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Control of magnetic characteristics of spin LEDs with a magnetic system „Mn delta layer — InGaAs/GaAs quantum well“ due to delta doping with an acceptor impurity

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Magnetic and luminescent properties of spin light-emitting diodes based on heterostructures with an InGaAs/GaAs quantum well and Mn and C delta-layers are studied. The dependences of the circular polarization degree of electroluminescence on the location of the C delta-layer relative to the quantum well and the Mn delta-layer are obtained. It is found that when the carbon delta-layer is localized in the quantum well region, the maximum value of the circular polarization degree is observed, while when the carbon delta-layer is localized between the quantum well and the Mn delta-layer, the degree of polarization is minimal. The obtained data are explained in terms of known models of the interaction of charge carriers in a quantum well with a closely located Mn delta-layer.

Keywords: spin LEDs, A3B5 heteronanostructures, spin polarization, Mn delta layer, circularly polarized electroluminescence.

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1. Introduction

Dilute magnetic semiconductors A^3B^5, strongly doped with transition element atoms, have long been considered as a promising base for building devices based on spin-dependent effects [1–4]. Considerable attention was paid to one of the representatives of this family — (Ga,Mn)As, for which the presence of spin-polarized holes during magnetization of the structure has been experimentally demonstrated [1,4,5]. Spin polarization of charge carriers is a necessary condition for observing spin-dependent phenomena. A more complex type of dilute magnetic semiconductor is a hybrid system containing an ultra-thin layer (Ga,Mn)As (delta layer Mn) and an InGaAs/GaAs quantum well separated by a thin (0−12 nm) spacer layer [6–9]. Even in early works, the prospects of such systems providing spin polarization of charge carriers in a quantum well were demonstrated. The high crystal quality of the magnetic impurity-free quantum wells, together with the presence of spin-polarized carriers, ensured the registration of a number of spin-dependent phenomena, in particular — circularly polarized emission [6,8].

At the same time, the description of the physics of such systems was accompanied by a discussion, some of the issues of which have not been resolved to this day. Thus, there is no complete understanding of the mechanism of ferromagnetic ordering in the delta layer of Mn (the very fact of the presence of ferromagnetism has been repeatedly confirmed [7,8,10]). It was shown in Ref. [11] that the magnetic order is most likely due to indirect exchange interaction through carriers localized in the impurity zone (Ga,Mn)As.

In addition, the mechanism of the effect of the Mn ferromagnetic delta layer on the spin polarization of carriers in the quantum well is not clear (the presence of spin polarization has also been unequivocally confirmed). A number of experimental results are interpreted from the point of view of the spin-dependent electron capture mechanism [12–14]. Some of the results are explained by the interaction of spin-polarized holes with Mn atoms [15–17].

Finally, the question of the influence of charge carriers localized in a quantum well on the magnetic properties of the Mn delta layer was discussed in the papers [10,11,18]. It was unequivocally shown in Ref. [11] that ferromagnetism in delta-Mn is also realized in the absence of charge carriers in the quantum well. At the same time, the possible influence of charge carriers localized at a small distance from the delta layer on the Curie temperature T_c was discussed in Ref. [18].

The last two questions relate to the description of the magnetic interaction in the (Ga,Mn)As/GaAs/InGaAs system, which is realized between Mn atoms and charge carriers in a quantum well. Contradictory experimental data obtained in a number of studies do not allow us to build a reliable model of interaction, and existing models are limited only by general provisions [17]. This paper experimentally studies the relationship between the magnetic properties of the Mn delta layer and the concentration of free carriers localized near it. Since previous experimental data do not provide an unambiguous answer as to which type of carriers is localized in the quantum well and is responsible for spin polarization, in this work the type of carriers was specifically determined by introducing a carbon delta layer, which is an acceptor impurity for GaAs. Thus, a layer of free holes was formed, localized in the potential barrier of the carbon delta layer. To assess the influence of this layer, its position in the system varied: three structures were formed in which carbon was introduced before the growth of the InGaAs quantum well, directly into the quantum well and between the quantum well and the Mn delta layer. The dependence of magnetic properties on the location of holes was investigated. The magnetic properties were evaluated by measurements of circularly polarized luminescence. It was previously shown that the magnetic field and temperature dependence of the degree of circular polarization of InGaAs quantum well radiation makes it possible to unambiguously judge the magnetization of the Mn delta layer and estimate the Curie temperature [15,18]. The study confirmed the presence of circularly polarized luminescence in the formed systems. In this paper, its dependence on the configuration of structures is considered.

