Room temperature spin injection in a light-emitting diode based on a GaMnSb/*n*-GaAs/InGaAs tunnel junction

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Abstract. The circularly polarized electroluminescence from an InGaAs/GaAs light-emitting diode with a (Ga,Mn)Sb/n^+GaAs tunnel junction was investigated in the temperature range of 10-300 K. The obtained polarization degree is believed to be driven by the spin injection of electrons from the valence band of ferromagnetic (Ga,Mn)Sb into the conduction band of n^+GaAs. The temperature dependencies of the polarization characteristics are determined by the ferromagnetic properties of the (Ga,Mn)Sb layer. The room temperature circularly polarized emission is prospective for the fabrication of a spin light-emitting diode with an injector based on a diluted magnetic semiconductor.

1. Introduction

Diluted magnetic semiconductors (DMS), such as (III,Mn)V, are considered to be prospective materials for implementation in devices using the spin degree of freedom [1-4]. The advantages of DMS are the good embeddability into most semiconductor spintronic structures and easy control of ferromagnetic properties by the variation of the growth parameters (Mn doping level, fabrication temperature, additional acceptor doping) [1-7]. However, the application of (III,Mn)V materials is limited by two major obstacles. First one is a hole type of conductivity in (III,Mn)V, since short spin relaxation times for holes (as compared to electrons) significantly limit the efficiency of spin transport [6,7]. The second obstacle is a low Curie temperature of DMS not exceeding 250 K (for (Ga,Mn)As) [3,4].

In order to implement spin injection of electrons from p-type (III,Mn)V layers, the Zener diode structure was suggested in [8,9]. In the cited papers, the efficient injection of spin polarized valence band electrons from a reverse biased (III,Mn)V/n-AlGaAs tunnel junction into a GaAs quantum well (QW) was obtained.

The second obstacle has not been overcome yet, to our knowledge. The only (III,Mn)V layers possessing ferromagnetic properties at room temperature are the two-phase systems containing Mn-V or Mn-III clusters in a (III,Mn)V matrix [10-12]. These clusters are proven to be responsible for the observation of a ferromagnetic signal from both SQUID magnetometer [11] and anomalous Hall effect [12] measurements. We note that the two-phase DMS are not often considered as the element of spintronic devices, which is probably due to the low spin injection efficiency from DMS layers caused by spin scattering at the MnV/(III,Mn)V, MnV/III-V heterointerfaces.

In the present paper, we report on the fabrication of (Ga,Mn)Sb/GaAs layers that demonstrate ferromagnetic properties up to room temperature and on the implementation of these layers in a spin light-emitting diode. The fabricated diodes emit circularly polarized light with a circular polarization degree of ~ 0.54% at 10 K, which was found to be slowly decreasing with the temperature increase reaching the value of 0.32% at 300 K.

2. Experimental technique

The structures were fabricated by the two-stage epitaxial growth method [13,14]. First, the layers of a light-emitting diode were grown by metal-organic vapor phase epitaxy (MOVPE) on a *p*-GaAs substrate at 600°C. The following sequence of the layers was formed: a *p*-GaAs buffer, an $In_{0,16}Ga_{0,84}As$ quantum well (QW) (dopped with C, $p \sim 8\times10^{17}$ cm^{-3}, width of d_{QW} = 16 nm), a 6 nm undoped GaAs, *n*–GaAs ($n \sim 10^{17}$ cm^{-3}, width of 50 nm), n^{+}GaAs ($n \sim 10^{18}$ cm^{-3}, width of 20 nm), n^{++}GaAs ($n \sim 10^{19}$, width of 20 nm). At the next stage, a 30 nm (Ga,Mn)Sb layer was grown in the same reactor at 340°C by laser sputtering of GaSb and Mn targets. The Mn content was estimated by the formula:

$$Y_{Mn} = \frac{t_{Mn}}{(t_{Mn}+t_{GaSb})}, \tag{1}$$

where t_{Mn}(t_{GaSb}) is the sputtering time of Mn(GaSb). In the present study Y_{Mn} = 0.5. The decrease of the growth temperature is required to prevent Mn diffusion into structure [13].

The final treatment of light-emitting diodes included the deposition of an Au contact on a (Ga,Mn)Sb surface and 500 μm mesa formation by means of photolithography and chemical etching. The back Ohmic contact was fabricated by means of sparkling of In foil. The schematic diagram of our structures is shown in figure 1 (a).

