Fabrication and luminescent properties of (In,Fe)Sb/GaAs/InGaAs diodes

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Abstract. The electrical and luminescent characteristics of InGaAs/GaAs spin light-emitting diodes with an injector based on (In,Fe)Sb were investigated and the circular polarization of the electroluminescence was obtained for such structure. It has been established that the deposition of (In,Fe)Sb layer does not introduce any additional defects into the region of near-surface quantum wells, but directly affects the (In,Fe)Sb/GaAs interface. It was found that the application of a thin protective layer of MgO between the ferromagnetic (In,Fe)Sb injector and the light-emitting structure minimizes this effect.

1. Introduction
Diluted magnetic semiconductors (DMS) are materials doped with transition element atoms. It possesses both ferromagnetic and semiconducting properties. Such materials can be used as the elements of spintronic devices, for example, as an injector in spin light-emitting diodes (SLED) [1]. Today one of the most promising magnetic semiconducting materials are (A3,Fe)B5 DMS and, in particular, (In,Fe)Sb, since its Curie temperature exceeds 300 K [2]. At the current stage of (A3,Fe)B5 technology level, the most important task is the effective integration of (A3,Fe)B5 into devices based on the most common optoelectronic material such as GaAs. In this work the fabrication of (In,Fe)Sb layer by the method of pulsed laser deposition (PLD) and its effect on the properties of an (In,Fe)Sb/InGaAs/GaAs spin light-emitting diodes was investigated.

2. Experimental technique
The samples were fabricated in four stages. At the first stage, two semiconductor heterostructures were grown by metal-organic vapor phase epitaxy at temperature of 600°C. The first structure was grown on the n-GaAs substrate and consisted of three In$_x$Ga$_{1-x}$As/GaAs quantum wells (QW) with different indium content ($x_1$=0.12; $x_2$=0.15; $x_3$=0.2) which located at different distances from the surface of the structure (30 nm, 70 nm and 110 nm respectively). The second heterostructure was grown on the p-GaAs substrate and consisted of single InGaAs/GaAs QW, which was located at 15 nm from the surface of the structure. At the next stage, the structures were coated with a 1 nm protective layer of MgO to prevent exposure by the laser plasma during the following deposition of the (In,Fe)Sb layer using the PLD method, and also to prevent the diffusion of Fe atoms into the light-emitting structure. At the third stage, an (In,Fe)Sb layer with a thickness of 40 nm was deposited on samples with a protective MgO layer and on the initial sample of the first structure at a temperature of 200°C by PLD technique. At the last stage of diode fabrication, Au contacts were deposited onto samples with an (In,Fe)Sb injector by electron beam evaporation in vacuum, then 500 μm mesa structures were made by photolithography and chemical etching, and a basic Ohmic contact was formed. Thus, three
samples were formed on the basis of the first structure with 3 QWs: 1 - SLED with an (In,Fe)Sb injector and a protective layer of MgO; 2 - SLED with an (In,Fe)Sb injector without a protective layer; 3 - the original light-emitting structure without contacts. In addition one sample of the second structure with one QW was formed: 4 – SLED with an (In,Fe)Sb injector and a protective layer of MgO. The schematic representation of the sample structures are shown at figure 1.

Figure 1. Structure scheme of the sample 1 (a); sample 2 (b); sample 3 (c); sample 4 (d).

The samples of the first structure (samples 1, 2 and 3) were investigated to determine the effect of the (In,Fe)Sb layer on the radiative characteristics of LEDs. The photoluminescence (PL) spectra were measured for samples 1, 2 and 3. For the excitation of photoluminescence, a He-Ne laser with a wavelength of 632 nm was used. For samples 1 and 2 the Au and (In,Fe)Sb layers were etched before measuring photoluminescence. The electroluminescence (EL) spectra were measured for diodes with an injector of (In,Fe)Sb (samples 1 and 2). For electroluminescence studies, a forward bias was applied to the samples (a positive potential with respect to the substrate was applied to Au contact). Excited EL radiation was detected from the substrate side. Measurement temperature was 77K.