2. Experimental technique

All the studied samples are spin light-emitting diodes based on heterostructures with an InGaAs/GaAs quantum well, carbon delta layer (δ-C) and Mn delta layer (δ-Mn). The samples were formed in several stages. In the first and second stages, the semiconductor part of the structures was formed on n^+-GaAs(100) substrates. The semiconductor part was grown using a combined method, combining metalorganic vapour phase epitaxy (MOVPE) and pulsed laser deposition (PLD) of solid-state targets. A special feature of this combined method is the ability to carry out both processes in the same growth cycle [19]. The following layers were sequentially grown for all three studied samples: at the first stage, a buffer layer n-GaAs, an InGaAs/GaAs quantum well, and a spacer layer i-GaAs were formed by the method of MOVPE. The substrate temperature was 600 °C. A carbon delta layer was formed in all structures. Its position relative to the layers of structures for all three samples was different: δ-C layer for Sample 1 was formed before the growth of the quantum well — in the GaAs buffer layer at a distance of 3 nm from the MOVPE; δ-C layer for Sample 2 was formed directly in the QW center, δ-C layer for Sample 3 was formed after the growth of the QW — in the GaAs spacer layer at a distance of 3 nm above the QW. Further, at the second stage of the growth cycle, the Mn delta layer and the thin cover layer of i-GaAs were successively formed. The substrate temperature was reduced to 400 °C for this purpose. Laser deposition was performed by sputtering solid-state targets (targets of metallic Mn and GaAs). Lowering the temperature of the growth process to 400 °C helps to reduce Mn diffusion in GaAs and allows the formation of a delta-shaped impurity distribution, while maintaining the structural perfection of the adjacent δ-Mn layers. It was shown earlier in Ref. [20] that Mn is concentrated in a thin layer without significant diffusive blurring and segregation. It is worth noting that for all the studied samples δ-Mn was technologically located at a distance of 7 nm from the quantum well.

The use of a combined method of MOVPE and laser deposition of targets in a single growth cycle makes it possible to ensure good crystal quality of the entire structure due to a high-temperature buffer layer and significantly reduce the diffusion of Mn impurities due to a decrease in the substrate temperature during the PLD process.

At the third stage of the technological process for the production of spin LEDs metal contacts based on Au were deposited on the surface of the formed semiconductor structures by electron beam evaporation in vacuum. Then, using photolithography and chemical etching, a mesastructure with a diameter of 500 μm was formed. At the last stage, a basic ohmic contact to the substrate was formed by spark ignition of the Sn foil.

Thus, three samples of a spin light-emitting diode were formed, which differed in the localization of the carbon delta layer. The diagrams of the samples are shown in Figure 1.

The degree of circular polarization of electroluminescence (EL) was studied for analyzing the mechanisms of interaction of magnetic Mn ions with charge carriers in a quantum well.

When the structure is introduced into a magnetic field directed perpendicular to the surface of the structure, the electroluminescence becomes partially circularly polarized [7–18]. The emission of circularly polarized radiation by structures is due to the presence of spin-polarized carriers in the active region. A standard scheme was used to measure the magnetic field dependence of circular polarization, and the degree of circular polarization of electroluminescence was calculated using the formula [21]:

$$P_{\mathrm{EL}} = (I_1 - I_2)/(I_1 - I_2) \times 100\,\% \qquad (1)$$

where P_{EL} is the degree of circular polarization of electroluminescence, I_1 and I_2 is the intensity of the electroluminescence components polarized in the left and right circles, respectively. The dependences $P_{\mathrm{EL}}(H)$ were measured in the temperature range 10−50 K using a closed-loop cryostat. The range of magnetic fields was 0−2500 Oe.

For structures with InGaAs quantum well, the value of the degree of circular polarization exactly corresponds to the value of the spin polarization of the carriers in the quantum well. Spin polarization, in turn, is associated with the magnetic interaction of charge carriers in the quantum well and Mn ions in the δ-Mn layer, the quantitative characteristics of spin polarization are determined by the features of such interaction. Therefore, the characteristics of circular polarization provide additional information regarding the magnetic properties of the delta-Mn layers. Thus, the temperature dependence of the degree of polarization makes it possible to estimate the value of the Curie temperature of the Mn ferromagnetic delta layer [18].

