Opt Quant Electron (2010) 42:89–95
DOI 10.1007/s11082-011-9437-z

Electron leakage effects on GaN-based light-emitting diodes

Joachim Piprek · Simon Li

Received: 22 September 2010 / Accepted: 9 January 2011 / Published online: 29 January 2011

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 (EBL). The simulations show a strong influence of the EBL acceptor density on the droop. We also find that the electron leakage decreases with increasing temperature, which contradicts common assumptions.

Keywords Gallium nitride · Light-emitting diode · Electron leakage · Efficiency droop · Electron blocker layer

1 Introduction

The GaN-LED efficiency droop phenomenon is currently the subject of intense research worldwide, as it delays general lighting applications of nitride LEDs. Efficiency droop is observed across a broad wavelength spectrum of InGaN/GaN LEDs (Yang et al. 2008) and also with ultraviolet AlGaN/AlN LEDs (Hirayama et al. 2009). It occurs in steady-state and in pulsed operation, i.e., it is not primarily caused by self-heating. Many proposals have been forwarded to explain the efficiency droop. Among them are carrier delocalization (Yang et al. 2008), enhanced Auger recombination (Shen et al. 2007), and electron leakage (Kim et al. 2007). A detailed discussion and contextualization of these proposals has recently been published (Piprek 2010).

We here investigate the influence of electron leakage on the efficiency droop. Electrons leaking from the multi-quantum well (MQW) active region into the p-doped LED layers

J. Piprek (✉)
NUSOD Institute LLC, Newark, DE 19714-7204, USA
e-mail: piprek@nusod.org

S. Li
Crosslight Software Inc., 121-3989 Henning Drive, Burnaby, BC V5C 6P8, Canada
e-mail: simon@crosslight.com

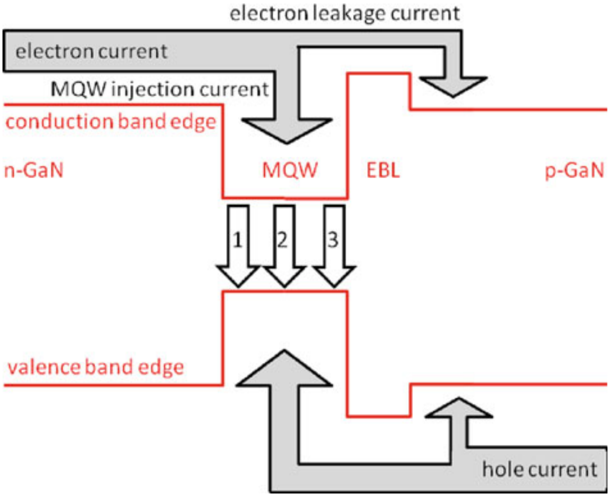

Fig. 1 Schematic illustration of LED current components (1—Shockley-Read-Hall recombination, 2—spontaneous emission, 3—Auger recombination, MQW-multi-quantum well active region, EBL—electron blocker layer)

capture holes before they reach the active region, thereby reducing the hole injection into the quantum wells (Fig. 1). 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. However, the EBL is often unable to completely stop electron leakage in nitride LEDs (Piprek and Li 2005). Direct experimental proof of electron leakage beyond the EBL was recently provided by measuring spontaneous emission from the p-side of the LED (Knauer et al. 2009; Vampola et al. 2009).

2 Model and parameters

We here employ the advanced LED device simulation software APSYS (Crosslight Software, 2010) which self-consistently computes carrier transport, the wurtzite electron band structure of the strained quantum wells, and the photon emission. 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 (Hader et al. 2008), we employ a value of $3.5 \times 10^{-34}\mathrm{cm}^6\mathrm{s}^{-1}$ which shows negligible impact on the internal quantum efficiency (IQE) of the LED. The SRH lifetime within the quantum wells depends on the device processing, we here use an estimated value of 100 ns.