The sample 4 was used to investigate the magnetic field dependence of the degree of circular polarization ($P_{EL}$) caused by a spin injection from a magnetized (In,Fe)Sb into GaAs. When structure was introduced into perpendicular magnetic field, the EL emission becomes partially circularly polarized. The degree of circular polarization $P_{EL}$ is calculated by the formula:

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

where $I(\sigma^+)$, $I(\sigma^-)$ are intensities of EL components polarized along the left and right circles, respectively.

The $P_{EL}$ magnetic field dependence of sample 4 was measured at a temperature 10 K in a closed-loop cycle cryostat.

3. Results and discussion
The photoluminescence spectra of the samples 1, 2 and 3 are presented at Figure 2a. The PL spectra show 3 peaks corresponding to radiative transitions in quantum wells with the corresponding In content. It can be seen that the PL intensities are the same in samples with (In,Fe)Sb and in initial structure. This indicates that the concentration of non-radiative recombination centres in the quantum well region did not change significantly after the deposition of (In,Fe)Sb layers. Consequently, the deposition of (In,Fe)Sb layer did not introduce any additional defects in the region of near-surface quantum wells.

The EL spectra of samples 1 and 2 are shown in Figure 2b. As can be seen from the presented spectra, in the (In,Fe)Sb/GaAs diode without the protective MgO layer, the EL peak from the closest-to-the-surface QW (with the highest In content) is completely quenched.
When applying a protective layer of MgO between the ferromagnetic injector and the light-emitting part of the SLED, the mentioned above peak is maintained, and the integral intensity of EL is also increased by several times. This leads us to a conclusion that (In,Fe)Sb deposition on the top of GaAs influences the properties of the surface. The MgO deposition prior to (In,Fe)Sb allows decreasing this influence.

Presumably, the quenching of EL from the nearest to the surface QW is associated with the formation of charged states in the surface region of GaAs, which create a strong electric field in the region of the first QW, even in the forward bias mode. In structures with MgO layer, the number of charged centers and the magnitude of inner electric field decrease, that significantly reduces the escape of carriers from the first QW and makes it possible to detect EL radiation.

Since the MgO deposition has shown the improvement of (In,Fe)Sb/GaAs interface quality, we have fabricated a spin-light emitting diode structure with (In,Fe)Sb/MgO injector (structure 4 at Fig.1).

**Figure 2.** (a) PL spectra of samples 1, 2 and 3; (b) EL spectra of studied samples 1 and 2, current through the structures = 100 mA. Measurement temperature in both cases = 77K.

**Figure 3.** Magnetic field dependence of $P_{EL}$ for investigated sample 4 and control structure without (In,Fe)Sb injector. The inset shows the electroluminescence spectrum for sample 4.
Figure 3 shows the magnetic field dependence of EL circular polarization degree ($P_{EL}(B)$) for sample 4 measured at temperature 10K.

As can be seen from Fig.3, the $P_{EL}(B)$ is a non-linear function of the applied magnetic field and the circular polarization value at the magnetization saturation is rather high ($\sim 0.7\%$). Such type of dependence is associated with the injection of spin-polarized electrons from ferromagnetic layer. It should be noted, that in similar sample but without MgO the EL was not detected. This confirms a conclusion, that MgO is a protective layer, which prevents the negative impact of (In,Fe)Sb on the luminescence characteristic of the structure. Also it should be noted, that the circular polarization of EL of a similar structure without (In,Fe)Sb layer was investigated (Au contact was directly deposited on the GaAs spacer layer). Magnetic field dependence of $P_{EL}$ for such a structure is shown on the figure 3. The value of the degree of circular polarization for control structure did not exceed 0.1%.

4. Conclusions

Thus, (In,Fe)Sb/GaAs/InGaAs SLED were formed and studied, and methods for increasing the intensity of EL by modifying the ferromagnet/semiconductor interface were considered. Also in this work, the spin injection of electrons from the DMS (In,Fe)Sb into the semiconductor structure based on GaAs with further recombination and emission of EL radiation from the QW region was obtained. The magnetic field dependences of the degree of circular polarization $P_{EL}$ were measured at temperature 10K.

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