On the mechanism of spin-polarized injection in (Ga,Mn)As/n+GaAs/InGaAs Zener tunnel diode

M Ved¹, M Dorokhin¹, E Malysheva¹, A Zdoroveyshchev¹, Yu Danilov¹, A Parafin² and Yu Kuznetsov¹

¹Physical Technical Research Institute of Lobachevsky State University of Nizhny Novgorod, Nizhny Novgorod, 603950 Russia
²Institute of Applied Physics, Russian Academy of Sciences, Nizhny Novgorod, 603950 Russia

Abstract. In the present work we have investigated the spin light-emitting diode structures based on InGaAs/GaAs quantum well and a (Ga,Mn)As dilute magnetic semiconductor as an injecting layer. The luminescent properties and the magnetic-field dependence of the circular polarization degree of the initial and annealed samples were measured. It was experimentally shown that the temperature dependence of circular polarization degree below the Curie point (~110 K) is determined by the thermally activated tunnelling of bound electrons from energetically split spin-up and spin-down subbands of magnetized (Ga,Mn)As. The approximation parameters allowed us to derive the values of the spin energy splitting in (Ga,Mn)As subband and the spin depolarization during the transfer from (Ga,Mn)As to the device active region.

1. Introduction

Diluted magnetic semiconductors (DMS) that combine semiconductor and ferromagnetic properties are promising elements of spintronic devices, since they are characterized by a high degree of carriers spin polarization (which is the main property), and the compatibility with the semiconductor technology [1]. The (Ga,Mn)As solid solution is considered as one of the most promising DMS because of its good compatibility with GaAs, which is the basic material of optoelectronic devices. The disadvantage of DMS, and in particular of (Ga,Mn)As, is the relatively low Curie temperature. The main method for obtaining (Ga,Mn)As layers with increased Curie temperature (~110K) is the epitaxial growth (Ga,Mn)As/GaAs layers by the low-temperature molecular-beam epitaxy technique [2]. An alternative method for obtaining DMS is pulsed laser deposition (PLD). Earlier it was shown that the layers obtained by this method are ferromagnetic with a Curie temperature not exceeding 40K. This is due to the fact that only a small fraction of the Mn atoms are embedded in the Ga substitutional position in GaAs lattice [3]. However it was recently demonstrated that the annealing of (Ga,Mn)As-based structures by a short-wave pulsed laser promotes the redistribution of Mn in the (Ga,Mn)As layer and, as a result, an increase of the Curie temperature [4].

The present work is devoted to the study of spin light-emitting diodes including (Ga,Mn)As layers. The spin LEDs were fabricated by the combined technique of a metal-organic vapor phase epitaxy (MOVPE) and pulsed lased deposition. The diode structure was based on the InGaAs/GaAs quantum
well (QW) and the (Ga,Mn)As layer which was used to inject the spin polarized holes into QW. We study the modification of SLED properties after the pulsed laser annealing of the structure.

2. Experimental technique

The as-grown samples were formed by combined epitaxial method. This method is described in detail in [2]. The following layers were sequentially grown by metal organic vapour-phase epitaxy at atmospheric pressure and a temperature of 600°C on p-GaAs (100) substrates: p-GaAs buffer layer; In$_x$Ga$_{1-x}$As QW (concentration $p \sim 8 \cdot 10^{17}$ cm$^{-3}$, width $d_{QW} = 10$ nm, In content $x \sim 0.12$); i-GaAs, n - GaAs layer with a gradient doping, heavily doped n$^+$ layer ($n \sim 7 \cdot 10^{18}$ cm$^{-3}$) and $\delta <Si>$ -layer (total electron concentration in n$^+$ GaAs and $\delta <Si>$ was $10^{19}$ cm$^{-3}$). Highly doped layer thickness was 30 nm. Then, GaMnAs layer was grown by the pulsed laser deposition of Mn and GaAs targets at a temperature of 290°C in the same reactor.

