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Temperature stabilization of spin-LEDs with a CoPt injector

A V Rykov, M V Dorokhin, P B Demina, A V Zdoroveyshchev and M V Ved'

Research Institute of Physics and Technology, Lobachevsky State University, Nizhni Novgorod, 603950, Russia

rikov@nifti.unn.ru

Abstract. Spin light-emitting diodes based on GaAs/InGaAs/AlGaAs heterostructures with a ferromagnetic CoPt injector have been fabricated and studied. To obtain stability of diodes at higher temperatures, heterostructures with three different combinations of a quantum well and barriers have been studied. A stable 2% circular polarization degree of electroluminescence was obtained at temperatures up to 300 K.

1. Introduction

Spin light-emitting diodes (spin-LEDs or SLEDs) based on A3B5 semiconductors are one of the key elements of spintronics [1]. Operation of SLEDs is based on electrical injection of spin-polarized carriers from a magnetized ferromagnetic injector layer followed by radiative recombination of injected carriers with unpolarized ones. The recombination process is accompanied by the emission of circularly polarized light. The degree of circular polarization is set by magnetization of the injector and can be controllably changed, for example, by an external magnetic field [1, 2].

Currently, the main task to be solved within the technology of spin light-emitting diodes is preservation of both high intensity and high polarization degree for a wide range of temperatures (including 300 K). The specific type of ferromagnetic injector layers including a thin interfacial MgO dielectric layer was developed in [3, 4] to obtain a high polarization degree. The question of high electroluminescence intensity at room temperature is very often ignored although most of SLEDs active regions tend to reveal temperature quenching of luminescence due to the thermal escape of carriers from the active region at room temperature.

In the present paper, we compare three types of SLEDs active regions based on AlGaAs/GaAs and/or GaAs/InGaAs heterostructures. We demonstrate that a relatively high confinement potential allows us to obtain room temperature luminescence. Spin light-emitting diodes based on structures under consideration emit circularly polarized light at 300 K thus the developed structures can be used for fabrication of SLEDs which would meet the mentioned requirements for their operation.

2. Structures fabrication and characterization

The series of heterostructures with different combinations of a quantum well and barriers was produced to study temperature quenching of luminescence in a quantum well (QW). The structures were grown by metal-organic chemical vapour deposition (MOCVD) process at a low pressure (100 mbar) and at 650ºC on semi-insulating GaAs. The first batch of structures (No.1-3) includes the following layers: a 500 nm p-$Al_xGa_{1-x}As$ buffer layer, a 11 nm $In_{0,22}GaAs$ QW and a 100 nm $Al_xGa_{1-x}As$ cap layer. The parameter x has been varied for $Al_xGa_{1-x}As$ barriers which acted as a confinement potential for carriers in a QW. The second batch of structures differs from the first one by its active region. Instead of a usual InGaAs QW, the two-step GaAs/InGaAs/GaAs QW was grown (structures 4 and 5). The test structure of a InGaAs QW in a GaAs matrix was grown as a reference (*T*).

Results of photoluminescence (PL) measurements at room temperature are shown in figure 1. The line at ~ 995 nm dominates in all spectra, this line corresponds to radiative transitions in the quantum well. Structures with higher confinement barriers (a higher Al content in the barrier) demonstrate a higher luminescence intensity of the QW peak relatively to the reference structure. The only exception is structure 1, in which a slight increase of the barrier height (10% Al in AlGaAs) is prevailed by the luminescence quenching effect caused by a large concentration of irradiative centers on the InGaAs/AlGaAs heterointerface. This effect is also responsible for the fact that structures 1 and 2 have significantly lower PL intensities than structures 4 and 5, respectively, despite the same AlGaAs barrier height.

PL spectra of the studied structures at 77 K are shown in figure 2. The same QW peak dominates in the spectrum; the emission wavelength is ~ 950 nm due to the bandgap increase with decreasing temperature. It is worth mentioning that thermal ejection of carriers is insignificant at liquid nitrogen temperature. Therefore, the quality of the structure and, in particular, the quality of the QW/barrier heterojunction take a top priority. Thus, the reference structure has the highest PL intensity and is followed by structures 4 and 5 with two-step QWs, as expected.

