Optica Applicata, Vol. XLV, No. 4, 2015
DOI: 10.5277/oa150409

Electroluminescence of InGaN/GaN heterostructures at the reverse bias and nitrogen temperature

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The electroluminescence spectra at reverse biases in LED InGaN/GaN heterostructures at liquid nitrogen temperatures were studied. At the reverse bias and $T = 77$ K, avalanche microplasmas breakdowns were observed. Electroluminescence spectra demonstrate two peaks caused by the recombination of carriers in different parts of the structure (quantum well and *p*-GaN layer). The temperature narrowing the half-width and the shift of electroluminescence spectra peaks inherent to microplasmas were observed.

Keywords: electroluminescence at reverse bias, InGaN/GaN heterostructures, defect.

1. Introduction

To realize the operative non-destructive diagnostics of InGaN/GaN heterostructures as a base for powerful LEDs, the electroluminescence (EL) at the forward bias, photo- and cathode-luminescence (PL, CL) [1], are used most often. At the same time, the application of the reverse bias in GaN structures enables to observe an avalanche microplasma breakdown that takes place predominantly within the ranges of critical extended defects and is accompanied by luminescence [2–11]. EL spectra at the reverse bias and operation temperatures were investigated in typical LED InGaN/GaN [3–7] and AlGaN/GaN heterostructures [8] as well as GaNP [9], ZnO/GaN [10, 11], GaAs [12] and Si [12, 13] structures.

In addition, some separate and well resolved lines in luminescence spectra, which are observed at lowered temperatures, contain information about the energy levels of recombination centers and defects, including deep levels (DL). From measurements of temperature dependences typical for luminescence spectra, it becomes possible to determine the temperature coefficients dE/dT, activation energy, *etc*.

At lowered temperatures, in particular at the liquid nitrogen one, EL spectra at reverse biases in LED heterostructures InGaN/GaN are not studied well. It is obvious that EL spectra can contain additional information about critical defects, whose influence prevails in characteristics of device structures. Investigation of EL spectra inherent to microplasmas (MP) at low temperatures is also important from the viewpoint of predicting the reliability of GaN structures. The study of MP breakdown is not limited by the above problems: for example, MP worsens the characteristics of Zener diodes and photodiodes based on GaN.

2. Experimental details

$In_xGa_{1-x}N$/GaN structures of powerful LEDs (P_{el} = 1 W, I_{nom} = 350 mA, the area of heterostructures was close to 1 mm^2) with various composition of indium in the quantum well (QW) $x = 0.2$ and 0.3 on Al_2O_3 substrate were investigated in this work. The colors of emission from these heterostructures were blue and green, respectively. The EL spectra of MP had a very weak intensity and were measured using a spectroradiometer HAAS-2000 (Everfine) with a long time of integration for clear detection of spectral lines. The time of spectral measurements was 5 or 10 min. For measurements in liquid nitrogen, a special cell with the output window was used.

Since the reverse current in LED structures InGaN/GaN at T = 77 K is practically one order lower than that at room temperature, the EL intensity of MP is also lower, being in proportion to the current [3, 4]. Therefore, to detect EL of MP at 77 K, it is necessary to apply higher voltages, which in some cases results in a shunting or catastrophic breakdown. Some results typical for three samples of LEDs with blue emission and the one with green emission are presented below.

3. Results

Adduced in Fig. 1 are MP spectra at T = 77 and 300 K for two heterostructures with $x = 0.2$. At room temperature, one can see the wideband with the maximum near 2.72 eV (Fig. 1**a**) and 2.65 eV (Fig. 1**b**). At liquid nitrogen temperature, one can see already two peaks at 2.80 and 2.65 eV (Fig. 1**a**) as well as 2.84 and 2.65 eV (Fig. 1**b**). Some shift of the short-wave wing in the spectrum at T = 77 K due to E_g increasing is also observed.

