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GaN-based bipolar cascade light-emitting diode with 250 % peak quantum efficiency

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Abstract GaN-based light-emitting diodes (LEDs) exhibit a severe efficiency droop with increasing current density. This paper analyses a new approach to circumvent the droop problem by inserting tunnel junctions into the multi-quantum well (MQW) active region, resulting in carrier recycling, a more uniform MQW carrier distribution, and less carrier loss. Self-consistent numerical simulations of such bipolar-cascade LED with four stages predict a quantum efficiency of 250 % at low power and still more than 100 % at high power, despite additional light absorption at the tunnel junctions.

Keywords InGaN/GaN · Light-emitting diode (LED) · Tunnel-junction · Bipolar cascade · Carrier recycling · Quantum efficiency · Wall-plug efficiency

1 Introduction

GaN-based light-emitting diodes (LEDs) are of major interest for applications in lighting, displays, sensing, biotechnology, medical instrumentation and other areas, but their development is handicapped by a significant efficiency reduction with increasing injection current (efficiency droop). Various physical mechanisms have been considered to explain the efficiency droop. Among them are enhanced Auger recombination (Shen et al. 2007), electron leakage (Kim et al. 2007), and density-activated defect recombination (Hader et al. 2010). While all these mechanisms were identified experimentally on different LEDs, conclusive evidence is still missing that the magnitude of any mechanism is sufficiently large to single-handedly cause the efficiency droop. However, all these proposals hold the rising carrier density inside the multi-quantum well (MQW) active region responsible for increasing carrier losses. Therefore, a possible solution lies in the reduction of the QW carrier density required for a given output power by adding quantum wells. But this concept is plagued by the non-uniform vertical carrier distribution commonly observed with thick InGaN MQW

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regions (David et al. 2008). Electrons have a lower effective mass and they move more easily across the MQW than holes, leading to relevant light emission only from the p-side quantum wells (Fig. 1). Consequently, a superior approach should be the cascading of thinner MQW regions with a tunnel junction in between, which allows for the repeated use of electrons and holes for photon generation. Such bipolar cascade (BC) devices were experimentally demonstrated for several types of light emitters, including GaAs-based lasers (van der Ziel 1982) and GaSb-based LEDs (Prineas et al. 2006). Dual-wavelength GaN-based LEDs utilized the same concept, but with two different active regions and three contacts (Ozden et al. 2001). Most recently, an analytical model was proposed which predicts a significant efficiency enhancement for stacked GaN-LEDs with up to 50 tunnel junctions (Akyol et al. 2013). However, this simple model gives the same result without tunnel junctions (Piprek 2014), i.e., the prediction is only based on the increasing total thickness of active layers. Using advanced numerical simulation (APSYS 2013), we here show that significant efficiency enhancements can be achieved in BC-LEDs without increasing the total number of quantum wells.

2 Models and parameters

The self-consistent simulation computes the semiconductor carrier transport equations coupled with a quantum-mechanical model for the photon emission from the InGaN/GaN quantum wells. The built-in polarization charge density at hetero-interfaces is calculated using a second-order model (Pal et al. 2011). Schrödinger and Poisson equations are solved iteratively in our quantum well model to account for the quantum confined Stark effect. The carrier transport model considers drift and diffusion of electrons and holes, Fermi statistics, and thermionic emission at hetero-interfaces. The hetero-interface band offset ratios between conduction band and valence band are 70:30 for InGaN/GaN and 55:45 for the AlGaN/GaN. Band-to-band tunneling is calculated using the common WKB approximation (Piprek 2003). The effective tunneling mass is adjusted to reproduce the published tunnel junction resistivity of $5.7 \times 10^{-4}\ \Omega\,\text{cm}^2$ (Akyol et al. 2013). Both Auger recombination and electron leakage are included as possible droop mechanisms. The coefficients for Shockley–Reed–Hall (SRH) recombination ($A = 5 \times 10^6$/s) and Auger recombination ($C = 2.4 \times 10^{30}\ \text{cm}^6$/s) are adjusted to find agreement with measurements (Fig. 2). Auger recombination clearly dominates the efficiency droop in this case. The ionization energy of Si donors in GaN is 20 meV. For Mg acceptors in AlGaN, the ionization energy is scaled linearly from 170 meV (GaN) to 470 meV (AlN). The acceptor density is assumed equal to the Mg density. Further model details can be found elsewhere (Piprek and Li 2005).

