Thermal quantum efficiency droop in blue InGaN/GaN LEDs

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Abstract. The contribution of several mechanisms to the external quantum efficiency (EQE) droop in blue InGaN/GaN LEDs occur at different current densities j and voltages in MQWs situated inside and outside of a depletion region around p-n junction. It is clarified that an increase in EQE droop at 300–400 K (j < 10 A/cm²) is due to non-radiative losses related to an enhancement in trap-assisted tunneling. It is also associated with a growth in the concentration of delocalized carriers. The main source of the EQE droop under direct current and at pulse mode when j > 30 A/cm² is non-equilibrium filling of lateral regions of different size within MQWs placed outside of depletion region by delocalized carriers activated by injection when voltage exceed a threshold value (U > Uθ). This leads to a decrease in localized potential and to the blue shift of EQE maximum over wavelengths followed by the EQE droop.

1. Introduction
The effect of thermal droop of external quantum efficiency (EQE) in power blue InGaN/GaN LEDs, which is observed in a wide temperature range (15-450 K) and current density j up to several kiloampere per square centimeter, has been studied for many years but is still a subject of many discussions [1, 2]. This effect reduces the efficiency of solid-state lighting and limits LED usage at high temperatures. Several mechanisms have been proposed to explain the phenomenon [1, 2] including Auger recombination, Shockley-Read-Hall non-radiative recombination, polarization effects, fluctuations of alloy and quantum well (QW) width, and carrier delocalization. Out of all the mentioned mechanisms, the delocalization of charge carriers is the least discussed one. It was shown [2] that at low current density (j < 3 A/cm²) experimental EQE dependences on current at 13–300 K are in agreement with ABC model simulations taking into account Auger recombination and Shockley-Read-Hall non-radiative recombination. However, this model failed to explain the lack of EQE temperature dependence and EQE decrease over increasing injection (including the results of pulse-mode measurements preventing overheating) in InGaN/GaN LEDs at j > 30 A/cm² and an increase in EQE droop at 300–400 K [2]. The aim of this work is to find out the contribution of delocalized carriers into the thermal EQE droop in a wide range of current densities as well as the origin of EQE droop at 300-400 K and at j > 30 A/cm² under direct current and at pulse-mode.

2. Experimental
The study is based on the assumption that the relative contribution of mechanisms causing the EQE droop that were suggested by different authors may manifest to a different extent with a voltage and forward current change and happen in different LED areas. We studied commercially available blue
(450-460 nm) InGaN/GaN LEDs having maximum EQE ~ 45-50% and 1 mm² active area. Electroluminescence spectra, EQE dependences on current in the pulse mode (100 ns pulses at 50 Hz), peak EQE values distribution, FWHM, and current-voltage (I-U) characteristics were investigated to clarify the contribution of delocalized carriers into the EQE droop at $j < 1 \text{ A/cm}^2$ and $j > 30 \text{ A/cm}^2$.

3. Results and discussion

A thorough investigation of EQE dependences on current up to 7 kA/cm² at 100-450 K in the pulse mode shows that a common shape of these dependences is in agreement with the earlier published results [1, 2]. Furthermore, EQE dependences almost completely coincide at $j > 40 \text{ A/cm}^2$, while EQE values fall to 5% at 7 kA/cm². Figure 1 (a, b) shows typical EQE dependences on current in blue LEDs at 280 K (curve 1) and 400 K (curve 2). The dependences are shown up to 2000 mA (0.2 kA/cm²) to better illustrate their peculiarities because it was found out that the shape of EQE dependences on current doesn’t change at 1000 – 7000 mA (0.1 – 0.7 kA/cm²). Figure 1 (b) presents the same dependences on a semi-logarithmic plot. The first region (region I) shows a quick growth in EQE over a current increase from 5 to 10 mA.

![Figure 1](image_url)

Figure 1. (a) EQE dependences on current at 280 K (curve 1) and 400 K (curve 2); (b) the same dependences in a semi-logarithmic plot. The vertical lines show current values corresponding to the p-n junction opening. The roman numerals indicate typical regions of EQE change with current.

