Comparative analysis of efficiency droop in InGaN/GaN light-emitting diodes for electrical and optical pumping conditions

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Abstract. The analysis of efficiency droop in InGaN/GaN light-emitting diodes for electrical and optical pumping conditions is presented. Authors show that room temperature efficiency droop is well described by ABC-model for both pumping regimes. For low temperatures additional ballistic leakage should be considered to explain efficiency droop for the case of electrical pumping.

The quantum efficiency of light-emitting diodes (LEDs) with multiple InGaN/GaN quantum wells (MQW) is the subject of intense basic and applied research. The reason for this is an effect referred to as the efficiency droop (ED). The effect manifests itself in a decrease in the external quantum efficiency with increasing pumping current density higher than \( j \approx 1-10 \, \text{A/cm}^2 \) (at temperatures \( T = 300 \, \text{K} \)), and is not caused by the LED overheating. Previously an approach of study was proposed including investigation of the temperature dependences of the quantum efficiency and ED effect under different conditions of luminescence excitation [1]. This work presents recent results of study of ED effect by using electroluminescence (EL) regime and photoluminescence (PL) regime with two type of optical pumping (355 and 405 nm).

Experiments were carried out for commercial blue LED-structure grown by MOVPE on the [0001] patterned sapphire substrate. An active n-type region of the structure consisted of the \( \text{In}_{0.15}\text{Ga}_{0.85}\text{N}/\text{GaN} \) MQWs and barriers with the thicknesses 2.5 and 15 nm, respectively. The thickness of the \( p-\text{Al}_{0.15}\text{Ga}_{0.85}\text{N} \) barrier layer was about 30 nm. According to datasheet the total thickness of LED active region was 200 nm. From this structure, planar light-emitting diodes with ohmic contacts Au/Ni and the resistance less than \( 10^{-2} \, \Omega \cdot \text{cm}^2 \) were made. The area of LED is 1 mm². In the experiment, we measured the dependence of the external quantum efficiency \( \eta \) on the current in the temperature range \( T = 10-300 \, \text{K} \) using a Janis cryostat, a Keithley 2636A SourceMeter, and a LeCroy104Xs oscilloscope. To prevent overheating at high current densities we used pulse regime (duration – 30 \( \mu \)s, frequency – 50 Hz).

Photoluminescence was excited by a pulsed YAG-laser with an average power of 35 mW (0.2-1 kHz, duration – 10 ns, 355 nm) and a semiconductor laser with a wavelength of 405 nm (LD Nichia NDV4642VFR, 0.2-90 kHz, duration – 15 ns, pulse power - 4 W). The driver for semiconductor laser were developed on a basis of avalanche S-diode [2,3]. To enhance the power density of laser radiation we used focusing by quartz lens (minimum diameter of laser spot on a sample was about 100 mkm).
Optical power was changed by neutral glass filters. The photoluminescence spectra were measured in the temperature range $T = 10$–300 K with an Ocean Optics spectrometer. Normalized electroluminescence and photoluminescence spectra are presented in fig. 1-4. Experiments are shown that the change in the optical pumping mode (405 or 355 nm) gives no difference in photoluminescence spectra. However the shapes of luminescence spectra for electro- and photoluminescence regimes are very different. For low temperature luminescence the spectrum can be decompose to sum of Gaussian-like spectra. And there is at least one additional peak at the high energy side of photoluminescence spectrum in comparison with electroluminescence data. The appearance of additional peak leads to effective red shift of wavelength under pumping mode change from photo- to electroluminescence. The shift is equal to 10-12 nm what can be explained by scatter of quantum wells properties in different structure samples, e.g. due to InN composition inhomogeneous. Another reason of wavelength shift appearance is the peculiar conditions of carrier injection at different pumping modes. It is well known that electrical pumping is accompanied by tunneling of carriers through energy states of defects in injection barriers. Such a process leads to a lowering of the open voltage in InGaN/GaN light-emitting diodes [4]. Obviously this effect leads to a lowering of photon emission energy what is equivalent to observed wavelength shift.

Figure 1. EL spectra for different current at $T = 10$ K.

Figure 2. PL spectra for different pumping optical power at $T = 10$ K.

Figure 3. EL spectra for different current at $T = 300$ K.