Built-in interface charges due to spontaneous and piezoelectric polarization are often calculated using the Bernardini model (Fiorentini et al. 2002). However, experimental investigations indicate weaker polarization than predicted, ranging from 20% (Chichibu et al. 1998) to 80% (Renner et al. 2002) of the theoretical value, with typical results near 50% (Zhang et al. 2004). This broad variation was attributed to partial compensation of the built-in polarization by fixed defect and interface charges (Ibbetson et al. 2000) or to inappropriate analysis of measured data (Brown et al. 2005). We therefore scale the predicted polarization charges by a factor of 0.5, which is in agreement with other investigations (Flory and Hasnain 2001).

Early numerical LED device simulations did not show an efficiency droop despite the inclusion of thermionic emission (Piprek and Li 2005; Bulashevich et al. 2006). 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 (Piprek 2003). In other words, the theoretically predicted EBL energy barrier was too high to allow for electron leakage. Electron leakage was only identified as possible origin of the efficiency droop after reducing the AlGaN band offset ratio to 50:50 (Kim et al. 2007), which we also adopt as default value in this investigation. Exact band offsets between nitride alloys are hard to measure or calculate (Piprek 2007), however, such a reduced band offset ratio seems more likely than an enhancement of the Auger recombination by four orders of magnitude (Shen et al. 2007).

Several of the material parameters discussed above will be varied in this study in order to evaluate their impact on the internal quantum efficiency (IQE). Self-heating and photon extraction are neglected here since we only analyze the IQE in pulsed operation.

3 Simulation results

We investigate a typical LED structure with five 2.5 nm thick $In_{0.15}Ga_{0.85}N$ quantum wells separated by 9 nm thick GaN barriers. The MQW is grown on Si-doped GaN (donor density $N_D = 2 \times 10^{18}$ cm^{-3}) and it is covered by a 20 nm Mg-doped $Al_{0.15}Ga_{0.85}N$ EBL (acceptor density $N_A = 5 \times 10^{18}$ cm^{-3}) followed by a Mg-doped GaN layer ($N_A = 10^{19}$ cm^{-3}). The exact nature of Mg doping in nitride materials is still not fully understood (see, e.g., Monemar et al. 2010) and we assume here that only about 10% of the Mg atoms are active acceptors (density N_A). The Mg acceptor activation energy is 0.17 eV in GaN and 0.215 eV in the EBL, leading to a very small free hole density typical for GaN devices.

Figure 2a shows the energy band diagram of this structure at 200 A/cm^2 current density including the electron and hole wave functions of each quantum well. The AlGaN EBL is located on the p-side of the MQW (cf. Fig. 1) and its effective energy barrier in the conduction band is reduced by band bending due to interface polarization charges. The vertical profile of the local electron current density is shown in Fig. 2b and it reveals strong electron leakage across the EBL at room temperature (T = 300 K). Of the 200 A/cm^2 electron current density injected into the MQW from the n-side (left in Fig. 2), only about 105 A/cm^2 feed the recombination inside the quantum wells, while about 95 A/cm^2 leak into the p-side (right in Fig. 2). Correspondingly, the IQE is only about 0.5 at 200 A/cm^2.

Surprisingly, the electron leakage decreases with increasing temperature (Fig. 3), which contradicts the general assumption that thermionic emission must increase with temperature (Laubsch et al. 2009). 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. 2a), resulting in reduced band bending and in a higher effective EBL energy barrier.

Figure 4 shows the calculated IQE curves with different polarization. The default polarization factor of 0.5 results in a typical efficiency droop with higher current. Without polarization, the droop disappears while full polarization dramatically reduces the efficiency. This strong impact of the polarization is mainly attributed to the reduction of the EBL energy barrier by