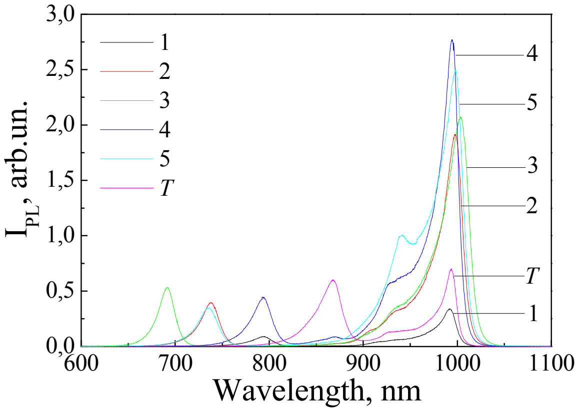

Figure 1. PL spectra measured at 300 K for the following structures: 1 - InGaAs/$Al_{0.1}$GaAs, 2 - InGaAs/$Al_{0.2}$GaAs, 3 - InGaAs/$Al_{0.3}$GaAs, 4 - InGaAs/GaAs/$Al_{0.1}$GaAs, 5 - InGaAs/GaAs/$Al_{0.2}$GaAs, *T* – InGaAs/GaAs (the reference sample).

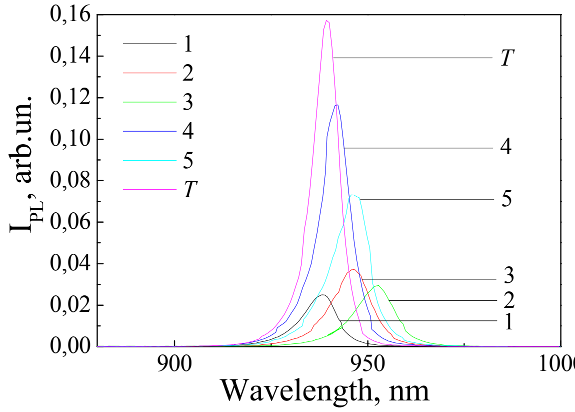

Figure 2. PL spectra measured at 77 K. PL intensity of the reference sample (*T*) divided by 2 for convenience.

3. Electroluminescence and circular polarization study

Spin light-emitting diodes (spin-LEDs) with a ferromagnetic CoPt injector were produced basing on the results shown in the previous section (figure 3). The diode structures were grown on a p^+-GaAs substrate and included a two-step $In_{0.23}$GaAs/GaAs QW and barriers with Al content $x = 22\%$. The top barrier for a QW (a spacer) included a 10 nm $Al_{0.22}$GaAs layer and a 10 nm GaAs cap. The cap layer prevents redundant oxidation of AlGaAs due to the inter-operational air exposure during SLED fabrication. A ferromagnetic Schottky CoPt contact was deposited on the structure surface by layer-by-layer deposition of Co and Pt at 200ºC using an electron beam [5]. To improve the efficiency of spin injection and the crystalline quality of the ferromagnetic layer (a semiconductor interface), a tunnel-thin Al_2O_3 layer was deposited (as a diffusion barrier [6]) on the GaAs surface before depositing the ferromagnetic CoPt layer.

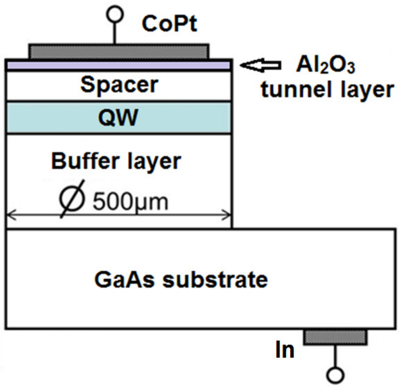

Figure 3. The scheme of a spin-LED device.

For electroluminescence (EL) measurements, a forward bias was applied to a sample CoPt/*p*-GaAs Schottky contact (a negative potential to the CoPt with respect to the In base). The EL circular polarization degree dependence on magnetic field was studied in the temperature range of 10 ÷ 300 K. Magnetic field was applied perpendicularly to structures' plane and has been varied in the range from -200 to 200 mT. The circular polarization degree of EL was defined as:

$$P = (I_+ - I_-)/(I_+ + I_-). \quad (1)$$

Here I_+ and I_- are the intensities of σ^+- and σ^--circularly-polarized components of EL, measured at a spectra maximum corresponding to radiative transitions in a QW. Emission of circularly polarized radiation with a wavelength corresponding to the QW is the evidence of spin-polarized carriers in the QW. In the situation when we apply a negative voltage to the structure, electrons of CoPt are injected into the conduction band of GaAs through the tunnel-thin Al_2O_3 film [7]. When we put the structure into magnetic field, the effective density of states of ferromagnetic material increases for carriers with «majority» spin and decreases for carriers with «minority» spin. That is why the carriers with mainly «majority» spin are injected into a semiconductor. In the end, spin-polarized electrons diffuse into the QW, then recombine with non-polarized holes supplied from the substrate.

