Electron Leakage Effects on the Efficiency Droop in GaN-based Light-Emitting Diodes

Joachim Piprek [a] and Zhan-Ming (Simon) Li [b]

[a] NUSOD Institute LLC, Newark, DE 19714-7204, United States, E-mail: piprek@nusod.org
[b] Crosslight Software Inc., 121-3989 Henning Drive, Burnaby, BC V5C 6P8 Canada

Abstract – **Nitride-based light-emitting diodes suffer from a reduction (droop) of the internal quantum efficiency (IQE) with increasing injection current. Using advanced device simulation, we investigate the impact of electron leakage on the IQE droop for different properties of the electron blocker layer. We also find that the electron leakage decreases with increasing temperature, which contradicts common assumptions.**

I. INTRODUCTION

The efficiency droop phenomenon is currently the subject of intense research worldwide, as it delays general lighting applications of GaN-based LEDs. Efficiency droop is observed across a broad wavelength spectrum of InGaN/GaN LEDs[1] and also with deep ultraviolet AlGaN/AlN LEDs.[2] It occurs in steady-state and in pulsed operation, i.e., LED self-heating has only a minor effect. Droop only weakly depends on the ambient temperature between 4K and 453K.[3] Many proposals have been forwarded to explain the efficiency droop. Among them are carrier delocalization,[1] enhanced Auger recombination,[4] and electron leakage.[5] However, none of these proposals is generally accepted.

We here investigate the influence of electron leakage from the multi-quantum well (MQW) active region on the efficiency droop. The flow of electrons beyond the MQW is a common problem in GaN-based devices and it is a reason for the typical implementation of an AlGaN electron blocker layer (EBL) on the p-side of the MQW active region (Fig. 1). However, the EBL is often unable to completely stop electron leakage in nitride LEDs.[6] Direct experimental proof of electron leakage beyond the EBL was recently provided by measuring spontaneous emission from the p-side of the LED.[7, 8] Electrons leaking into the p-doped LED layers capture holes before they reach the active region, thereby reducing hole injection into the quantum wells (Fig. 1).

II. MODEL AND PARAMETERS

We here employ the advanced LED device simulation software APSYS[9] which self-consistently computes carrier transport, the wurtzite electron band structure of the strained quantum wells, and the photon emission spectrum. Schrödinger and Poisson equations are solved iteratively in order to account for the quantum well deformation with changing device bias (quantum-confined Stark effect). The transport model includes drift and diffusion of electrons and holes, Fermi statistics, built-in polarization and thermionic emission at hetero-interfaces, as well as Shockley-Read-Hall (SRH) recombination and Auger recombination of carriers. Based on direct calculations of the Auger parameter,[10] we employ a value of $C = 3.5 \times 10^{-34} cm^6 s^{-1}$ which shows negligible impact on the IQE. The SRH lifetime within the quantum wells depends on the device processing, we here use an estimated value of $\tau = 100ns$.

Built-in interface charges due to spontaneous and piezoelectric polarization are often calculated using the Bernardini model.[11] However, experimental investigations indicate weaker polarization than predicted, ranging from 20%[12] to 80%[13] of the theoretical value, with typical results near 50%.[14] This broad variation was attributed to partial compensation of the built-in polarization by fixed defect and interface charges[15] or to inappropriate analysis of measured data.[16] We therefore scale the predicted polarization charges by a factor of 0.5, which is in agreement with other investigations.[17]
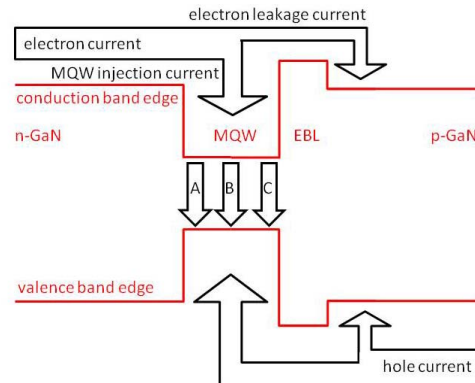

Fig. 1: Schematic illustration of LED current components (A – Shockley-Read-Hall recombination, B – spontaneous emission, C – Auger recombination).