The second region (region II) demonstrates a slight increase in EQE ~ 3 % over a current growth from 10 to 40 mA at 280 K and from 10 to 100 mA at 400 K despite the fact that the current increases two-fold at 280 K and ten-fold at 400 K. The third region (region III) indicates a remarkable EQE droop with a further current increase when a bias exceeds a threshold voltage ($U > U_{th}$) up to 300 mA. It should be noted that up to this current value the shapes of EQE dependences on current under direct current and at pulse mode practically coincide. The fourth region (region IV) is the same for all dependences and does not depend on temperature. I-U characteristics and peak EQE value distribution and FWHM over the wavelengths were studied to clarify the observed peculiarities. The I-U characteristics (Figure 2) has a typical for blue LEDs region of excessive tunneling current at $U < 2 \text{ V}$ and an injection current region with a non-ideality factor $n = 2$. The vast majority of works consider this region as an experimental fact allowing one to explain radiative and non-radiative recombination in the framework of the ABC model, excluding mechanisms behind the EQE droop related to the carrier transport [2]. The current temperature dependences at a fixed bias in the injection region of forward I-U characteristics shown on Figure 2 and 3 have a considerably weaker temperature dependence than that described by the Shockley equation. This points out on the contribution of non-injection transport mechanisms. The reverse I-U characteristics as shown in numerous works [3] can’t be described the Shockley equation and requires more complicated carrier transport mechanisms to explain the observed experimental results. The vast majority of works use a trap-assisted tunnelling (TAT) to describe excessive tunnelling current at a low bias. The best physical interpretation of this model seems to be visually shown in [4] (Figure 4). The phonon assistance in the tunneling (which is not illustrated on Figure 4) and the contribution of non-injection losses in n⁺ and p⁺ regions are an important part of the model.
The depth of phonon penetration is 100 nm [5]. According to a model describing conventional p⁺-n⁻-n⁺ semiconductor structures pierced by conducting shunts or defects (including extended defects) in a space charge region of p-n junction [6], this tunneling mechanism leads to a considerably more complicated distribution of charge carriers in an active region around p-n junction as well as in low resistance layers. It should be noted that a strong dependence of current on voltage up to ~ 2.5 V and its intensification with a temperature growth (Figures 2 and 3) is in good agreement with the semiclassical simulation of trap-assisted tunneling in GaN-based light-emitting diodes introduced in [7] that is based on the model shown on Figure 4. This mechanism leads to non-radiative losses. Thus, an enhancement in TAT process at 300-400 K revealed at I-U characteristics seems to be one of causes behind the EQE droop at 300-400 K. It should be noted that many scientists have applied the TAT process to investigate features of I-U characteristics [3, 4]. However, the vast majority of works analyzing the EQE droop with a notable exception of [8] usually neglect it [2]. The contribution of TAT to the EQE droop at 400 K has never been considered. Another mechanism is related to thermalized (delocalized) carriers occurring in the active area of LED when temperature increases and preactivation of coupled Si whose activation energy is 30-50 meV happens. High Si concentration up to ~ 10\(^{18}\) cm\(^{-3}\) is usually incorporated in LED structure to suppress native defects of acceptor type. This process is limited by a narrow temperature range. Both mechanisms are revealed in earlier p-n junction opening at 400 K (Figure 5, curve 1) than at 300 K (Figure, curve 2). Moreover, a growth in the concentration of delocalized carriers can be identified by broadening FWHM over a temperature increase from 300 to 400 K at 5 mA (Figure 6, a).
Figure 6. Electroluminescence spectra of InGaN/GaN LED at 50-420 K under different current values: (a) 5 mA; (b) 100 mA.

Thus, the origin of EQE droop in the temperature range 300-400 K at $j < 10$ A/cm$^2$ relates to the intensification of trap-assisted tunneling and an increase in the concentration of delocalized carriers at 300-400 K.

To clarify the causes behind the EQE droop at $U > U_{th}$ (region III on Figure 1), peak EQE values and FWHM distributions over wavelengths (Figure 7, a and b) at the same current and voltage values that shown on Figure 1 were studied. It was clarified for numerous LEDs that the shape of these distributions at $U > U_{th}$ differ fundamentally from that at $U < U_{th}$, i.e. at p-n junction opening under direct current and at pulse mode. In the first case (regions I and II on Figure 7, a), the quick EQE growth with a current increase at a fixed wavelength shows the process of radiative recombination of localized carriers. Furthermore, it might be assumed that the equilibrium filling of QWs takes place since FWHM does not change and carrier localization occurs in the QWs situated in a depletion region (regions I and II). C-V profiling indicates that only two QWs are situated in the depletion region at 0 V [9], while the rest of QWs and barriers are filled by electrons (Figure 8). A slight shift in the wavelengths with close EQE values might be explained by the Stark effect. It should be noted that no noticeable EQE decrease is observed. On the contrary, at $U > U_{th}$ (region III) the non-equilibrium filling of QWs takes place since FWHM increases continuously over wavelengths with a current increase and is followed by the EQE droop.