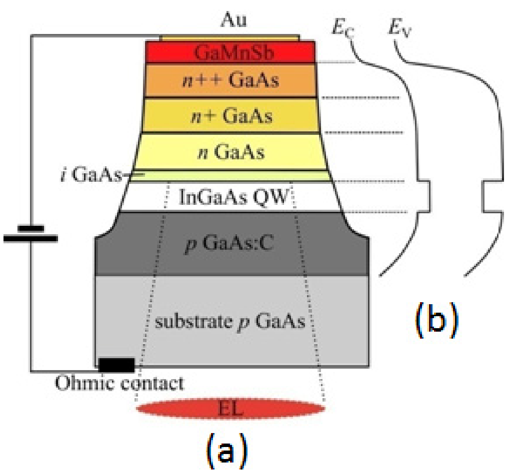

Figure 1. (a) The schematic diagram of the spin-LED structure; (b) the band diagram of a *p*-(Ga,Mn)Sb/*n*-GaAs/InGaAs junction with the applied bias.

The measurements of each sample started from the test investigations of *I*-*V* characteristics at 300 K. The electroluminescence (EL) spectra of the samples were measured in the temperature range of 10 - 300 K. The magnetic field B = –0.3 ÷ +0.3 T was normal to the QW plane (Faraday geometry). The EL emission was collected from the back of a sufficiently transparent substrate (figure 1 (a)). For the EL measurements, the negative (with respect to the substrate) potential was applied to the top Au contact thus the reverse bias of a (Ga,Mn)Sb/n^{++}GaAs tunnel barrier was achieved causing electron injection from the valence band of (Ga,Mn)Sb into the conduction band of n^{++}GaAs, as in [15].

The degree of circular polarization of the EL emission $P_C(B)$ was calculated by:

$$P_C = \frac{(I_+ - I_-)}{(I_+ + I_-)}, \tag{2}$$

where $I_+(I_-)$ are the emission intensities of the optical transition in the QW at σ^+ (σ^-) polarization.. In order to certify the spin injection process, the control measurements of circularly polarized photoluminescence (PL) were also carried out. Spin injection is not involved in the PL process, thus the PL polarization degree (if any) cannot be attributed to the spin injection. The magnetization of the samples was investigated at 300 K by an alternating gradient force magnetometer with a sensitivity of about 10^{-7} emu in a magnetic field of up to ± 180 mT. The magnetic field was applied perpendicular to the sample surface. The details of the gradient force magnetometry technique were described in [16].

3. Experimental results and discussion

I-V characteristics of the diode are shown in figure 2. In the applied measurement geometry the diode represents two *p-n* junctions in the opposite bias conditions. The kink followed by the rapid increase of the diode current is observed at the *I-V* curves when the negative bias $U \approx -0.6 \div -1.2$ V is applied to the top contact. Such a kink probably corresponds to the situation when the top of the valence band of (Ga,Mn)Sb coincides with the bottom of the conduction band of *n*+GaAs (figure 1 (b)). In this mode, tunneling of electrons from (Ga,Mn)Sb into GaAs takes place, and the holes are injected into the InGaAs QW from the forward-biased *p*-substrate/*n*-GaAs junction [9]. When the temperature is increased, the kink voltage decreases evidencing the role of the thermally activated tunneling mechanism at higher temperatures.

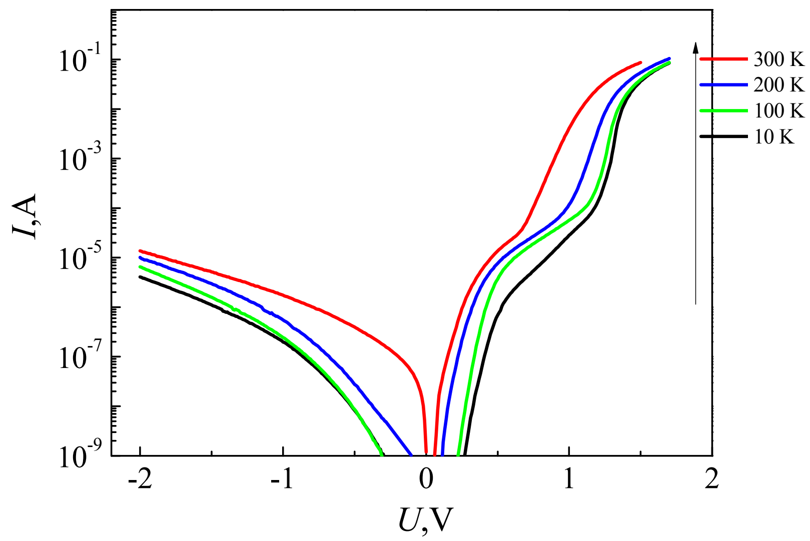

Figure 2. The *I-V* characteristics of the investigated diode structure measured at different temperatures.