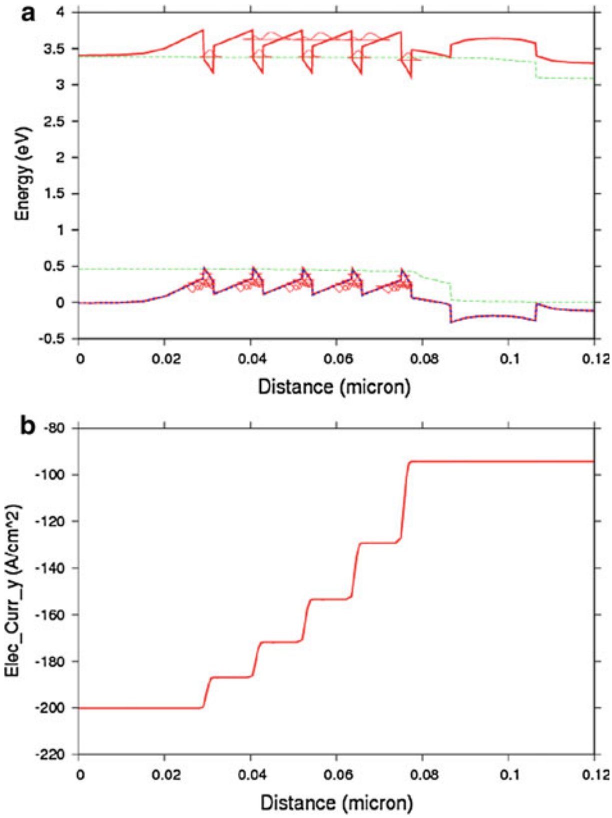

Fig. 2 **a** Energy band diagram near the MQW including quantum well wave functions. **b** Local electron current density near the MQW at $T = 300\,K$ (same window as in **a**)

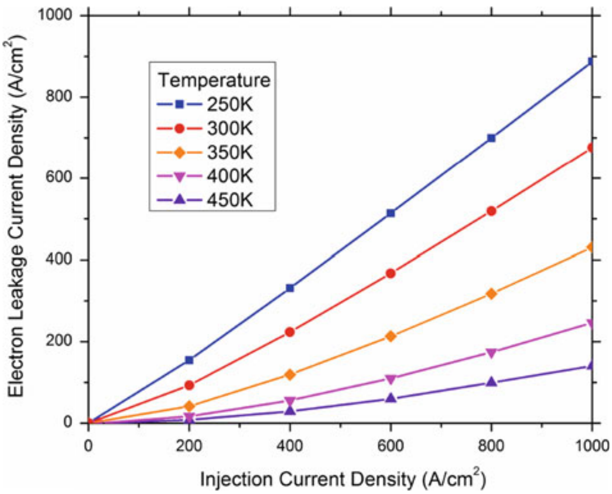

Fig. 3 Leakage current density vs. total current density at different temperatures

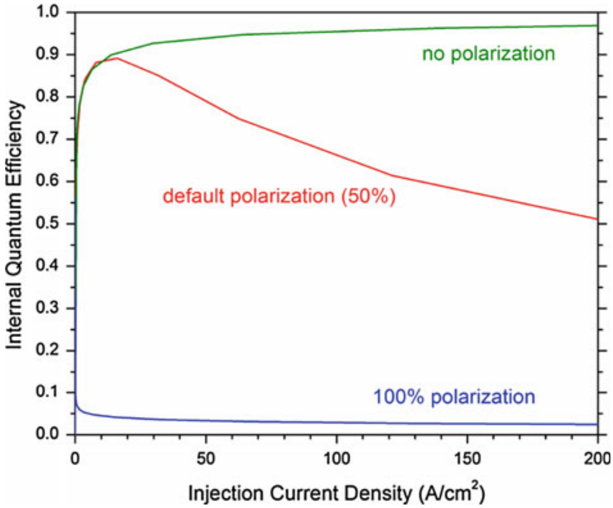

Fig. 4 IQE vs. current density with different polarization (300 K)