Early numerical LED device simulations did not show an efficiency droop despite the inclusion of thermionic emission.[6,18] The main reason for the missing efficiency droop was the high band offset ratio of $\Delta E_c : \Delta E_v = 70 : 30$ assumed for nitride semiconductors.[19] In other words, the theoretically predicted EBL energy barrier was too high to allow for sufficient electron leakage. Electron leakage was only identified as possible origin of the efficiency droop after

reducing the AlGaN band offset ratio to 50:50,[5] which we also adopt in this investigation. Exact band offsets between nitride alloys are hard to measure or calculate,[20] however, such a reduced band offset ratio seems more likely than a strongly enhanced Auger recombination.[4]

Self-heating and photon extraction are neglected in this study since we only analyze the pulsed IQE. Further details on models and parameters can be found elsewhere.[6]

<center>III.   SIMULATION RESULTS</center>

We investigate a typical LED structure with five 2.5nm thick $In_{0.15}Ga_{0.85}N$ quantum wells separated by 9nm thick GaN barriers. The MQW is grown on $2x10^{18}cm^{-3}$ Si-doped GaN and it is covered by a 20nm p-$Al_{0.15}Ga_{0.85}N$ EBL (Mg: $3x10^{18}cm^{-3}$) followed by an $10^{19}cm^{-3}$ Mg-doped GaN layer. The Mg acceptor activation energy is 0.17 eV in GaN and 0.215eV in the EBL, leading to a very small free hole density typical for GaN devices. Figure 2 shows the energy band diagram of this structure at j=1000 A/cm^2 current density. The simulated electron leakage at room-temperature (T=300K) can be approximated as function of the MQW injection current using $j_{leak}=0.019 \times j_{MQW}^{1.81}$ ($j=j_{MQW}+j_{leak}$, cf. Fig. 1). This simple function may be used in rate equation models and it is mathematically more convenient than the equivalent form $j_{leak}= 0.16 \ j^{1.21}$ (all current densities are given in A/cm^2). Practical high-brightness LED operation requires at least j=200 A/cm^2. At this current density, our device exhibits almost 50% leakage current and an IQE of 0.52 (Fig. 3). The default IQE curve in Fig. 3 shows a significant efficiency droop after reaching a peak efficiency of 0.81 at j=5 A/cm^2.
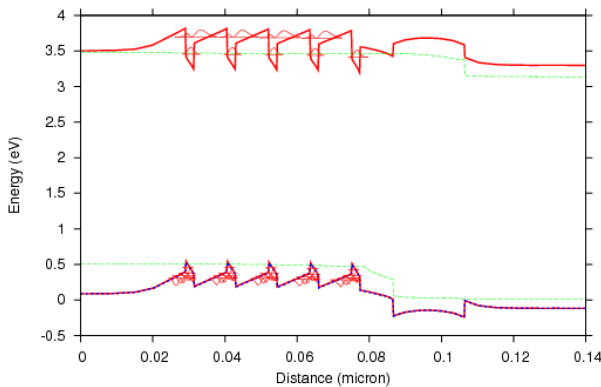
Fig. 2: Energy band diagram near the MQW including quantum well wave functions.

Surprisingly, the simulated electron leakage decreases with increasing ambient temperature, which contradicts the general assumption that thermionic emission must increase with temperature.[3] While this assumption is in principle correct, it is counteracted by an improved hole injection into the MQW with rising temperature, which leads to a higher hole/electron ratio inside the QWs. As a consequence, the net electrostatic field is reduced inside the layer between p-side QW and EBL (cf. Fig. 2), resulting in reduced band bending and in a higher effective EBL energy barrier.

