Unified Model for the GaN LED Efficiency Droop

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Nitride-based light-emitting diodes (LEDs) suffer from a reduction (droop) of the internal quantum efficiency with increasing injection current. This droop phenomenon is currently the subject of intense research worldwide, as it delays general lighting applications of GaN-based LEDs. Several proposals have been forwarded to explain the efficiency droop. Among the suggested droop mechanisms are defect-related recombination, Auger recombination, and electron leakage. However, different sample preparation and measurement conditions as well as the application of different models lead to a confusing and sometimes contradicting variety of efficiency droop observations and explanations. This paper combines different droop models in a simple yet unified framework and it helps to bring more clarity to the ongoing droop discussion.

Keywords: gallium nitride, light-emitting diode, efficiency droop, electron leakage, Auger recombination, defect-related recombination, modeling

1. INTRODUCTION

Thus far, GaN-based LEDs deliver high efficiency only at relatively low current and at relatively low brightness. At the elevated injection current required in practical high-brightness applications, the LED efficiency is substantially reduced. This efficiency droop phenomenon is observed across a broad wavelength spectrum, with and without self-heating. It originates in carrier loss mechanisms which prevent electron-hole pairs from generating photons inside the active layer, thereby reducing the internal quantum efficiency (IQE). Several and partially contradicting proposals have been developed to explain the IQE droop. Among them are density-activated defect recombination (DADR),[1] enhanced Auger recombination,[2] and electron leakage.[3] A review of droop explanations was recently published, proposing a unified yet simple approach to model the IQE droop.[4] The present paper further develops this model and compares different droop mechanisms.

2. IQE MODEL

The internal quantum efficiency is the ratio of the photon number generated inside the quantum wells to the number of electrons injected into the LED. The IQE can also be defined as the fraction of the total current I that feeds the radiative recombination inside the quantum well

$$\eta_{IQE} = I_{rad} / I = I_{rad} / (I_{rad} + I_{lost}) \tag{1}$$

The total current can be split up into carriers that generate photons in the quantum well (I_{rad}) and carriers that are lost to other processes (I_{lost}). Efficiency droop only occurs if I_{lost} increases stronger than I_{rad} with rising current injection. Thus, most droop investigations focus on possible carrier loss mechanisms in GaN-based LEDs.

In general, carrier losses can occur inside or outside the quantum wells. Non-radiative recombination processes inside the quantum well can either be defect-related recombination (I_{def}) or Auger recombination (I_{Auger}).[5] Carrier

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recombination outside the quantum wells is caused by carrier leakage (I_{leak}). Thus, the total LED injection current can be split up into four parts

$$I = I_{rad} + I_{def} + I_{Auger} + I_{leak} \tag{2}$$

establishing three principal droop mechanisms: defect-related recombination, Auger recombination, and carrier leakage (Fig. 1).

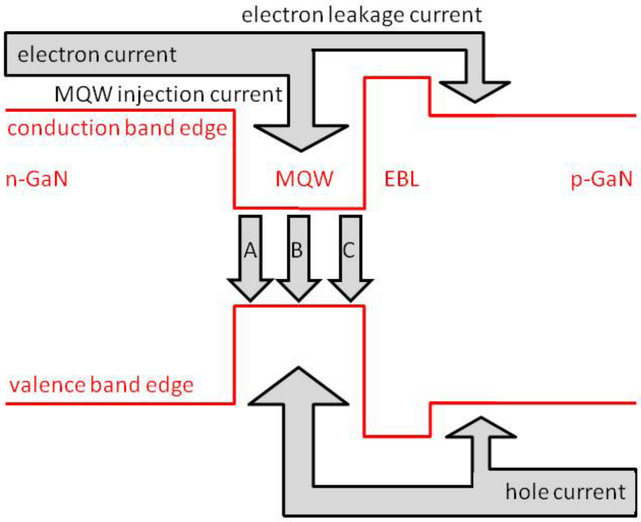

Figure 1 Schematic illustration of LED current components (A – defect-related recombination, B – radiative recombination, C – Auger recombination, MQW – multi-quantum well, EBL – electron blocker layer).

The first three contributions in (2) are related to the well-known ABC model for carrier recombination inside the quantum well

$$I_{QW} = I_{def} + I_{rad} + I_{Auger} = qV_{QW} (A\,n + B\,n^2 + C\,n^3) \tag{3}$$

with the electron charge q, the active volume V_{QW} of all quantum wells, the QW carrier density n, the defect-recombination parameter A, the radiative coefficient B, and the Auger coefficient C.

The parameter $A=1/(2\tau_{SRH})$ is proportional to the defect density and it is related to the Shockley-Read-Hall (SRH) recombination lifetime τ_{SRH}. However, SRH recombination characterized by a constant SRH lifetime is unable to cause efficiency droop. Recently, Hader et al. proposed the inclusion of density-activated defect recombination (DADR)[1]. It is activated above a critical carrier density n_{DADR}, when some quantum well carriers spill over from regions with lower potential and are thereby able to reach defect recombination centers characterized by a lower recombination lifetime τ_{DADR}. The total defect recombination current is calculated as

$$I_{def} = q\,V_{QW}\,A\;\;n = \;q\,V_{QW}\;n \,/\, (2\tau_{SRH}) \qquad \text{for } n < n_{DADR} \tag{4a}$$

$$I_{def} = q\,V_{QW}\;\;n/(2\tau_{SRH}) + q\,V_{QW}\,(n-n_{DADR})^2/(2\,n_{DADR}\,\tau_{DADR})\,) \qquad \text{for } n > n_{DADR} \tag{4b}$$