Figure 2 shows the MP spectra of the structure no. 1 at T = 77 K. These are changed with increasing the current from 1.9 up to 2.2 mA (curves 1 to 3). Besides, one can observe the intensity growth of the band at λ = 469 nm (2.65 eV). The half-width of this band is close to 14 nm (curve 3) at the reverse bias. The half-width of EL spectrum at the forward bias (T = 300 K) is equal to 25 nm (curve 4). The new appearing band in the spectrum 3 is ascribed to EL emission from the quantum well, the half-width of which is lower due to nitrogen temperature. A similar growth of the EL peak related

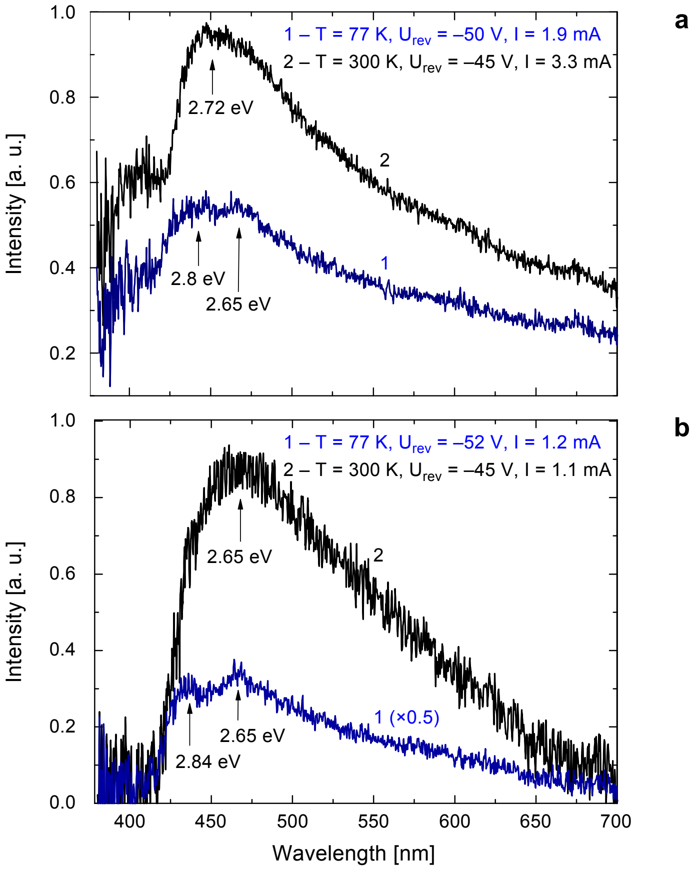

Fig. 1. EL spectra of microplasmas at the reverse bias of the $In_{0.2}Ga_{0.8}N/GaN$ structures no. 1 (**a**) and no. 2 (**b**).

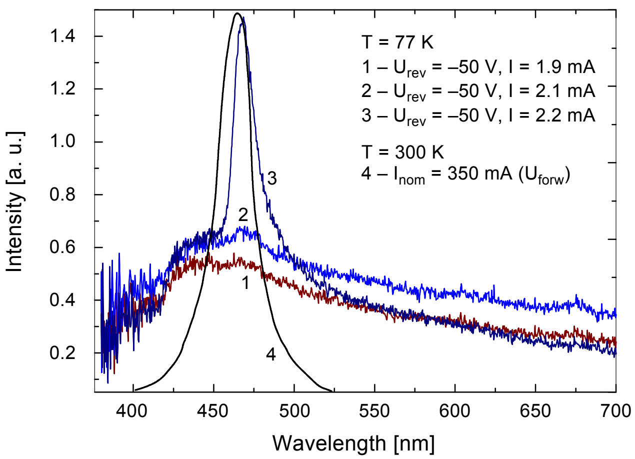

Fig. 2. EL spectra of the $In_{0.2}Ga_{0.8}N/GaN$ structure no. 1 with increasing the current.