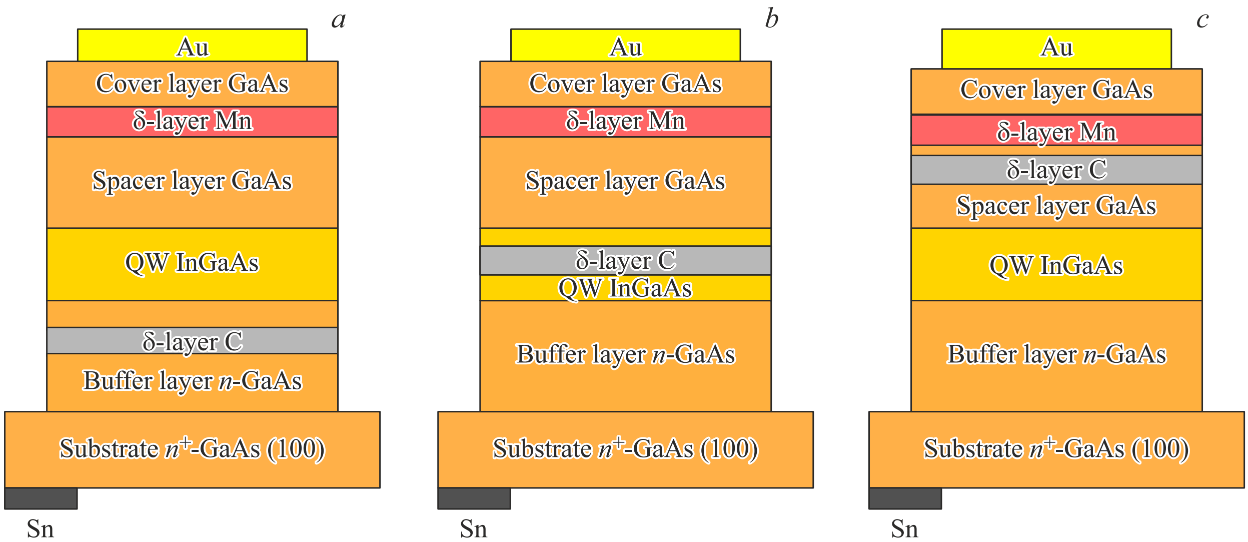

Figure 1. Schemes of the studied spin light-emitting diodes: *a*) Sample 1, *b*) Sample 2, *c*) Sample 3.

An attempt is made in this paper to perform „forced“ localization of holes by embedding a carbon delta layer in various areas of the system relative to the quantum well and the Mn delta layer. The purpose of this manipulation was to evaluate the effect of holes on the magnetic interaction between charge carriers in a quantum well and Mn ions.

3. Results and discussion

Figure 2 shows the electroluminescence spectra for Sample 1, measured at temperatures of 10 and 50 K. One dominant peak is observed in these spectra, which is associated with the radiative transition in the InGaAs/GaAs quantum well. It is worth noting that the intensity of electroluminescence practically did not change in the

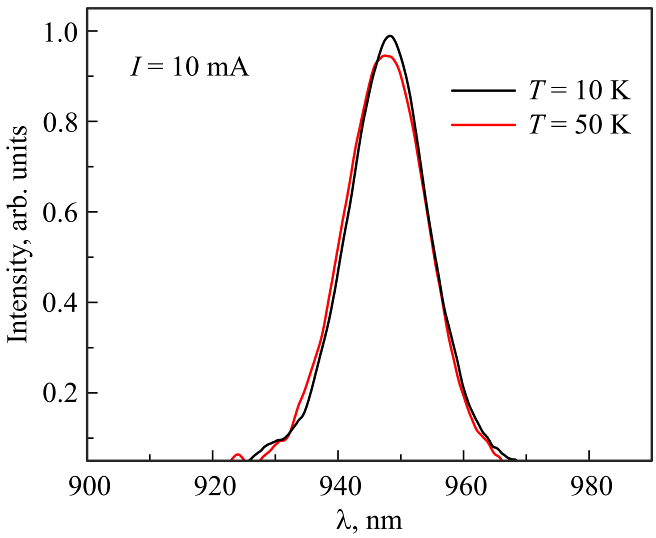

Figure 2. Electroluminescence spectra for the Sample 1.