In order to modify the (Ga,Mn)As structure and to increase the Curie temperature the pulsed laser annealing of the samples surface was used [3]. The annealing experiments were performed using the excimer laser LPX-200 on KrF (wavelength 248 nm, pulse duration ~ 30 ns, energy density in the pulse 290 mJ/cm$^2$). It was earlier demonstrated that the laser annealing leads to an increase of the concentration of electrically active Mn in diluted magnetic semiconductor layers, and, as a consequence, to an increase of the Curie temperature [3]. In our work, we have studied both the as-grown and annealed structures in order to characterize the influence of annealing on the electroluminescence properties.

To form the diode structure an Au Ohmic contact was deposited onto the surface of the samples and the sparking of In foil was used to create the Ohmic contact to the base. The electroluminescent radiation of the samples was detected in the reverse bias mode (negative voltage onto top (Ga,Mn)As contact with respect to the base). The formed structures are shown in Figure 1.

![Figure 1. Scheme of the studying structures.](image)

When spin light-emitting diodes are introduced into an external magnetic field, their emission becomes partially circularly polarized. Studies of circularly polarized electroluminescence were carried out using standard measurement techniques with a quarter wave plate and a polarizer [1]. The degree of circular polarization of EL ($P_{EL}$) was calculated by the formula:

$$
P_{EL} = \frac{I(\sigma^+) - I(\sigma^-)}{I(\sigma^+) + I(\sigma^-)} \cdot 100\% ,
$$

where $P_{EL}$ is the degree of circular polarization of electroluminescence; $I(\sigma^+)$, $I(\sigma^-)$ are the intensities of the left and right circularly polarized EL components respectively.

3. Results and discussion

Measurements of magnetic field dependences of $P_{EL}$ for as-grown sample and for annealed sample at different temperatures were performed. It was shown, that for the as-grown structure, the maximum operating temperature of the spin light-emitting diode (i.e., the temperature at which non-linear
magnetic field dependence of a polarization degree is conserved) is 25K. The detailed measurements of as-grown samples were performed in [4].

After the pulsed laser annealing of the structures, the diode operating temperature has increased to ~110 K, due to an increase of the Curie temperature of the (Ga,Mn)As layer. The magnetic field dependences of structure after laser annealing is shown in Figure 2.

![Figure 2](image1.png)

*Figure 2. Magnetic field dependence of $P_{EL}$ for annealed sample. Diode current – 10mA.*

The increase of the Curie temperature is presumably due to the redistribution of Mn in the layer of a dilute magnetic semiconductor: most of Mn becomes embedded into the lattice sites. In addition, the luminescence intensity, as well as the magnitude of the degree of circular polarization after laser exposure, remained almost without changes. It means that the laser impact affected basically the ferromagnetic injector, while maintaining the parameters of the light-emitting diode.

The comparison of the temperature dependence of the degree of circular polarization for the as-grown and annealed structures is shown at Figure 3.

![Figure 3](image2.png)

*Figure 3. Temperature dependence of the degree of circular polarization for as-grown and annealed structures ($I = 10mA$, $B = 300mT$) and a curve approximating dependence for annealed structure by the formula 2 (red line).*

Let us discuss the mechanism of spin injection from (Ga,Mn)As into semiconductor structure. The band diagram of studied structure is shown in Figure 4.
Figure 4. The scheme of the spin injection process in the studied samples.

The rapid drop of the polarization degree near the Curie point can obviously be attributed with the decrease of spin polarization in (Ga,Mn)As because of the demagnetization of the sample. At the temperature, which is far below the Curie point the relatively small decrease of $P_{EL}$ with increasing $T$ was obtained. We believe that in the low-temperature range (10-80 K) the magnetization value of (Ga,Mn)As does not change significantly and the detected $P_{EL}$ decrease is due to the decrease of the current spin polarization. The latter can be defined as

$$\eta = \frac{j^\uparrow - j^\downarrow}{j^\uparrow + j^\downarrow} \cdot 100\%,$$

(2)

where $j^\uparrow (j^\downarrow)$ - is a spin-up and spin-down current respectively. These currents are determined by the probability of tunnelling and thermal activation through a potential barrier for charge carriers with different spins (shown schematically at Fig.4). When the structure is introduced into an external magnetic field (to a saturation of magnetization), energy levels of charge carriers with parallel and antiparallel spins in the DMS layer split and, as a result, the probability of tunnelling for carriers with the majority spin increases. Then the spin polarized current and the EL polarization degree are determined only by the thermal energy of the charge carriers.