The EL spectrum of the investigated sample is shown in figure 3. One can see a peak at 1.375 eV dominating in the spectrum. This line corresponds to the main radiative transition in the quantum well. When the magnetic field is applied, the intensities of the polarized EL components σ^+ (σ^-) differ from one another, thus one can determine the circular polarization of the EL emission with eq. (2). The dependencies of the circular polarization degree on magnetic field, measured at 10 and 300 K, are shown in figure 4 (plots 1 and 2, respectively).

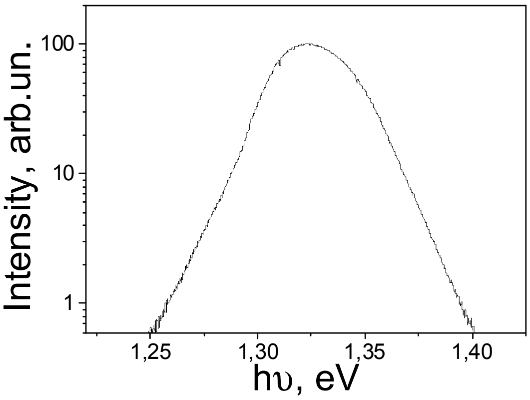

Figure 3. The electroluminescence spectrum of the sample measured at 77 K at a diode current of 10 mA.

The graphs in figure 4 demonstrate non-monotonic dependencies with a hysteresis loop. Note that the $P_C(B)$ dependence measured at 300 K is similar to the magnetization vs B dependence measured at the same temperature (figure 4: circles, curve 2 and a line, curve 3, respectively). We also note that the PL polarization degree of the investigated sample does not exceed 0.1 % (figure 4, curve 4). Both results are believed to be clear evidence of the spin injection [2] being the major reason for the observed EL circular polarization. Taking into account the polarity of the applied bias, we suppose the spin injection of electrons from (Ga,Mn)Sb into the InGaAs/GaAs heterostructure to be similar to that into the (Ga,Mn)As/GaAs one [10,18]. The contribution of magnetic circular dichroism to the polarization (as in [19]) is believed to be negligible since the EL emission is collected from the back of the sample and thus does not pass through the ferromagnetic layer. Also, it is worth noticing that the change in n^{++}-GaAs doping parameters (increase from 10^{19} to ~1.5×10^{19} cm^{-3}) leads to a nearly twofold decrease in P_{EL} (not shown to prevent data overload in figure 4). This cannot be explained by the magnetic circular dichroism effect but is in good agreement with the Zener diode tunneling mechanism [19].

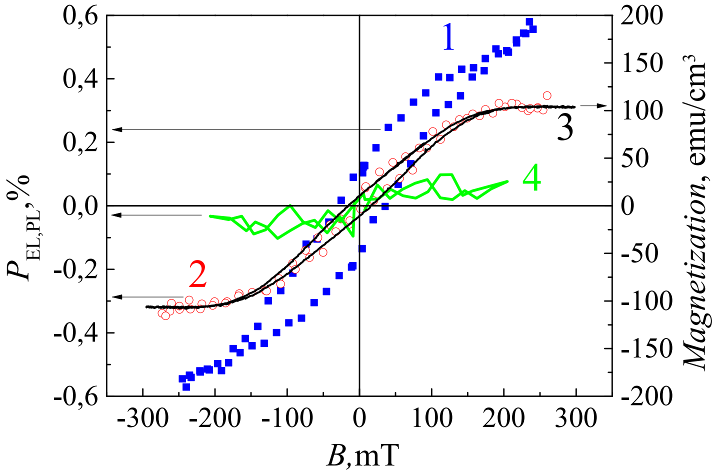

Figure 4. The magnetic field dependencies of the EL polarization degree (symbols, curves 1, 2) at a diode current of 20 mA) and of the magnetization (line, curve 3) of the investigated sample measured at temperatures of 10 K (1) and 300 K (2, 3). Curve 4 corresponds to the magnetic field dependence of the photoluminescence polarization degree of the investigated sample measured at 300 K.

The temperature dependence of the polarization degree is shown in figure 5. In the temperature range of 10 ÷ 50 K the polarization degree is temperature independent, at $T > 50$ K a monotonic linear decrease of P_C is observed. At $T = 300$ K, the polarization degree $P_C = 0.3$ %. The parameters of the hysteresis loop are also temperature-dependent (insert in figure 5). One can see that both the polarization degree in remanence (at $B = 0$) and the coercive field (at which $P_C = 0$) decrease with increasing temperature.