The parameters $\tau_{SRH,}$ $\tau_{DADR,}$ and n_{DADR} are obtained from fits to IQE measurements neglecting Auger recombination and leakage.[1]

Another variation of the simple ABC model (3) was proposed by David and Grundmann,[6] who employ a carrier-density dependent radiative coefficient $B(n)=B_0/(1+n/n_0)$ and fit parameters B_0 and n_0 to calculate the radiative current

$$I_{rad} = q\, V_{QW}\, B(n)\; n^2 = q\, V_{QW}\, B_0 n^2/(1+n/n_0)\ . \tag{5}$$

The leakage current cannot be easily described by a simple equation and it is often neglected. Özgür et al.[7] used the formula $I_{leak}=bI^k$, however, this approach is hard to integrate into an analytical IQE model. We proposed a slightly different approach by relating the leakage current I_{leak} to the current I_{QW} injected into the quantum wells [4]

$$I_{leak} = a\, I_{QW}{}^{m}. \tag{6}$$

Numerical simulations show that this formula provides a very good approximation for carrier leakage by thermionic emission from the quantum wells.[8] However, it may also be used to describe fly-over carriers that are not captured by the quantum wells,[9] or defect-assisted carrier tunneling.[10,11]

Based on the general equations (1-3), the different contributions outlined above can be unified by the simple IQE formula

$$\eta_{IQE} = I_{rad}\ /\ (I_{QW}\ +\ a\, I_{QW}{}^{m}). \tag{7}$$

The different droop mechanisms can be separated or combined by choosing different parameter sets. For instance, picking a=0 and C=0 eliminates leakage and Auger recombination and results in an efficiency droop that is dominated by carrier recombination. The injection current density is given by

$$j = I\ /\ A_{QW} = (I_{QW} + a\, I_{QW}{}^{m})\ /\ A_{QW} \tag{8}$$

with the active quantum well area A_{QW}.

3. DISCUSSION

This unified droop model simply combines the different droop formulas discussed in the literature. However, the model does not determine which of the three possible carrier loss mechanisms is the main cause for the efficiency droop: Auger recombination, defect-related recombination, or leakage. As shown in the following, different parameter sets can give almost identical results. As an example, we here use room-temperature IQE measurements on 523nm InGaN/GaN single-quantum well LEDs published by Laubsch et al.[12] Neglecting DADR and carrier leakage, the authors extract the Auger coefficient $C = 3.5 \times 10^{-31}\ cm^6s^{-1}$ from their measurement. The solid line in Fig. 2 shows the fitted IQE characteristic of their model ($A = 4.7 \times 10^6\ s^{-1}$, $B = 1.2 \times 10^{-12}\ cm^3s^{-1}$).

An almost identical IQE characteristic can be obtained by replacing the Auger recombination with DADR and employing $B(n)=B_0/(1+n/n_0)$ with $B = 7 \times 10^{-11}\ cm^3s^{-1}$ and $n_0 = 5 \times 10^{18}\ cm^{-3}$.[6] The triangles in Fig. 2 give the resulting IQE characteristic using the fit parameters $\tau_{SRH} = 8$ ns, $\tau_{DADR} = 4.5$ ns and $n_{DADR} = 4 \times 10^{17}\ cm^{-3}$.

Replacing the Auger recombination in the original model with the leakage formula (6) results in the squares shown in Fig. 2 ($a=0.4\ A^{-0.77}$, $m=1.77$, $A = 4.7 \times 10^6\ s^{-1}$, $B = 1.2 \times 10^{-12}\ cm^3s^{-1}$).

A similar exchangeability of IQE formulas has been demonstrated for other measurements.[4,7] Thus, direct experimental evidence is needed for any proposed droop mechanism.

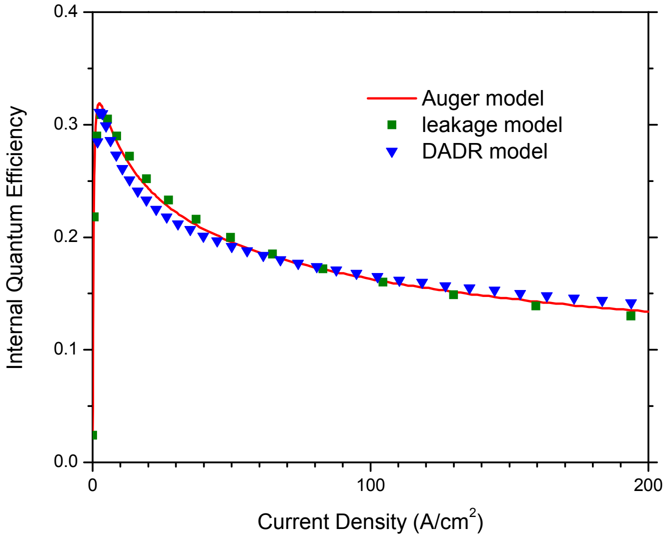

Figure 2 Calculated internal quantum efficiency vs. current density using different droop models.

4. SUMMARY

A unified model for the nitride LED efficiency droop is proposed. This simple model considers Auger recombination, density-activated defect recombination as well as carrier leakage as potential explanations of the efficiency droop. We also demonstrate that fitting of an IQE formula to IQE measurements is not sufficient to establish any single mechanism as cause of the efficiency droop, as different models can give almost identical results.

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