Figure 7. Peak EQE values distribution (curve 1) and FWHM (curve 2) over wavelengths at: (a) 280 K; (b) 400 K. Roman numerals displays the same typical regions of EQE dependences on current shown on Figure 1. Vertical lines indicates the values of current and voltage corresponding to the p-n junction opening.
The opening of p-n junction is accompanied by an increase in the concentration of delocalized carriers activated by injection. They fill all active region of LED including the lateral regions of alloy fluctuations in QWs situated outside of the depletion region. The existence of such regions whose lateral dimensions vary from several nanometers to several microns in QWs is well known. Some of them contain reduced barriers which are revealed in the shape of forward I-U characteristics at $U < 2.5$ V (Figure 2). These peculiarities as well as low values of diffusion length in nitrides make it possible to suggest that delocalized carriers can recombine before relaxing into global energy minima and complicated carriers dynamic takes place under injection current [10]. The coexistence of local regions containing barriers of different height can lead to a current growth and subsequently to the overflow of shallow wells. This results in the escape of carriers from those wells, their tunneling to the neighboring deeper wells and trapping. This is equal to an increase in a barrier height in a deep well. This process occurs continuously with growing current, leading to the formation of a "quantum-escape staircase". The existence of such a quantum staircase results in a change in wavelengths over the current increase. It also leads to a change in peak EQE values over wavelengths, the loss of carriers due to trapping and a reduction in localizing potentials. The reduction in localizing potentials up to 60 meV was observed during the study of electroluminescence spectra in blue LEDs [11]. An increase in voltage is followed by a growing number of MQWs situated outside of the depletion region. This leads to a declining impact of radiative recombination of localized carriers and a decrease in maximum EQE values. The comparison of FWHM in electroluminescence spectra in LEDs at the same temperature (Figure 7) but at different currents (5 and 100 mA) indicates that FWHM broadening due to delocalized carriers activated by injection is more prominent than that due to thermalized carriers at 400 K when the current density is already ~ 10 A/cm². Thus, the injection-activated delocalized carriers are prevalent at $j > 30$ A/cm² and the EQE droop does not depend on temperature. Another mechanism contributing to the EQE droop at $j > 40$ A/cm² is a diffusion of delocalized carriers and their non-radiative recombination at extended defects including grain boundaries [12].

4. Conclusion
The study allowed us to find out several mechanisms responsible for the EQE droop in InGaN/GaN LEDs at 50-450 K. The relative contribution of these mechanisms to the EQE droop depends on forward current and voltage values, and also on the placement of MQWs which could be situated inside or outside of a depletion region around p-n junction. It is clarified that the filling of MQWs situated inside and outside of depletion region differs noticeably under direct current and at pulse mode. The filling of quantum states in QWs situated in a depletion region is equilibrium. It determines the effective radiative recombination of localized carriers at $j < 10$ A/cm². On the contrary, the filling of MQWs situated outside of the depletion region is non-equilibrium. The mechanism takes place...
since FWHM increases continuously over wavelengths with a current increase and is followed by the EQE droop. The process intensifies when the p-n junction opens at \( U > U_{th} \) \((j > 30 \text{ A/cm}^2)\). It is followed by a growth in delocalized carriers activated by injection. We suggest that interactions between delocalized carriers a lateral regions of alloy fluctuations in QWs whose lateral dimensions vary from several nanometers to several microns lead to the formation of a “quantum-escape staircase” over growing current. Moreover, they also result in reduced localized potential, the blue shift in maximum EQE values, and the EQE droop. The formation of a “quantum-escape staircase” is considered hypothetically. This assumption requires a careful theoretical and experimental examination. It is shown that the origin of an increase in the EQE droop in the temperature range 300-400 K at \( j < 10 \text{ A/cm}^2 \) is related to the intensification of trap-assisted tunneling. The intensification of trap-assisted tunneling occurs when non-radiative recombination is localized outside of MQWs and the concentration of temperature-activated delocalized carriers grows. The latter process is completed by Si activation in QWs and barriers. A growth in forward voltage results in a decrease in the number of QWs in the depletion region and a decrease in maximum EQE values. As a result, their contribution to EQE starts declining over a forward voltage increase. The injection-activated delocalized carriers prevail at \( j > 30 \text{ A/cm}^2 \) and the EQE droop does not depend on temperature.

Another mechanism contributing to the EQE droop at \( j > 40 \text{ A/cm}^2 \) is a diffusion of delocalized carriers and their non-radiative recombination at extended defects including grain boundaries [12].

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