The features of carrier transport in the ferromagnetic semiconductor quantum well structures

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The Mn delta-doped GaAs layers are the subject of intensive studying by a number of research groups involved in the development of semiconductor spintronic devices [1-2]. One of the interesting areas of their application is a light-emitting diode, which produces circularly polarized light. In [3,4] it has been shown to us that Mn delta-doped GaAs layer itself possesses ferromagnetic properties.

In GaAs structures only with single Mn delta-doped layer ferromagnetic properties were revealed by carrier transport investigations [3,4]. Galvanomagnetic measurements at low temperatures showed the presence of anomalous, planar Hall effect, anisotropic and negative magnetoresistance, that evidence about a ferromagnetism. In this paper we present the investigation of the peculiarity of the carrier transport in GaAs structures containing InGaAs quantum well in addition to Mn delta-doped layer.

The structures were grown by the combined method of metal-organic chemical vapor deposition and pulse laser sputtering. Firstly a set of undoped layers was grown on i-GaAs (001) substrate by vapor-phase epitaxy at 600°C: 0.25 µm buffer GaAs layer, 10 nm thick $In_xGa_{1-x}As$ quantum well and 3 nm GaAs spacer layer. Then 0.2 monolayer thick Mn delta-doped layer and 20 nm thick GaAs cap layer were deposited at 400°C using laser sputtering of metallic Mn and undoped GaAs targets, respectively. The In content was varied in range from $x = 0.1$ to 0.3 for different structures. Also the reference structure only with a single Mn delta-doped layer was fabricated.

The structure only with a single Mn delta-doped layer demonstrates at 10 K nonlinear Hall resistance dependence on magnetic field ($R_H(H)$) with hysteresis loop (coercive field ≈ 90 Oe) and saturation at magnetic field about 2000 Oe (Fig 1, dependence 1). This indicates the presence of clear ferromagnetic properties and domination of anomalous Hall effect in $R_H(H)$ dependences.

The structures with a quantum well beside Mn delta-layer demonstrate at 10 K differ character of the Hall resistance dependence. The shape of the $R_H(H)$ curves depends on indium content in InGaAs layer and consequently on the energy depth of a quantum well (Fig 1). With increasing In content the contribution from normal Hall effect increase. For the structure with the most deep quantum well the $R_H(H)$ dependence is linear, consequently, it determines by normal Hall effect (Fig 1, dependence 3). Is it indicates about the absence or weakening of ferromagnetic properties? In our opinion ferromagnetic properties of structures with Mn delta-doped layer have no direct relation to presence of InGaAs quantum well and its depth and related to intrinsic ferromagnetism of a Mn delta-layer. The insertion of a quantum well leads to appearance of an additional conducting channel for free charge carriers (holes). The distribution of charge carriers in a structure depends on quantum well depth. Fig. 2 shows calculated band diagrams and carrier distribution at 77 K for the structure only with single Mn delta-layer (Fig 2*a*) and for the structures with Mn delta-layer and deep quantum well (Fig 2*b*).

For the structure only with single Mn delta-layer all carriers are localized in the ferromagnetic region of delta-doped layer (Fig 2*a*) and only these carriers determine the transport properties of the structure. In contrast to this case, for the structure with deep quantum well (with In content is 0.3, Fig. 2*b*) the most part of free carriers is localized in the region of quantum well. Inasmuch as mobility of carriers localized in deep InGaAs quantum well at low temperatures is high, these carriers determine the transport properties of the structure. At the same time the carriers localized in region of Mn layer can determine the ferromagnetic properties of the structure. As the transport of carriers localized in InGaAs quantum well leads to predominance of the normal Hall effect, the question about the degree of spin polarization of these carriers still remains open.

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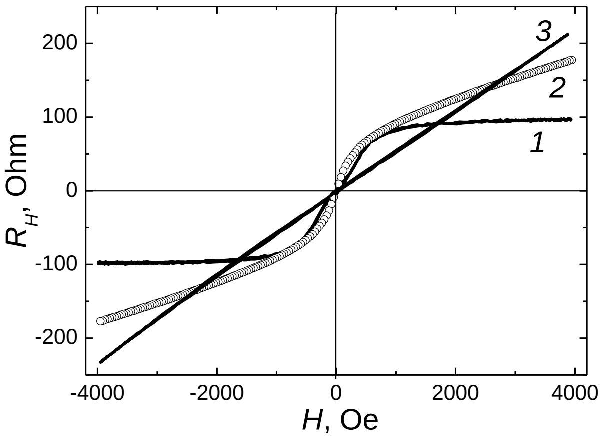

Fig. 1. Magnetic field dependences of Hall resistance at 10 K. *1* - The structure without InGaAs quantum well, *2* - The structure with InGaAs quantum well (In content is 0.15), *3* - The structure with InGaAs quantum well (In content is 0.3).

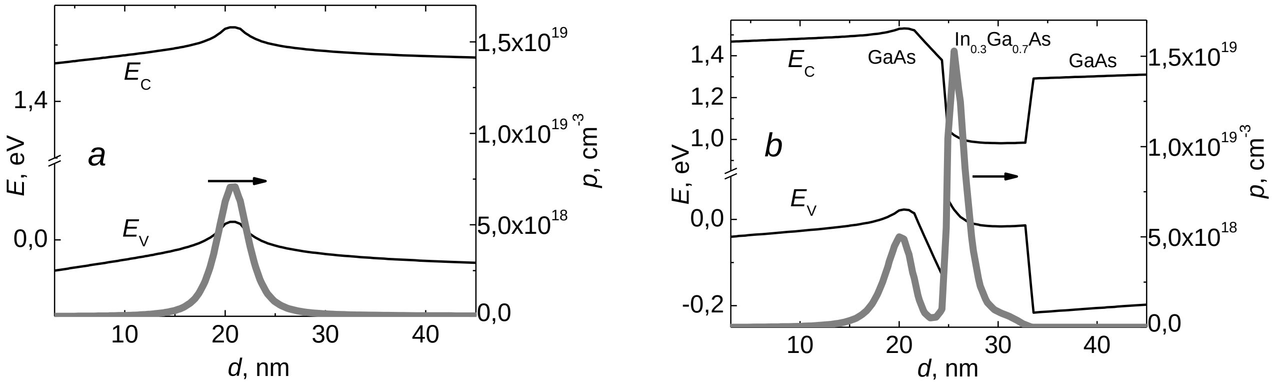

Fig. 2. Calculated band diagrams and carrier distribution at 77 K. *a* - The structure without InGaAs quantum well, *b* - The structure with deep InGaAs quantum well (In content is 0.3).