3 Results and discussion

For comparison and model validation, we first simulate a conventional blue LED according to published design specifications (Lin et al. 2012). The reference device includes eight 2-nm-thick $In_{0.12}Ga_{0.88}N$ QWs separated by 15-nm-thick GaN barriers. A 45-nm-thick p-$Al_{0.15}Ga_{0.85}N$ electron blocker layer (EBL) is grown on top of the MQW, covered by a p-GaN cap layer (see Fig. 1). Figure 2 demonstrates the good agreement between simulated LED performance and published experimental results. These measurements are performed in pulsed operation so that self-heating effects can be neglected in our analysis. A typical photon extraction efficiency of EXE = 80 % is assumed. The contact resistivity is fitted to

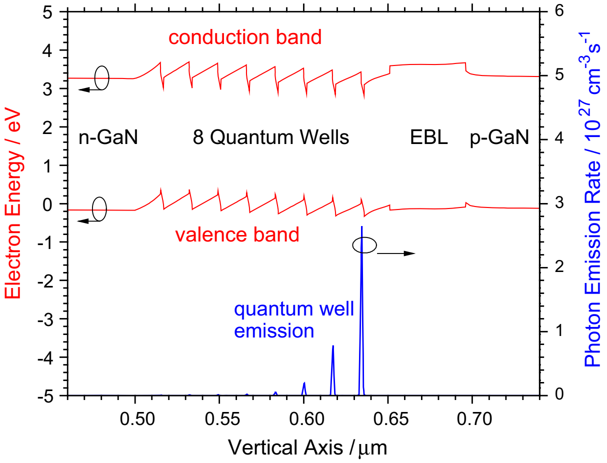

Fig. 1 Energy band diagram and photon emission rate for the reference LED without tunnel junction at a current density of 200 A/cm^2

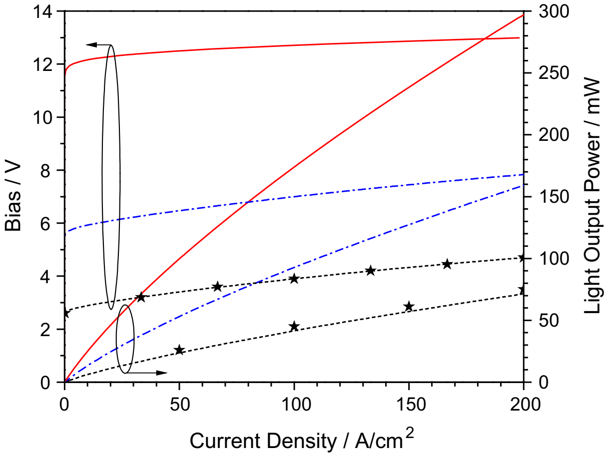

Fig. 2 LED bias and output power versus current density: *stars* measurement, *lines* simulation (*dash* reference LED, *dash-dot* two-stage BC-LED, *solid* four-stage BC-LED)

$5 \times 10^{-3}\ \Omega\,\mathrm{cm}^2$. The device area is 200 μm × 200 μm, i.e., a current density of 200 A/cm^2 corresponds to 80 mA total current.