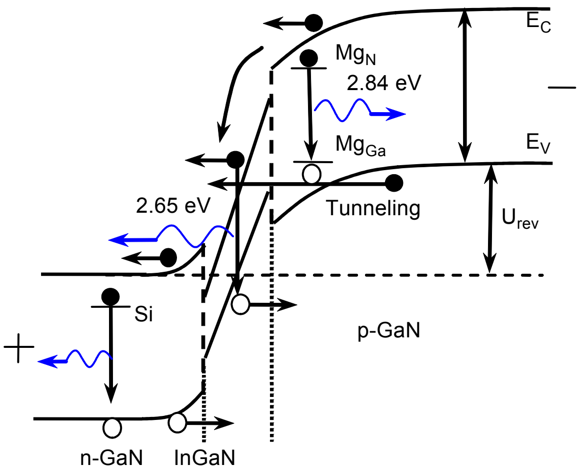

Fig. 3. Energy diagram of the InGaN/GaN heterostructure at the reverse bias; ● – electrons, ○ – holes.

with the QW $Al_{0.1}Ga_{0.9}N$ at room temperature with increasing the reverse bias (from 6.5 up to 14.3 V) was observed in [8] for *p-i-n* AlGaN diode as well as for GaAs *p-n* junction [12].

Contrary to the band peak at 2.65 eV, the intensity of the band at 2.8 eV does not practically grow with current (Fig. 2). Let us consider the diagram in Fig. 3. There takes place the injection and acceleration of electrons from the *p*-GaN and holes from the *n*-GaN layer as well as excitation of new carriers (multiplication), then their separation by the field and recombination. There occurs an act of ionization (at the defect), drift in the field (acceleration) and recombination. Besides, due to a very small thickness of the InGaN layer, tunneling is available there (Fig. 3). Impact ionization takes place due to this tunneling of electrons from the valence band of the *p*-GaN into the InGaN layer and further into the *n*-GaN, and this ionization takes place predominantly in QW and *n*-GaN layer [6].

Two peaks in the spectra at $T = 77$ K correspond to two different transitions. The peak at 2.65 eV corresponds to recombination in QW, while the peak at 2.80–2.84 eV arises due to recombination with participation of the pair deep donor – shallow acceptor Mg_{Ga} (DAP), see Fig. 3. It is the most probable that the role of this donor is performed by Mg_N, since the emission energy corresponding to the transition Mg_N–Mg_{Ga} is close to 2.87 eV [14]. As the *p*-GaN layer is doped with magnesium up to the level 10^{19}–10^{20} cm^{-3}, Mg_N donors arise simultaneously with Mg_{Ga} acceptors [1, 14]. Also in [15], the PL band at 2.88 eV in GaN:Mg is related with DAP and N vacancies as donors. In the work [16], after low-energy electron irradiation of InGaN/GaN structures (when the *p*-layer is doped with magnesium), there arose the band peaking at 2.8 eV.

In addition to the results adduced in Figs. 1 and 2, in Fig. 4 the MP spectrum at $T = 300$ K (1) and at $T = 77$ K (2) of the structure no. 3 is shown. It can be seen that

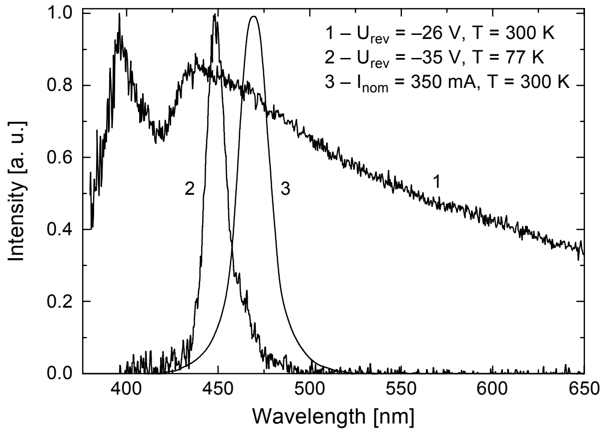

Fig. 4. EL spectra of the $In_{0.2}Ga_{0.8}N$/GaN structure (sample no. 3).

the spectra are sharply different here: the spectrum at the nitrogen temperature is narrow and practically coincides with the spectrum at the forward bias, but is rather shifted. This shift is mainly caused by the quantum-confined Stark effect (QCSE) [4, 7], but also the temperature increase of E_g takes place. The shift between the spectra 2 and 3 reaches 21 nm. Besides, one can observe temperature contraction of the spectrum half-width: at the forward bias it is equal to 22 nm (spectrum 3), while at the reverse bias it is only 13 nm (spectrum 2).