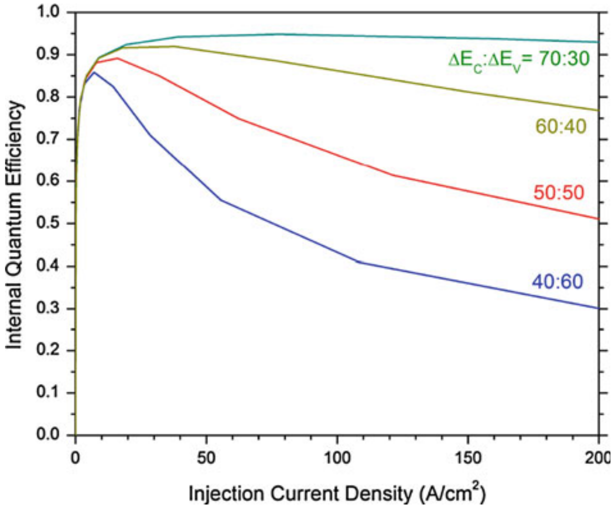

Fig. 5 IQE vs. current density with the AlGaN band offset ratio as parameter (300 K)

interface polarization charges and to the corresponding escalation of electron leakage (Piprek 2010).

Figure 5 plots IQE curves for different values of the AlGaN band offset ratio (default: 50:50). With increasing offset ratio, the EBL energy barrier for electrons grows and the leakage is reduced.

Finally, we vary the density N_A of active acceptors in the EBL (Fig. 6). With low acceptor density in the EBL, the simulated IQE is small (lower curve in Fig. 6a) because the EBL doping is insufficient to compensate for the fixed polarization charges at the MQW-EBL interface (here: $+3.2 \times 10^{12}\text{cm}^{-2}$). This leads to significant band bending near that interface and a reduction of the effective EBL energy barrier blocking electron leakage (Fig. 6b).

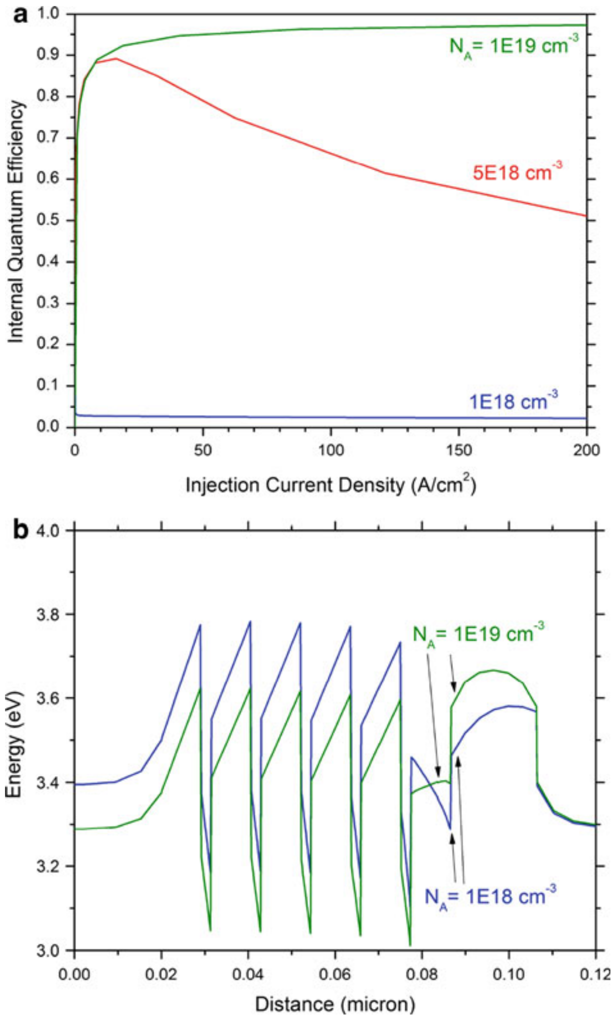

Fig. 6 **a** IQE curves for different EBL acceptor densities N_A at T = 300 K. **b** Conduction band profiles for different EBL acceptor densities (200A/cm^2, 300 K)

With higher N_A, the negatively charged acceptors compensate for the positive polarization charges and thereby eliminate the band bending that reduces the energy barrier for electrons, as shown in Fig. 6b. This finding is in agreement with earlier investigations on laser diodes (Piprek et al. 2006) and it may explain the variation of experimental LED results. The Mg supply is usually turned on for the first time during the growth of the EBL and the acceptor density near the MQW-EBL interface may therefore be lower than intended.