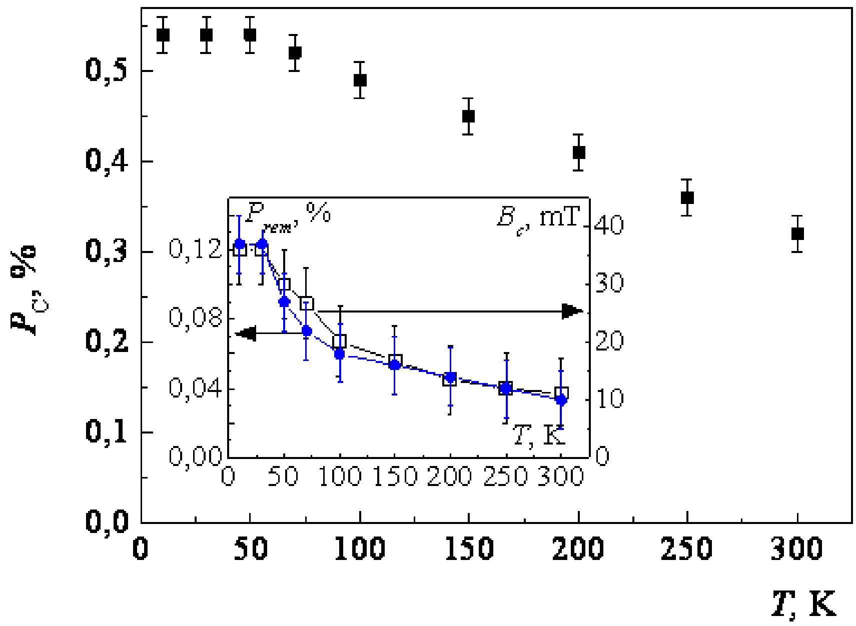

Figure 5. The temperature dependence of the EL polarization degree of the investigated sample measured in a magnetic field of 250 mT and a current of 20 mA. The insert shows the temperature dependence of the polarization degree in remanence (closed circles) and the coercive field (open squares) measured in the same conditions.

The temperature dependencies are driven by the magnetic properties of a (Ga,Mn)Sb layer. The monotonic decrease of the P_C with temperature is relatively extended and thus cannot be attributed to reaching the Curie temperature (for which an abrupt decrease of P_C is more typical [6]). One can suggest that the $P_C(T)$ dependence is associated with the increasing role of spin scattering [2] for higher temperatures. Also, the decrease of both the polarization degree in remanence and coercive field with the increase of T (insert in figure 5) can probably be attributed to the variation of magnetic properties of (Ga,Mn)Sb. A similar effect has been reported in [17] for the samples with MnAs clusters embedded into a GaAs matrix. In the cited paper, it was reported on a fivefold decrease of the coercive field and a nearly 60 percent decrease of magnetization with the temperature increasing from 5 to 300 K which is in good correlation with our result. However, no explanation on such magnetic properties variation was suggested. We believe that, in our case, MnGa or MnSb clusters are responsible for the preservation of ferromagnetic properties up to 300 K. The open question is whether there is an interaction between the clusters causing ferromagnetic ordering. To clarify the issue some additional investigation of ferromagnetic properties of (Ga,Mn)Sb films is to be carried out.

Two important features of our results are the spin injection and ferromagnetism of a (Ga,Mn)Sb semiconductor both obtained at room temperature. Previously, it has been shown that the room temperature ferromagnetism of (Ga,Mn)Sb layers, grown by laser sputtering in the identical conditions, is due to the MnGa clusters, which are formed in a (Ga,Mn)Sb matrix [18]. Such systems were rarely used for the spin injection, however, we demonstrated that the spin-polarized electrons can be injected from (Ga,Mn)Sb into GaAs even at room temperature, which, to our knowledge, is the highest spin injection temperature for the structures based on the diluted magnetic semiconductors [2,6,9,20]. A low polarization degree is probably due to the poor (Ga,Mn)Sb/GaAs interface quality [18], which, however, can be improved by the proper selection of the growth parameters.

4. Conclusion

In conclusion, we have investigated the circularly polarized electroluminescence from an InGaAs/GaAs light-emitting diode with a (Ga,Mn)Sb/n^+GaAs tunnel junction. The obtained polarization degree is believed to be due to the spin injection of electrons from the valence band of ferromagnetic (Ga,Mn)Sb into the conduction band of n^+GaAs. The effect persists up to 300 K, which is prospective for the fabrication of a room-temperature operating spin light-emitting diode on the basis of a diluted magnetic semiconductor.

Acknowledgments

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