In this sample for $U_{rev} = –34$ V at $T = 77$ K MP emission was so weak that we could not detect it. After keeping the sample under $U_{rev} = –36$ V for 10 min, we observed the irreversible breakdown, the structure failed. LED no. 3 has a lower voltage for MP switching on, lower value of the breakdown voltage, which along with availability of the band near 400 nm indicates a higher concentration of defects [7].

It has been ascertained that the EL intensity inherent to MP at room temperature is higher than that at nitrogen temperature.

Let us consider EL spectra of MP observed in the heterostructure $In_{0.3}Ga_{0.7}N$/GaN possessing green emission. Like to the previous case of the sample no. 3, in this heterostructure at the reverse bias one can observe the narrow band typical for forward bias (Fig. 5). But in this structure, the spectrum for the reverse bias is narrow even at $T = 300$ K due to predominant recombination in QW $In_{0.3}Ga_{0.7}N$ and not in the adjacent GaN layers, since conductivity in the $In_{0.3}Ga_{0.7}N$ layer is higher than that in $In_{0.2}Ga_{0.8}N$.

The spectra for forward and reverse biases are shifted due to the QCSE [4, 7] by 19 nm (Fig. 5, spectra 1 and 3), but the temperature shift of the spectrum 2 relatively to the spectrum 1 is absent. The latter can be presumably explained by S-like behavior of the luminescence peak with temperature changing from 10 up to 300 K [17].

The half-width of the spectra when applying the reverse voltage is close to 36 nm at 300 K and 25 nm at 77 K, while for I_{nom} it is equal to 42 nm, which is higher than

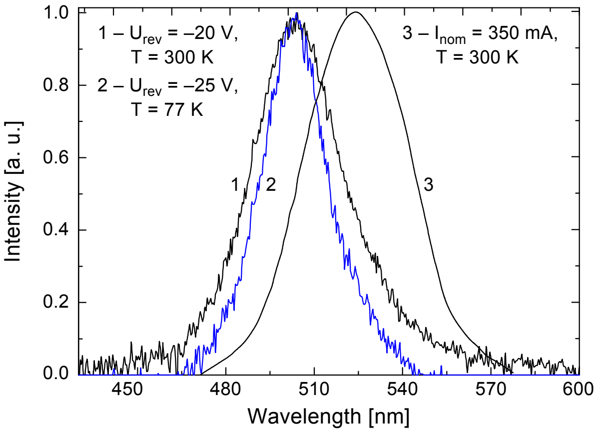

Fig. 5. EL spectra of the $In_{0.3}Ga_{0.7}N/GaN$ structure.

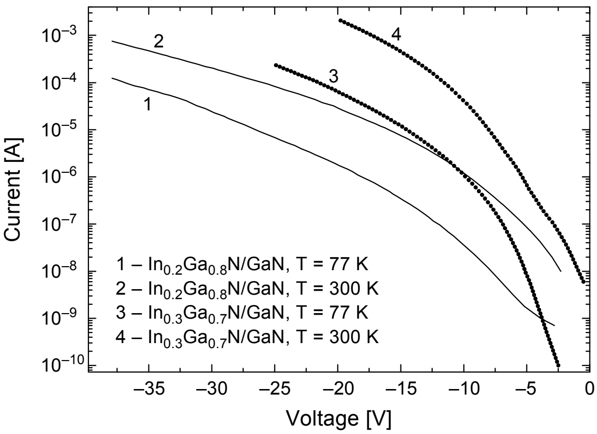

Fig. 6. Reverse CVCs of the $In_{0.2}Ga_{0.8}N/GaN$ (1, 2) and $In_{0.3}Ga_{0.7}N/GaN$ (3, 4) heterostructures at $T = 77$ K (1, 3) and $T = 300$ K (2, 4).

that in the structure $In_{0.2}Ga_{0.8}N/GaN$ due to higher disordering and segregation of indium in QW InGaN [17].

As it can be seen from the reverse current-voltage characteristics inherent to the studied heterostructures (Fig. 6), the current value at $T = 77$ K is approximately one order lower, which results in "switching off" of the part of MP, and the current passes predominantly via remaining MP.

