How to Identify the Primary Cause of the GaN-LED Efficiency Droop

Joachim Piprek

NUSOD Institute LLC, Newark, DE 19714-7204, United States, E-mail: piprek@nusod.org

Abstract – **GaN-based light-emitting diodes exhibit a strong efficiency droop at high current, which has been attributed to Auger recombination and electron leakage, respectively. It still remains unclear which of these mechanisms dominates in any given case. Even advanced numerical simulations of experimental characteristics can support either mechanism, due to uncertain material parameters. This paper demonstrates how the comparative investigation of temperature effects can lead to a clear distinction between both mechanisms.**

GaN-based LEDs are of interest for many applications but their performance is handicapped by a significant efficiency reduction with increasing injection current (efficiency droop).[1] Several physical mechanisms have been proposed to explain the efficiency droop, most prominently electron leakage from the quantum wells (QWs) [2] and Auger recombination inside the QWs,[3] respectively. Very few direct measurements of either mechanism are published thus far, none of which established a dominating magnitude. All quantitative analyses of the efficiency droop are based on modelling and simulation. Different and partially contradicting models were shown to produce good agreement with measured efficiency vs. current characteristics. Thus, the search for the origin of the efficiency droop turned into a validation problem for GaN-LED efficiency models. Simple models, that consider only one of the possible droop mechanisms, are unable to distinguish between competing explanations. Numerical models that include several possible droop mechanisms, still depend on various material parameters some of which are not exactly known. Published droop simulations typically use not only different parameter sets but are applied to different device examples, so that a direct comparison is very difficult.

We here compare the two leading droop explanations by simulating the same measurements on the same device using the same numerical model with two different sets of two key material parameters: the Auger recombination coefficient C and the acceptor density N_A inside the AlGaN electron blocking layer (EBL). The EBL's ability to stop electron leakage strongly depends on N_A because negatively charged acceptors are able to compensate for positive polarization charges at the EBL interface to the active region.[4] However, only a small and unknown fraction of Mg atoms used for p-doping turn into AlGaN acceptors, so that this crucial simulation parameter is typically much smaller than expected, and the leakage current potentially much larger. The other crucial parameter, C, is even more uncertain. Realistic microscopic models for Auger recombination in InGaN QWs are still not available and C parameters extracted from measurements vary over two orders of magnitude.[5]

Our study utilizes the APSYS software[6] which is widely used for GaN-LED simulations and which covers a wide spectrum of physical mechanisms, including the two mechanism of interest here.[7] Our LED device example comprises five 3-nm-thick QWs emitting at 450nm that are covered by a p-$Al_{0.13}Ga_{0.87}N$ EBL and a p-GaN cladding layer.[8] LED characteristics measured at room temperature are depicted by symbols in Fig. 1.

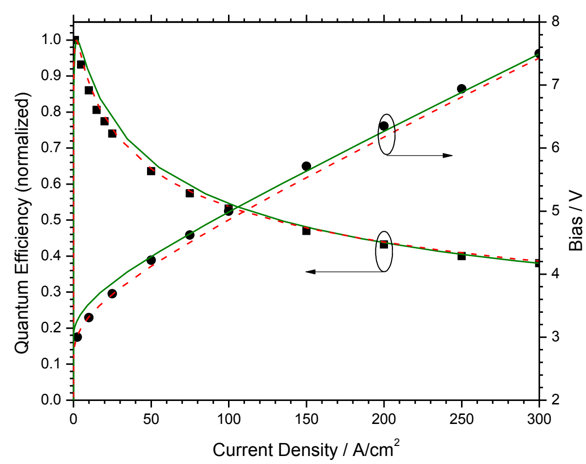

Fig. 1: Normalized quantum efficiency and bias vs. current density (T=25ºC): symbols– measurement,[8] dashed red line – simulation with negligible leakage; solid green line – simulation with negligible Auger recombination.