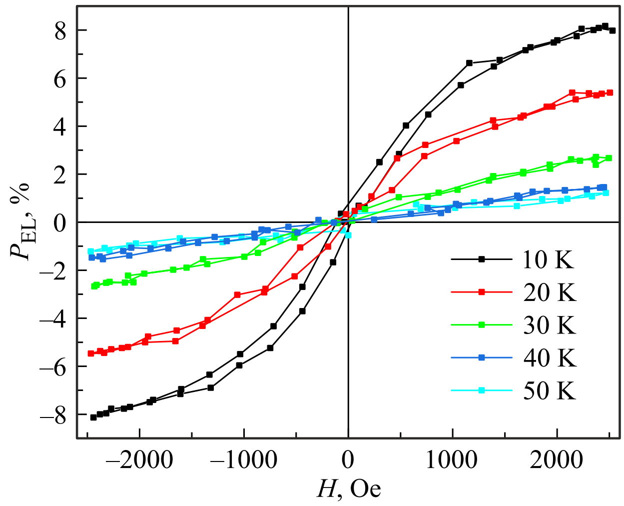

Figure 3. Magnetic field dependences of the degree of circular polarization $P_{EL}(H)$ for Sample 2, measured in the temperature range 10−50 K.

temperature range of 10−50 K. For the other two samples, the EL spectra, as well as their temperature dependences, had the same shape.

Figure 3 shows the magnetic field dependences $P_{EL}(H)$ measured for the Sample 2 at different temperatures (10−50 K). Based on the dependences measured at low temperatures, two regions can be distinguished: a region of rapid increase in the degree of polarization (magnetic fields from 0 to 1000 Oe) and a region of slow change in the degree of polarization with increasing field (magnetic fields greater than 1000 Oe). The area of rapid growth of P_{EL} is attributed to the magnetic properties of δ-Mn and is associated with the gradual saturation of magnetization of this layer. The region of slow growth of P_{EL} is attributed to the Zeeman splitting of levels in the InGaAs/GaAs quantum well and has a linear dependence on the magnitude of the magnetic field. It is necessary to analyze the area of rapid increase of the degree of polarization for evaluation of the magnetic interaction of charge carriers and the Mn delta layer.

As the measurement temperature increases, the degree of circular polarization of the electric field decreases. This trend is attributable to the approximation of the measurement temperature to the Curie temperature of the δ-Mn layer. The dependence $P_{\mathrm{EL}}(H)$ becomes linear in the magnetic field at temperatures near 40 K. The temperature value for which the dependence $P_{\mathrm{EL}}(H)$ becomes close to linear corresponds to the Curie point of the δ-Mn layer. The circular polarization of the electron above the Curie point is caused only by the Zeeman splitting of levels in the quantum well.

To estimate the contribution of the ferromagnetic Mn delta layer, the contribution of Zeeman splitting was subtracted from the value of the degree of circular polarization:

$$P_{\mathrm{EL}}^{\mathrm{Mn}}(H) = P_{\mathrm{EL}}(H) - P_{\mathrm{Z}}(H), \quad (2)$$

where $P_{\mathrm{Z}}(H)$ is the value of the degree of circular polarization associated with the Zeeman splitting of levels, calculated from the slope of the linear section of the dependence $P_{\mathrm{EL}}(H)$.

Figure 4 shows the resulting magnetic field dependences of the degree of $P_{\mathrm{EL}}^{\mathrm{Mn}}$ circular polarization of all the studied samples, measured at a temperature of 10 K. It can be seen that similar nonlinear magnetic field dependences $P_{\mathrm{EL}}^{\mathrm{Mn}}(H)$ are observed for all three samples, while the magnitude of the circular polarization of the EL depends on the localization of charge carriers relative to the Mn delta layer and the quantum well. Thus, the maximum value of $P_{\mathrm{EL}}^{\mathrm{Mn}}$, which was 5 % at $H = 2500$ Oe, is observed for Sample 2, in which the carbon delta layer is located directly in QW.

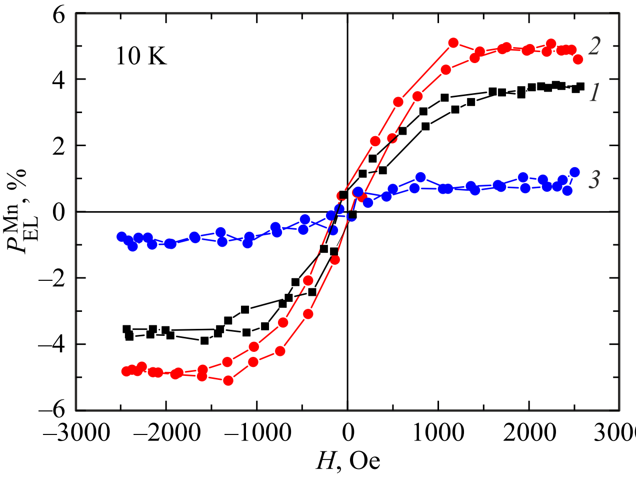

Figure 4. Magnetic field dependences of the degree of circular polarization $P_{\mathrm{EL}}^{\mathrm{Mn}}(H)$ for the studied samples, measured at a temperature of 10 K. The curve numbers correspond to the sample numbers.