4 Summary

In conclusion, we have demonstrated that the material properties of the electron blocker layer have a strong impact on electron leakage and efficiency droop. For suppression of the efficiency droop, it is important to achieve high Mg acceptor doping densities at the interface between blocker layer and the last quantum well barrier. We also show that increasing ambient temperatures reduce the electron leakage due to improved hole injection.

References

Brown, I.H. et al.: Determination of the piezoelectric field in InGaN quantum wells. Appl. Phys. Lett. **86**, 131108 (2005)

Bulashevich, K.A. et al.: Simulation of visible and ultraviolet group-III nitride light emitting diodes. J. Comput. Phys. **213**, 214 (2006)

Chichibu, S.F. et al.: Effective band gap inhomogeneity and piezoelectric field in InGaN/GaN multiquantum well structures. Appl. Phys. Lett. **73**, 2006 (1998)

Crosslight Software, Burnaby, Canada (http://www.crosslight.com)

Fiorentini, V. et al.: Evidence for nonlinear macroscopic polarization in III–V nitride alloy heterostructures. Appl. Phys. Lett. **80**, 1204 (2002)

Flory, C.A., Hasnain, G.: Modeling of GaN optoelectronic devices and strain-induced piezoelectric effects. IEEE J. Quant. Electron. **37**, 244 (2001)

Hader, J. et al.: On the importance of radiative and Auger losses in GaN-based quantum wells. Appl. Phys. Lett. **92**, 261103 (2008)

Hirayama, H. et al.: 222–282 nm AlGaN and InAlGaN-based deep-UV LEDs fabricated on high-quality AlN on sapphire. Phys. Status Solidi A **206**, 1176 (2009)

Ibbetson, J.P. et al.: Polarization effects, surface states, and the source of electrons in AlGaN/GaN heterostructure field effect transistors. Appl. Phys. Lett. **77**, 250 (2000)

Kim, M.H. et al.: Origin of efficiency droop in GaN-based light-emitting diodes. Appl. Phys. Lett. **91**, 183507 (2007)

Knauer, A. et al.: MOVPE growth for UV-LEDs. Proc. SPIE **7231**, 72310G (2009)

Laubsch, A. et al.: On the origin of IQE-‘droop’ in InGaN LEDs. Phys. Status Solidi C **6**, S913 (2009)

Monemar, B. et al.: Mg-related acceptors in GaN. Phys. Status Solidi C **7**, 1850–1852 (2010)

Piprek, J., Li, S.: Ch 10. In: Piprek, J. (ed.) Optoelectronic Devices: Advanced Simulation and Analysis., Springer, New York (2005)

Piprek, J.: Semiconductor Optoelectronic Devices: Introduction to Physics and Simulation. Academic Press, San Diego (2003)

Piprek, J. et al.: Effects of built-in polarization on InGaN/GaN vertical-cavity surface-emitting lasers. IEEE Phot. Technol. Lett. **18**, 7 (2006)

Piprek, J. (ed.): Nitride Semiconductor Devices: Principles and Simulation. Wiley-VCH, Berlin (2007)

Piprek, J.: Efficiency droop in nitride-based light-emitting diodes. Phys. Status Solidi A **207**, 2217 (2010)

Renner, F. et al.: Quantitative analysis of the polarization fields and absorption changes in InGaN/GaN quantum wells with electroabsorption spectroscopy. Appl. Phys. Lett. **81**, 490–492 (2002)

Shen, Y.C. et al.: Auger recombination in InGaN measured by photoluminescence. Appl. Phys. Lett. **91**(14), 141101 (2007)

Vampola, K.J. et al.: Measurement of electron overflow in 450 nm InGaN light-emitting diode structures. Appl. Phys. Lett. **94**, 061116 (2009)

Yang, Y. et al.: Investigation of the nonthermal mechanism of efficiency rolloff in InGaN light-emitting diodes. IEEE Trans. Electron. Dev. **55**, 1771 (2008)

Zhang, H. et al.: Measurement of polarization charge and conduction-band offset at InGaN/GaN heterojunction interfaces. Appl. Phys. Lett. **84**, 4644–4646 (2004)