The first simulation assumes that the majority of Mg atoms form AlGaN acceptors ($N_A=10^{19}cm^{-3}$) which almost completely suppresses electron leakage. Without leakage, the measured efficiency characteristic is fitted by using a large QW Auger coefficient of C = 5 x 10^{-30} cm^6/s, i.e., the efficiency droop is exclusively caused by Auger recombination. This C-parameter is slightly higher than extracted from other measurements, since it does not include the electron-hole separation typical for InGaN/GaN QWs, which is considered separately in the APSYS model.[5] The simulated efficiency and bias characteristics are in good agreement with the measurements (dashed red lines in Fig. 1).

In the second simulation, the AlGaN acceptor density is reduced to N_A=2.6 x 10^{18} cm^{-3} which leads to strong electron leakage because the effective EBL energy barrier is reduced. By removing QW Auger recombination (C = 10^{-34} cm^6/s), the measured characteristics can still be reproduced quite well (solid green lines in Fig. 1). The small remaining differences are not sufficient to clearly eliminate one of the droop explanations. In fact, intermediate EBL acceptor densities would lead to a coexistence of both droop mechanisms in this simulation.

Thus, additional characteristics are required to identify the dominating droop mechanism. Various groups measured a decline of the GaN-LED efficiency with increasing ambient temperature.[2,9,10] We here investigate this effect by increasing the temperature in both simulations to T=150°C, without changing any other input parameter. The resulting internal quantum efficiency IQE is plotted in Fig. 2. The measured external quantum efficiency EQE depends on the photon extraction efficiency EXE which is not exactly known, so that an experimental extraction of IQE is hardly possible (EQE = IQE x EXE). Thus, the IQE difference at room temperature as shown in Fig. 2 does not help to distinguish between both droop mechanisms. Note that the reported experimental efficiency was normalized (Fig. 1). However, rising ambient temperature leads to opposite changes of the two droop mechanisms.

Electron leakage from the QWs is reduced at higher temperature (solid lines in Fig. 2) due to improved hole injection into the QWs.[4] The large AlGaN acceptor ionization energy leads to a very small free hole density at room temperature which rises with higher temperature. The corresponding efficiency enhancement clearly contradicts all reported measurements, i.e., electron leakage based on thermionic emission is unable to explain this efficiency droop behaviour. Electron tunnelling via defect levels is only relevant at very low current.[11] Direct measurements show enhanced leakage at lower temperatures,[10] thereby confirming our simulation results.

If the efficiency droop is mainly caused by QW Auger recombination, the simulated temperature effect is close to the measurements (dashed lines in Fig. 2). Surprisingly, this agreement is not caused by changing the Auger coefficient, which is considered temperature independent here, based on earlier findings.[9] The calculated efficiency reduction is mainly caused by a reduced radiative emission rate and an enhanced Shockley-Read-Hall recombination at higher temperatures. Secondary leakage of high-energy (hot) electrons generated by Auger recombination is not included here since the travel distance of hot electrons remains unclear. Monte-Carlo simulations suggest that less than 5% of hot Auger electrons eventually leak into the p-doped layers of the LED.[12]

In summary, advanced simulation of temperature effects exclude thermionic emission leakage as primary cause of the GaN-LED efficiency droop; however, minor leakage may still occur in some LEDs.[13] Only the Auger recombination model correctly reproduces the measured efficiency reduction with increasing ambient temperature.

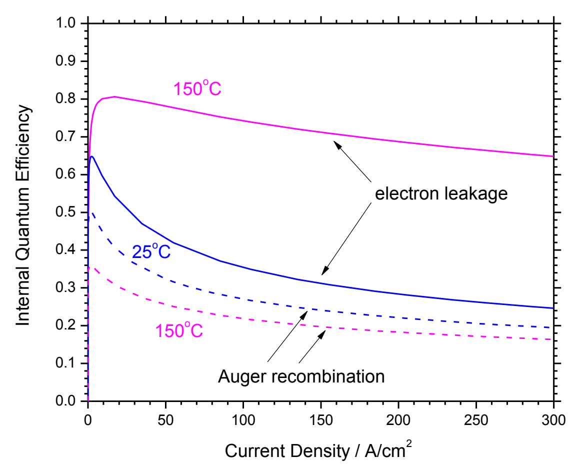

Fig. 2: Internal quantum efficiency vs. current density as simulated at different ambient temperatures: dashed lines – negligible electron leakage, solid lines - negligible Auger recombination).

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