Circularly polarized electroluminescence in LED heterostructures with InGaAs/GaAs quantum well and Mn δ-layer

S.V. Zaitsev a,*, V.D. Kulakovskii a, M.V. Dorokin b, Yu. A. Danilov b, P.B. Demina b, M.V. Sapozhnikov c, O.V. Vikhrova b, B.N. Zvonkov b

a Institute of Solid State Physics, Russian Academy of Sciences, 142432 Chernogolovka, Russia
b Physico-Technical Research Institute of N.I. Lobachevskii State University, 603950 Nizhny Novgorod, Russia
c Institute for Physics of Microstructures, Russian Academy of Sciences, 603950 Nizhny Novgorod, Russia

1. Introduction

Intensive development of spintronics invoked strong interest in new semiconductor materials possessing ferromagnetic (FM) properties [1]. One of the most prospective materials of this kind is a GaMnAs diluted magnetic semiconductor (DMS) which is intensively studied now [2,3]. The FM transition temperature $T_c$ as high as 170 K was observed in epilayers of this DMS compound [4]. In the GaMnAs free holes are supplied by Mn atoms that act not only as a local magnetic moment but also as an acceptor in the Ga cation position [3]. Despite the microscopic FM mechanisms in GaMnAs are still discussed, at present it is convincingly shown that free holes and/or holes in acceptor band play determining role in formation of the FM state, interacting with magnetic atoms [3]. The increase of local hole concentration in a two-dimensional (2D) channel by means of δ-doping with Mn has led to the increase of $T_c$ up to 250 K [5].

The main advantage of GaMnAs is a possibility to use it both as a hole injector in light emitting diodes (LEDs) and as a spin aligner [6]. In present paper we study LEDs with InGaAs/GaAs quantum well (QW) and nearby Mn δ-layer. We found that introducing of such δ-layer grown at low temperature allows to achieve both high values of the electroluminescence (EL) circular polarization degree and to increase the EL efficiency of LEDs.

2. Experimental section

A combined technique of metal-organic vapor phase epitaxy (MOVPE) at atmospheric pressure and pulse laser deposition (PLD) was applied for growth of the studied structures. Structure design is shown in inset in Fig. 1. First, the n-doped GaAs buffer layer, a 10-nm-thick In$_x$Ga$_{1-x}$As QW ($x = 0.1–0.2$) and a thin undoped GaAs spacer with thickness $d_z = 2, 3, 5$ and $10$ nm were grown on the n'-GaAs (100) substrates by use of MOVPE at temperature 650 °C. Then in the same reactor a δ-layer of Mn with a nominal thickness of 0.4 monolayer (ML) and a cap layer of GaAs (20 nm) were formed using PLD of metallic Mn and undoped GaAs, respectively. Targets were sputtered with a focused beam of pulsed YAG: Nd laser. Using the PLD allows to decrease the growth temperature $T_g$ down to 400 °C and thus to minimize Mn diffusion inside the active area of the LED. A top 0.5 mm diameter Au
Schottky contact to the GaAs cap layer was thermally deposited in vacuum. Before deposition the structures were kept in a dry atmosphere which always results in a formation of about 5-nm-thick natural oxide layer on the GaAs surface [7]. The ohmic contacts to substrates were formed by alloying of the tin pads. Two reference LEDs were also studied: the first one is a Be δ-doped diode with \( d_\delta = 3 \) nm (reference LED #1), and the second one with a QW and a 20-nm GaAs cap layer without δ-doped layers (reference LED #2). Additional structures for transport measurements were grown by the same techniques on the semi-insulating (i-GaAs) substrates and a standard Hall bars were etched.

Forward bias EL and photoluminescence (PL) were measured at temperatures \( T = 77 \) and 1.8 K. Measurements at 1.8 K were done in the Faraday geometry (magnetic field \( B \) is normal to the sample surface) in magnetic cryostat with a superfluid He. The EL emission was collected from the back side of the reference substrate. The degree of circular polarization \( P_c \) is defined as \( P_c = (I_+ - I_-)/(I_+ + I_-) \), where \( I_+ \) and \( I_- \) are intensities of the \( \sigma^+ \) (\( \sigma^- \)) polarized EL emission spectrum, corresponding to optical transition in the QW.

3. Results and discussion

The EL spectra at \( T = 77 \) K of the LED with Mn δ-layer \( (x = 0.1, d_\delta = 10 \) nm) and of the reference LED #2 \( (\delta = 0 \) nm, no δ-doping) are shown in Fig. 1(a). Spectral band at 1.415 eV corresponds to the QW emission. One can see that the EL intensity \( I_{EL} \) of the LED with δ-layer is more than one order of magnitude larger than that of the reference LED #2. This is in agreement with our previous investigations where we have shown that the LED efficiency increases significantly when acceptor C δ-layer is included into the cap layer [8]. We suggest that the acceptor δ-layer promotes hole injection from the Schottky contact with the mechanisms of such enhancement are discussed in Ref. [8]. The \( I_{EL} \) magnitude non-monotonously depends on the spacer between δ-layer and QW with a maximum at \( d_s = 10 \) nm (Fig. 1(b)).