The sharper slope of current-voltage characteristic (CVC) for LED with green emission comparing to LED with blue emission (Fig. 6) can be explained by the higher concentration of defects, which is caused by the disorder in the InGaN layer related with the enhanced indium content (from $x = 0.2$ to 0.3) as well as by extended defects [18]. The transport-mechanism of current for the reverse CVC in these structures is known

– it is Mott variable-range hopping [19], and only after reaching some voltage, the CVC dependence becomes linear due to many active MPs [20].

4. Discussion

At room temperatures, various LED GaN structures possess predominantly wide EL spectra under the reverse bias [3–8], which is caused by recombination of carriers on impurities and diverse defects in the layers adjacent to the *p*-*n* junction, while the wideband of MP spectra corresponds to recombination of carriers mainly at the external boundaries of a space charge region [6].

The availability of two peaks at the nitrogen temperature (Fig. 1) as well as the growth of one of them with increasing the current (Fig. 2) indicate two different recombination areas, namely: quantum well and the adjacent GaN layer with participation of DAPs. It is the most probable that the band peaking at 2.80–2.84 eV in Figs. 1 and 2 corresponds to emission from DAP Mg_{Ga} (acceptor) to Mg_N (donor) present in the GaN layer heavily doped with magnesium (up to 10^{19}–10^{20} cm^{-3}).

Using the obtained figures, it was ascertained that those MPs present at T = 300 K were kept at T = 77 K too but some part of them disappeared. Location of MP under these temperatures fully coincides. The appearance of narrow bands instead of the wide ones (Figs. 2, 4, 5) indicates band-to-band carrier recombination only in the QW area, since the spectral look is the same as that for forward bias. When the voltage is increased, the conductivity of MP grows, but the amounts of free carriers and respectively hot electrons are lower at the nitrogen temperature, and the width of the area where the avalanche ionization current takes place is narrower. Respectively, the recombination area is localized in QW.

It is known that threading dislocations serve as sources of MPs in these structures [3–5, 7], but at the same time it is also known that the current passes along the In-rich areas, because of higher conductivity. Spatial non-uniformity in distribution of In content inside the InGaN layer relatively to the mean In content becomes more pronounced with x growth and leads to localization of charge carriers [17]. Inside In-rich layers (x = 0.3), the current passes through the areas enriched with In due to solid solution phase decomposition, bulk and surface In segregation, indium accumulation near various defects including dislocations. In the paper [21], for instance, the model of LED as a set of microdiodes connected in parallel and possessing different amounts of In in QW was considered. Sizes of areas comprised by *p*-*n* microjunctions are determined by fluctuations in the In content inside the active layer. The absence of the wide MP spectrum from the structure with green emission (Fig. 5) indicates recombination of carriers predominantly in QW, in particular due to nanoinclusions enriched with indium [17].

On the other hand, lowering the temperature results in changing ionization parameters (threshold ionization energy, mean free path, drift velocities of carriers [20] as well as thermal and electrical conductivities, *etc*.), which results in the temperature dependence of MP parameters.

Third, MP channels contain shallow and deep levels and lowering the temperature leads to their elimination via filling them. If DL remains filled inside a depletion layer (for example at lowered temperatures), it results in changing the breakdown voltage inherent to the *p*-*n* junction. Since the part of DL is filled, it also influences the EL spectrum.

5. Conclusions

As ascertained in this work, typical $In_{0.2}Ga_{0.8}N$/GaN LEDs that under forward bias possess one band in the blue range, at the reverse bias and $T = 77$ K demonstrate EL MP spectra with two peaks caused by recombination of carriers in different parts of the structure (QW and *p*-GaN layer). It enables the additional study of recombination centers in a wider region of the depletion layer where impact ionization near extended critical defects takes place.

We have observed the temperature narrowing of the half-width and the shift of EL spectra peaks inherent to microplasmas. The EL spectrum of MPs in $In_{0.3}Ga_{0.7}N$/GaN structures at $T = 77$ K contains one peak, which is caused by higher conductivity of the $In_{0.3}Ga_{0.7}N$ layer.

Acknowledgements – Publications are based on the research provided by the grant support of the State Fund For Fundamental Research (project F64/49-2015).

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Received April 8, 2015
in revised form June 5, 2015