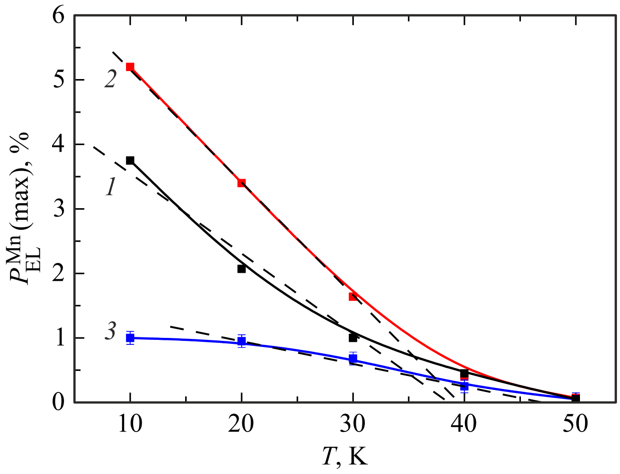

Figure 5. Temperature dependences $P_{\mathrm{EL(max)}}^{\mathrm{Mn}}$ of the studied samples. The curve numbers correspond to the sample numbers.

For Sample 1, in which the delta layer C is located in the GaAs buffer layer at a distance of 3 nm from the QW, $P_{\mathrm{EL}}^{\mathrm{Mn}} = 4$ % at $H = 2500$ Oe. For Sample 3, in which δ-C is located in the spacer layer between the layer δ-Mn and QW, the degree of circular polarization of the EL turned out to be minimal and amounted to < 1 % at $H = 2500$ Oe.

Figure 5 shows the temperature dependences of the maximum values of the degree of circular polarization $P_{\mathrm{EL(max)}}^{\mathrm{Mn}}$ obtained at $H = 2500$ Oe for the three studied samples. It can be seen that the dependencies $P_{\mathrm{EL}}^{\mathrm{Mn}}(T)$ have a similar form for Samples 1 and 2.

A sharp decrease in the degree of circular polarization is observed in the temperature range from 10 to 30 K, the dependence becomes more gentle with a further increase in temperature. The dependence $P_{\mathrm{EL(max)}}^{\mathrm{Mn}}(T)$ obtained for Sample 3 differs from the dependencies for the other two samples. In this case, the value of the degree of circular polarization does not change in the low temperature range (10–20 K), and $P_{\mathrm{EL(max)}}^{\mathrm{Mn}}$ decreases above 20 K, like in the previous two cases. The gradual decrease in the degree of circular polarization near the Curie point is due to the percolation character of the magnetic ordering of structures with a Mn delta layer. When passing through the percolation threshold, some regions of the structure with a locally high Mn concentration may retain ferromagnetic properties (while there is no interaction between these regions) [22]. The material as a whole becomes paramagnetic, in this case, in order to estimate the Curie temperature, it is necessary to extrapolate the sharp decline region $P_{\mathrm{EL(max)}}^{\mathrm{Mn}}$, as shown in Figure 5.

Extrapolation of the temperature dependence of the degree of polarization to the point $P_{\mathrm{EL(max)}}^{\mathrm{Mn}} = 0$ allows estimating the Curie temperature of the ferromagnetic δ-Mn layer in accordance with the procedure described in Refs. [15,16,18]. The values obtained are shown in the table. The value of T_{c} was ~ 37 K for Samples 1 and 2, and it is equal to ~ 47 K for Sample 3. A summary table of the

The maximum values of the degree of circular polarization and the Curie temperature for the studied samples

Sample number	$P^{\mathrm{Mn}}_{\mathrm{EL(max)}}$ at 10 K, %	T_{C}, K
1	3.8 ± 0.1	37 ± 5
2	5.2 ± 0.1	37 ± 5
3	1 ± 0.1	47 ± 5

results of the study of all the studied samples is provided in the Table.