Without changing the total number of 8 quantum wells, we now introduce a p-GaN/n-GaN tunnel junction into the MQW of the reference device, together with a p-AlGaN EBL to suppress electron leakage from each MQW set. The corresponding band diagram and photon emission profile are shown in Fig. 3. The photon generation in this BC-LED works as follows. Conduction band electrons are injected from the left-hand side, recombine within the first MQW, and then move inside the valence band to the tunnel junction, where they are transferred into the conduction band of the second MQW stack, so that they get a second chance to generate photons. The emission profiles of each MQW set are almost identical. The total light output is significantly higher than with the reference LED but the bias is also much

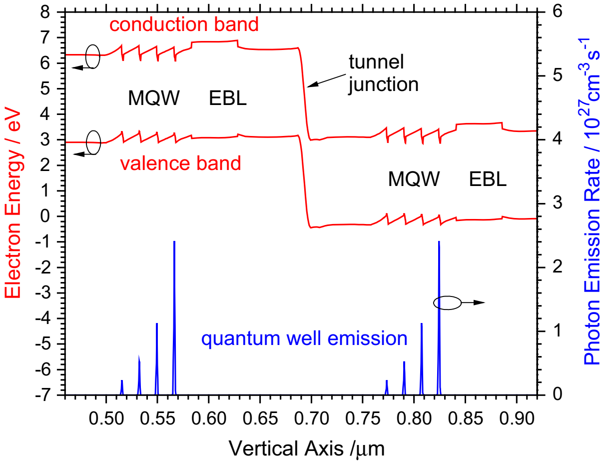

Fig. 3 Energy band diagram and photon emission rate for a two-stage BC-LED at a current density of 200 A/cm^2

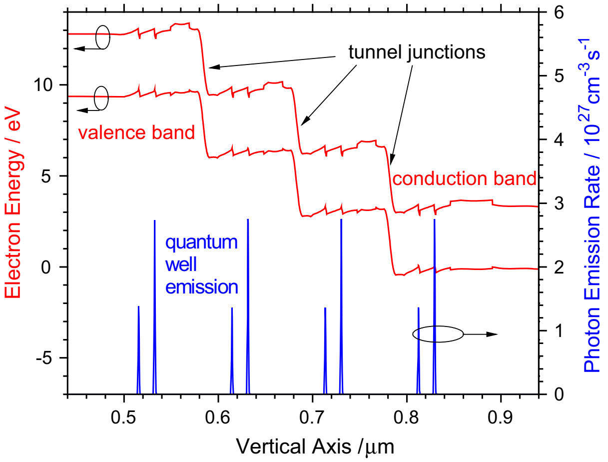

Fig. 4 Energy band diagram and photon emission rate for a four-stage BC-LED (200 A/cm^2)

larger due to the additional band gap (Fig. 2). Figure 4 shows the same vertical profiles with three tunnel junctions that divide the MQW into four QW pairs. The QW emission is even more uniform and the total light output is more than 4 times higher than with the reference device, accompanied by more than 12 V total bias (Fig. 2).

The external quantum efficiency (EQE) is defined as ratio of the emitted number of photons to the number of injected carriers. Since three tunnel junctions give each carrier four opportunities to generate photons, the EQE could be as high as 400 % without losses of carriers or photons. Carrier losses are described by the internal quantum efficiency (IQE) and photon losses by the light extraction efficiency EXE (EQE = IQE × EXE). The efficiency droop is commonly attributed to carrier losses, mainly Auger recombination in our case, which reduce the IQE. The original extraction efficiency of EXE = 80 % is hardly affected by the tunnel junctions. Using an absorption coefficient of 125/cm (Huang et al. 2010) for the