Figure 4. PL spectra for different pumping optical power at $T = 300$ K.
To compare EL and PL results the experimental dependences were plotted in coordinates $\eta = \eta(n_{inj})$, were $\eta$ was calculated in arbitrary units from optical power $P$ as $P/n_{inj}$. The value $n_{inj}$ represents the number of injected carriers per second per unit area (injection rate). In the case of electrical pumping this value was calculated as

$$
n_{inj} = \frac{I}{e \cdot S},
$$

where $I$ - current, $e$ - electron charge, and $S$ - area of LED.

In the case of optical pumping the calculation of $n_{inj}$ is difficult because of amount of reflected and absorbed radiation in p-layer must be considered. Moreover for accurate determination of $n_{inj}$ the diffusion and recombination processes of nonequilibrium carriers in p-layer should be involved. Therefore to simplify the problem we used normalization which based on experimental data for wavelength shifts of luminescence spectra with pumping. It is well known that in [0001] InGaN/GaN LEDs blue shift is observed with the pumping increase, and it is explained by Stark effect [5]. We observed this effect under different pumping conditions. For all conditions luminescence spectra start to shift at the point of maximum efficiency for room temperature (or saturation of efficiency). At the electrical pumping this point corresponds to $n_{inj} = 2 \cdot 10^{18} \text{cm}^{-2} \text{c}^{-1}$, and it was used for normalization of PL experimental data.

The normalization were used for room temperature because of low temperature luminescence spectra is complex, and it is unclear how to compare EL and PL data for low temperature. On the other hand it is clear blue shift for both regimes at $T = 300$ K as presented on the fig. 5, and it can be fitted by theoretical curve under assumption of Stark effect [6].

For determination of absolute value of quantum efficiency we also normalized experimental data. Normalization was performed by maximum efficiency which corresponds to lowest temperature. Doing so we assume that at temperature $T = 10$ K and low injection level an internal quantum efficiency (IQE) equals to 100% for EL and PL pumping. In an experiment this case is realized if two conditions take place. Firstly, significant leakage of carriers from multiple quantum wells to p-region should not be observed at low injection level, e.g. tunneling leakage. Secondly, at low injection level internal quantum efficiency is determined by Shockley–Read and radiative recombination process. First condition is correct in our experiment because of crystal quality of LED structures is high and tunneling leakage current is negligible in comparison with recombination current (density of threading dislocations is about $(3-7) \cdot 10^7 \text{cm}^{-2}$). Therefore we can use ABC-model for description of internal quantum efficiency dependence on injection level for PL-data:

![Figure 5](image_url)
\[
IQE = \frac{B \cdot n^2}{A \cdot n + B \cdot n^2 + C \cdot n^3},
\]

(2)

where A, B, and C are the temperature dependent Shockley–Read, radiative, and Auger recombination coefficients, respectively, and \( n \sim n_{\text{nj}} \) (for linear recombination regime) is the concentration of non-equilibrium carriers in the MQWs.

Experimental results for quantum efficiency after normalization are presented on the fig. 6 and fig. 7. The highest quantum efficiencies measured at \( T = 300 \) K have similar values (~56-65\%) for PL and EL regimes. Moreover the experimental curves have the same form. It follows that for EL regime, the quantum efficiency at room temperature is mainly described by ABC-model (2).

At the low temperature the experimental results for PL and EL regimes are very different. The threshold value \( n_{\text{nj}} \) for beginning of efficiency droop shifts from \( 2 \cdot 10^{18} \) cm\(^{-2}\)c\(^{-1}\) (for PL) to \( 10^{16} \) cm\(^{-2}\)c\(^{-1}\) (for EL). The beginning of strong blue shift at \( T = 10 \) K for EL regime is observed only at \( n_{\text{nj}}=10^{20} \) cm\(^{-2}\)c\(^{-1}\). This fact indicates that there is no sufficient concentration of carriers in quantum wells for Stark effect observation. Additional analysis of the current-voltage characteristics had shown that at low temperatures the ballistic leakage of electrons from active region is the most likely mechanism which is determined the efficiency droop in InGaN/GaN LEDs [7].

Figure 6. Dependence of normalized internal quantum efficiency on injection rate for \( T = 10 \) K.

Figure 7. Dependence of normalized internal quantum efficiency on injection rate for \( T = 300 \) K.

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