To evaluate the spin polarization degree in low temperature range the following formula was used:

$$P_{EL}(T) = P_0 \frac{1 - \exp\left(\frac{-\Delta U}{kT}\right)}{1 + \exp\left(\frac{-\Delta U}{kT}\right)} \cdot 100\%,$$

(3)

where $P_0$ – the carriers spin polarization in magnetized (Ga,Mn)As divided by the depolarization factor [5]; $\Delta U$ – the difference of energy levels of charge carriers with parallel and antiparallel spins in the DMS layer. The approximation of the experimental $P_{EL}(T)$ dependence by the formula (3) with the $P_0$ and $\Delta U$ being used as the adjustable parameters is given at Fig.3 (solid line). One can see that there is a good agreement between the experimental data and the approximation curve taking into account the experimental error.

The energy splitting value used for approximation was $\Delta U = 9.55$ meV. This value correlates well with the values of the energy splitting between spin-up and spin-down bands of magnetized (Ga,Mn)As in [6] – 5-11 meV and in [7] – 9-12 meV. This, in turn, is in good agreement with the spin injection picture plotted at Fig.4 since within the thermally activated tunnelling process the spin polarized current should indeed be dependent on the potential barrier difference for spin-up and spin-down carriers.

The $P_0$ value derived from the approximation was 0.56 %. Within the known value of spin polarization in (Ga,Mn)As (calculated in [8] from the Andreev Spectroscopy measurements;
$P \sim 57\%$) one can estimate the depolarization factor as high as 100. This value corresponds to the decrease of electron spin polarization due to the spin scattering during the injection through a highly doped n+GaAs and p-GaAs layers.

Thus the energy difference $\Delta U$, which was revealed from the approximation of experimental curve is in good agreement with the values obtained from completely different experiments [6,7]. We believe that such agreement is the evidence of the validity of the theory used.

It should be noted that the approximation by formula (3) is only applicable at temperatures far below the Curie temperature, because of when approaching the Curie point, the (Ga,Mn)As demagnetization becomes the most significant factor influencing the polarization degree.

In conclusion we have investigated the temperature dependence of circular polarization degree of spin light-emitting diodes based on p-GaAs/InGaAs/n-GaAs/n+GaAs Zener tunneling diode structure with the (Ga,Mn)As layer deposited on the top n+GaAs. The laser annealing of the top (Ga,Mn)As have led to the increase of the SLED operating temperature. The analysis of $P_{ar}$ temperature dependence has revealed the mechanism of thermally activated tunneling of bound electrons from energetically split spin-up and spin-down subbands of magnetized (Ga,Mn)As.

**Acknowledgments**

Authors would like to acknowledge Dr. B.N. Zvonkov for the fabrication of investigated samples. This study was supported by the Russian Foundation for Basic Research (projects 18-37-00358 (growth of samples by metal organic vapour-phase epitaxy and pulsed laser deposition), 16-07-01102), Ministry of Education and Science of Russian Federation (project 8.175.2017/PP) and the scholarship of the president of the Russian Federation (SP-2450.2018.5).

**References**

[1] Holub H, Bhattacharya P 2007 *J. Phys. D: Appl. Phys* **40** R179
[2] Dietl T, Ohno Y 2014 *Rev. Mod. Phys.* **86** 187.
[3] Vikhrova O, Danilov Yu, Zvonkov B, et.al. 2017 *Physics of the Solid State* V.59(11) 2150.
[4] Malysheva E, Dorokhin M, Ved’ M, et.al. 2015 *Semiconductors* V.49(11) 1448.
[5] S.H. Liang, T.T. Zhang, P. Barate, et.al. 2014 *Phys.Rev.B* **90** 085310.
[6] Dietl T 2001 *Phys. Rev. B* **63** 195205.
[7] Linnarsson M, Janzen E, Monemar B, et.al. 1997 *Phys.Rev.B* **55** 6938.
[8] S. Piano, R. Grein, C.J. Mellor, et.al. 2011 *Phys.Rev.B* **83** 081305(R).