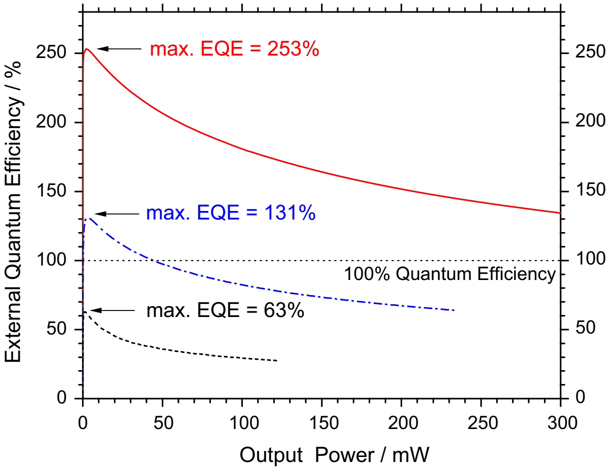

Fig. 5 LED quantum efficiency versus output power (*dash* reference LED, *dash-dot* two-stage BC-LED, *solid* four-stage BC-LED)

15nm thick tunnel-junction p-GaN layer ($5 \times 10^{19}\,\mathrm{cm}^{-3}$ Mg), we obtain less than 0.1 % EXE reduction for the four-stage BC-LED. Even a 100 times stronger tunnel junction absorption would still result in EXE = 75 %.

The EQE efficiency characteristics simulated for our three devices are shown in Fig. 5. The EQE peaks at 63 % for the reference device, at 131 % with one tunnel junction and at 253 % with three tunnel junctions. This peak efficiency occurs at low QW carrier densities and it is limited by SRH recombination while the Auger recombination rate is still small. Note that the EQE is plotted versus output power; plotting it versus current density would be misleading since any given current density injected into the BC-LEDs is accompanied by higher input and output powers than with the reference device (Fig. 2). The goal is to achieve high efficiency at high output power. Despite efficiency droop, our four-stage LED with three tunnel junctions still exhibits EQE values above 100 % at output powers above 300 mW (Fig. 5).

However, the most instructive efficiency parameter is the ratio of output power to input power [wall plug efficiency (WPE)]. In our four-stage LED, the WPE increases to 40 % at 100 mW output power, compared to 17 % with the reference device (Fig. 6). The WPE enhancement is even larger at higher power and it is mainly attributed to the more uniform QW carrier density. Auger recombination scales with the third power of the QW carrier density, so that a more uniform distribution of the same total number of MQW carriers results in less total carrier loss.

4 Summary

In summary, self-consistent numerical LED simulation is employed to study the performance of tunnel-junction-cascaded active regions. Due to the non-uniform carrier distribution in typical InGaN MQWs, the insertion of multiple tunnel junctions into the active region is shown to enhance the LED efficiency. This tunnel-junction design enables a repeated use of electrons and holes for photon generation. Without increasing the number of quantum wells,

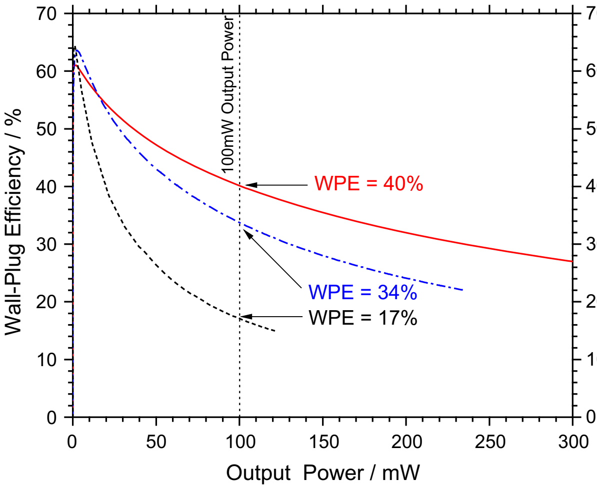

Fig. 6 LED wall-plug efficiency versus output power (*dash* reference LED, *dash-dot* two-stage BC-LED, *solid* four-stage BC-LED)

the insertion of three tunnel junctions leads to 250 % peak quantum efficiency as well as to more than double the wall-plug efficiency at high output power.

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APSYS by Crosslight Software. www.crosslight.com

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