In Fig. 2 are depicted the EL spectra of the LED with \( d_s = 5 \) nm at low \( T = 1.8 \) K and \( B = 0 \) and 9 T. The QW transition energies increase with \( B \) and have close to linear dependencies (inset in Fig. 2). Absence of Landau levels which are typical at high \( B \) [9] is probably related with the broadening effect due to charged defects. The decrease of \( d_s \) to 2 nm results in a significant decrease of \( I_{EL} \) (Fig. 1(b)) and huge increase of the QW line width \( (> 20 \text{meV}) \). The operating current \( (I_o) \) of the diode with \( d_s = 2 \) nm (when a reasonable EL signal is obtained) is \( > 20 \) mA, which is much higher than in LED with \( d_s = 5 \) nm \( (I_o = 5 \) mA). Mn impurity in the low \( T \) grown GaAs is known as a source of nonradiative recombination centers which quench PL even at very low Mn contents [10]. Thus, the observed EL quenching can be explained by the increase of nonradiative recombination rate with the decrease of the distance between the QW and Mn δ-layer resulting in incorporation of Mn atoms to the QW. One can estimate the Mn diffusion length of about 1–2 nm in GaAs grown at \( T_g = 400 \) °C.

The EL of LEDs with Mn δ-layer is strongly circularly polarized at \( B > 0 \) (Fig. 2). The dependencies of \( P_c(B) \) are given in Fig. 3. One can see that the values of \( P_c \) in the reference structures are small and linearly increase with \( B \) up to \( 0.1 \) (\( B = 9 \) T) which is related to a small Zeeman splitting (\( < 0.5 \) meV) in the QW. In the structures with Mn \( P_c(B) \) dependencies are significantly nonlinear: they show a fast increase at \( B < 1–2 \) T and slower rise in higher \( B \). The value \( P_m = P_c(B = 9 \) T) shows a non-monotonic dependence on \( d_s \) for \( x = 0.1 \): it increases with decreasing \( d_s \), reaches maximum of \( P_m \approx 38 \% \) at \( d_s = 5 \) nm and then drops for \( d_s = 2 \) nm (inset in Fig. 3). The highest value of \( P_m \approx 50 \% \) was found in the LED with \( d_s = 3 \) nm and \( x = 0.2 \). It is important to emphasize that values of \( P_c(B) \) in LEDs with Mn δ-layer significantly exceed ones in both reference diodes (Fig. 3) which unambiguously evidences about...
determining role of Mn δ-layer in strong spin polarization of recombining carriers in the QW [11].

In the studied forward biased LEDs the holes are injected from the Schottky gate [9]. One can suggest a possibility of hole polarization during its transport due to interaction with the magnetic moments of Mn in δ-layer. Then the spin-polarized holes are injected into QW. However, such interpretation faces some general objections. The first one is a rather small thickness of δ-layer (2–3 nm) that results in a very small estimated interaction time (~1 ps or less) for typical hole mobility values. The second objection arises from a strong dependence of \( P_n (B) \) on \( d_z \) which should be weaker when the spin injection is considered. Spin injection experiments with FM Schottky LEDs have shown a small difference between spin loss when the injected hole is transported through the cap layer ≤30 nm [12] which is in contrast to the strong dependence of \( P_n \) on \( d_z \) (Fig. 3).

Another explanation is that the holes are polarized after capturing into QW, interacting via a strong p-d exchange with Mn atoms [13], similar to the case of MnAs/GaAs digital heterostructures [14]. It is confirmed by the \( P_n (B) \) dependencies of PL of the same samples without Schottky contact which show close to the EL case values. Some difference might be related to different band bending in different conditions. Generally, it confirms that the hole spin alignment takes place in the QW. Contribution due to band bending in different conditions. Generally, it confirms that the hole spin alignment takes place in the QW.

The second objection arises from a strong dependence of \( R_s (T) \) on \( T \) that the QW is the main conductivity channel at low temperatures (Fig. 3). Its magnitude is of the same order in the whole temperature range. At \( T \approx 40 \) K one can distinctly see a broad maximum which is characteristic to the 3D and 2D FM structures and results from the increased carrier scattering on spin fluctuations at \( T > T_c \) [16]. This confirms the suggestion of effective interaction of holes in the QW with the tunnelling close Mn δ-layer.

4. Conclusion

A possibility to increase the intensity and obtain strongly circular polarized electroluminescence by means of δ-doping by Mn is experimentally demonstrated at low temperature in Schottky diodes with a near contact QW. High values of polarization are caused by the exchange interaction of holes in the QW with Mn atoms in the δ-layer giving rise to spin polarization of holes. The exchange character of interaction is independently confirmed by the peculiarity in the temperature dependence of resistance characteristic to the ferromagnetic transition. It opens exciting prospects to obtain circular polarized emitters for optoelectronics based on high-\( T_c \) DMS compounds like GaMnAs.

Acknowledgements

This work was partly supported by Russian Foundation for Basic Research (Grants 07-02-01153, 08-02-00548 and 08-02-97038), Ministry of Education of Russian Federation (Project RNP 2.2.2.2. 4737), Civilian Research and Development Foundation (Grant RUJX–001–NN–06/BP1M01) and Program of Russian Academy of Sciences “Spin-dependent effects in solids and spintronics”.

References