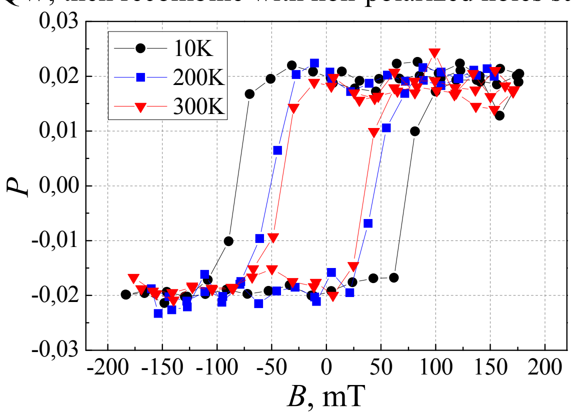

Figure 4. EL circular polarization degree of diodes with InGaAs/GaAs QWs in an $Al_{0,22}GaAs$ matrix.

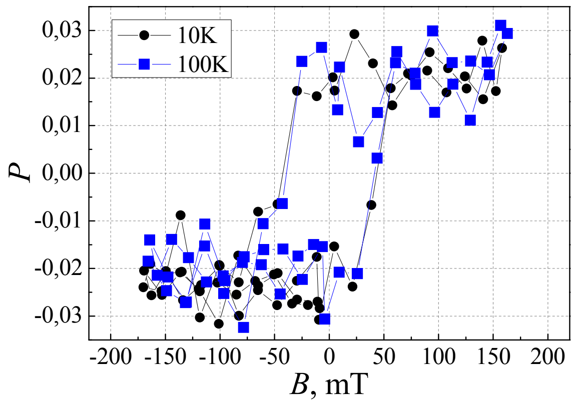

Figure 5. EL circular polarization degree of diodes with InGaAs QWs in a GaAs matrix (reference sample).

Electroluminescence studies of diodes with a CoPt injector have shown a 2% circular polarization degree at temperatures from 10 K up to 300 K. We believe that the observed EL circular polarization is caused by spin injection process described above. Other mechanisms that could be responsible for the circularly polarized emission (mainly magnetic circular dichroism) are insignificant in our measurement scheme. Indeed, the EL emission was collected from the back of the sample, i.e. the detected part of the EL signal transferred not through the CoPt layer but through the transparent GaAs substrate.

We note that there was no sign of temperature decrease of the polarization degree in the temperature range from 10 to 300 K according to the error levels (figure 4). A hysteresis loop characteristic for the ferromagnetic CoPt layer was observed [5]. The coercive field is temperature dependent, the width of the loop decreases with temperature increase. Diodes with a conventional InGaAs QW in a GaAs matrix with a 20 nm GaAs spacer were used as a reference for the studied SLEDs. Diodes with this kind of configuration of the active region and with the CoPt Schottky contact have a relatively weak electroluminescence, which affects the polarization degree measurements and causes a high dispersion of results (figure 5). In addition, a significant temperature quenching of EL prevents us from observation of electroluminescence and a circular polarization at room temperature. Spin-LEDs with the two-step InGaAs/GaAs QW in an AlGaAs matrix demonstrated a stable electroluminescence with polarization at room temperature. The studied SLEDs have shown a higher EL intensity and a significantly lower dispersion of a polarization degree magnitude in comparison to conventional SLEDs.

Thus, we have manufactured spin-light emitting diodes based on different active regions and investigated the circularly polarized emission of these diodes. We have demonstrated that both temperature quenching and non-radiative recombination influence the EL intensity and prevent EL observation at room temperature. Fabrication of the high-quality InGaAs/GaAs/AlGaAs quantum well allows us to improve the quality of interfaces and to increase the QW confinement potential. This results in stable observation of EL circular polarization at room temperature.

Acknowledgments
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