Let's discuss the results of studies of circularly polarized electroluminescence. According to the known concepts and results in Refs. [16,18,19], which were obtained on similar structures, the delta layer of carbon in the GaAs matrix forms a band bending, which creates a potential well for holes. The potential well is formed due to an electric field induced by negatively charged carbon ions in GaAs [23]. The width of the potential well is determined by the concentration of C atoms. Mn atoms in GaAs are also an acceptor impurity, however, as was shown in Ref. [23], the magnitude of the electric field of Mn ions is significantly lower than that of carbon ions, since the Mn delta layer is dominated by conductivity in the impurity band and charge carriers are localized in Mn states [11,23]. Thus, the introduction of a carbon delta layer introduces additional holes into the system, which are localized near it.

From the point of view of magnetic properties, the studied system is a hybrid combining the magnetic moments of Mn atoms and the magnetic moments of holes localized in the area of the carbon delta layer. The relationship between holes localized in a quantum well and a nearby delta layer of Mn was demonstrated in Refs. [17,24]. It has been shown that spin-polarized holes in the QW orient the spin of Mn ions in the delta layer. In turn, the Mn spin affects the spin polarization of holes in the quantum well. In accordance with the results presented in Refs. [11,15,17,23,24], Mn atoms in the delta layer and nearby holes form a single magnetic system that reacts to an external magnetic field interconnectedly.

It should be noted that even in the absence of free holes, the delta layer of Mn exhibits magnetic properties: this was shown in Ref. [25] for structures with a single delta-Mn and in Ref. [11] for structures where the hole concentration was artificially suppressed (by the introduction of radiation defects). However, the presence of holes modifies the magnetic properties of the system, which is apparently related to the interaction of holes and Mn atoms. Electrically excited holes in conditions of low current density do not significantly affect the magnetic properties of the system due to their low concentration.

Thus, the sample structures shown in Figure 1 represent three different magnetic systems, the properties of which are determined by the specific configuration of the hole wave function and the position of the delta-Mn. The most effective interaction of holes with Mn atoms is realized according to Ref. [18], if the energy levels of the holes coincide in energy with the levels of Mn in GaAs. This is exactly the situation that occurs for holes localized in the area of the quantum well in Sample 2, for which the highest degree of circular polarization is recorded (Figure 3, curve *2*). Shifting the carbon delta layer to a greater distance from the Mn delta layer slightly reduces the degree of circular polarization, but at the same time the P_{EL} value remains high, since the region of hole localization near the carbon delta layer has a finite width and includes a nearby quantum well. For this reason, magnetic systems based on Sample 1 and Sample 2 slightly differ, which determines the proximity of the temperature dependences P_{EL} (Figure 5, curves *1* and *2*) and the close values of the degree of circular polarization.

Significant differences were recorded for Sample 3, for which the value of P_{EL} is significantly lower than in Samples 1 and 2, and the estimated value of the Curie temperature is slightly higher. In this system, the free holes are located closest to the Mn delta layer, and, consequently, the dimensions of the magnetic system itself (delta-Mn,+,holes) in the case of Sample 3 are lower than in Samples 1 and 2. The magnetic interaction of Mn and holes is also influenced by the electric field of carbon ions.

The results obtained indicate that the additional holes introduced affect the properties of Mn, which is quite consistent with early work on such systems [26,27]. Therefore, the carbon delta layer is a tool that allows controlling the magnetic properties of the system and the spin polarization of carriers in the active region of the structure (the quantum well). The mechanism of magnetic interaction is quite complex to describe, and, according to the results in Ref. [17], refers to a type of exchange interaction between states associated with an admixture of Mn and hole states in GaAs or the region of dimensional quantization.

Thus, in this paper, the influence of the position of the carbon delta layer on the magnetic properties and circularly polarized electroluminescence in heterostructures with an InGaAs/GaAs quantum well and a nearby delta layer of Mn is studied. It is shown that the magnetic characteristics of the system (the shape of the hysteresis loop, the Curie temperature) and the degree of circular polarization of electroluminescence depend on the specific location of carbon relative to delta-Mn and the quantum well, which is due to the formation of a hybrid magnetic system delta-Mn + holes, the efficiency of the exchange interaction in which depends on its specific configuration. From the point of view of practical applications, localization of the carbon delta layer in the quantum well region is of interest, because this provides an increase in the degree of polarization and registration of a closed hysteresis loop on magnetic characteristics.

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Conflict of interest

The authors declare that they have no conflict of interest.

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