Figure 3 shows the influence of EBL material properties on the simulated efficiency droop. The default material parameters give good agreement with typical IQE characteristics (middle curve). The upper curve is generated by changing the AlGaN EBL band offset ratio from $\Delta E_c:\Delta E_v = $ 50:50 to 70:30 (note that the InGaN band offset ratio is 70:30 in both cases). As a result, the EBL energy barrier is higher in the conduction band and the electron leakage is significantly reduced. The lower curve in Fig. 3 is based on the assumption of full built-in polarization charges at all interfaces according to the theoretical prediction.[11] The positive polarization charge density at the MQW-EBL interface is therefore higher ($6.4x10^{12}cm^{-2}$, default: $3.2x10^{12}cm^{-2}$) which leads to more band bending and a reduced effective EBL energy barrier. The electron leakage current increases dramatically and reduces the internal quantum efficiency to about 0.02.

Further results and discussion will be presented at the conference, including the effect of EBL doping.
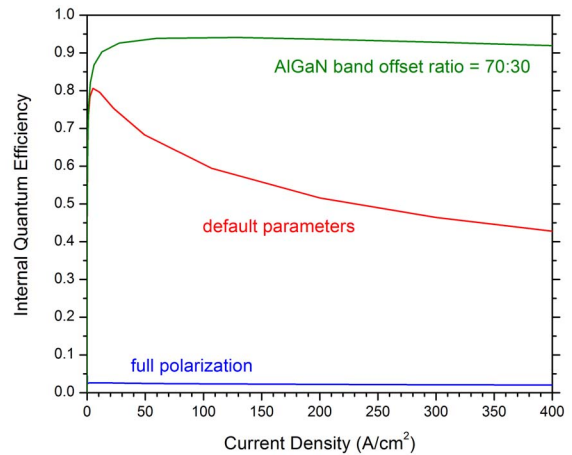
Fig. 3: IQE curves for different EBL material parameters.

<center>REFERENCES</center>

[1] Y. Yang et al., IEEE Trans. Electron Dev. **55**, 1771 (2008)
[2] H. Hirayama et al., Phys. Status Solidi A **206**, 1176 (2009)
[3] A. Laubsch et al. Phys. Status Solidi C 6, S913 (2009).
[4] Y. C. Shen et al., Appl. Phys. Lett. 91(14), 141101 (2007).
[5] M. H. Kim et al., Appl. Phys. Lett. **91**, 183507 (2007).
[6] J. Piprek and S. Li, Chapter 10 in: Optoelectronic Devices: Advanced Simulation and Analysis, edited by J. Piprek (Springer, New York, 2005).
[7] A. Knauer et al., Proc. SPIE, Vol. 7231, 72310G (2009)
[8] K. J. Vampola et al., Appl. Phys. Lett. 94, 061116 (2009).
[9] Crosslight Software, Burnaby, Canada (http://www.crosslight.com).
[10] J. Hader et al., Appl. Phys. Lett. **92**, 261103 (2008).
[11] V. Fiorentini et al., Appl. Phys. Lett., **80**, 1204 (2002).
[12] S. F. Chichibu et al., Appl. Phys. Lett. 73, 2006, 1998.
[13] F. Renner et al., Appl. Phys. Lett., vol. 81, pp. 490-492, 2002.
[14] H. Zhang et al., vol. 84, pp. 4644-4646, 2004.
[15] J. P. Ibbetson et al., Appl. Phys. Lett., vol. 77, 250 (2000).
[16] I. H. Brown et al., Appl. Phys. Lett., vol. 86, 131108, 2005.
[17] C. A. Flory and G. Hasnain, IEEE J. Quant. Electron. **37**, 244 (2001).
[18] K.A. Bulashevich et al., J. Comput. Physics **213**, 214 (2006)
[19] J. Piprek, Semiconductor Optoelectronic Devices: Introduction to Physics and Simulation (Academic Press, San Diego, 2003)
[20] J. Piprek (ed.) Nitride Semiconductor Devices: Principles and Simulation, Wiley-VCH, Berlin, 2007.