hall effect measurement data contradict the data on measurements of the magnetization on the SQUID magnetometer, demonstrating magnetic ordering in these samples at low temperatures.

Magnetoresistance in all samples changes a sign from negative to positive when temperature increases. In the temperature interval 4.2 - 30 negative magnetoresistance is observed. At temperatures above 30 K it is observed positive magnetoresistance. As an example in fig. 4 we plot magnetoresistance of QD sample 617 at different temperatures.

![Figure 4](image1.png)  
**Figure 4.** Magnetoresistance of QD sample 617 at different temperatures.

Complicated dependence of resistance on magnetic field may be explained by the contribution to magnetoresistance spin-dependent scattering of carriers. In our opinion, the observable experimental facts testify that the presence of the fluctuation potential in the 2D conducting channel of the structures, formed by QD layer or quantum well, caused by non-uniform distribution of Mn ions plays a significant role in the magnetotransport phenomena [5]. Additional disorder introduced to conducting layer by replacing of QW by QD layer did not change the peculiarities of the transport properties of the structures. Thus the fluctuation potential and non uniform distribution of the Mn plays a key role in structures.

Fig. 5 shows data on the magnetoresistance for QW structure (#419) with low Mn content. The field dependence of $R_{xx}$ is not described by the classical law $(AR_{xx}/R_{xx})\sim B^2$, which points to the importance of the contribution of the spin-dependent negative magnetoresistance. This contribution already becomes dominant below 30 K, while the region of transition to positive magnetoresistance shifts toward the region of high fields. If we assume that the contributions of the negative and positive magnetoresistances are additive and subtract the dependence of the magnetoresistance at $T = 33.3$ K from the curve $AR_{xx}(B)/R_{xx}(0)$ at $T = 21$ K, we will obtain the form of the $AR_{xx}(B)/R_{xx}(0)$ curve typical for spin-dependent magnetoresistance in these systems in the vicinity of the ferromagnetic transition. As the temperature is decreased, Shubnikov-de Haas (SdH) oscillations appear against the background of negative magnetoresistance (see Fig. 5). One frequency from one filled dimensional quantization band in the quantum well is observed in the oscillations. The concentration of the two-dimensional electrons determined from this frequency equals $3.4 \times 10^{11} \text{ cm}^{-2}$, which agrees well with the Hall effect data.

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