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Blue light emitting diode exceeding 100% quantum efficiency

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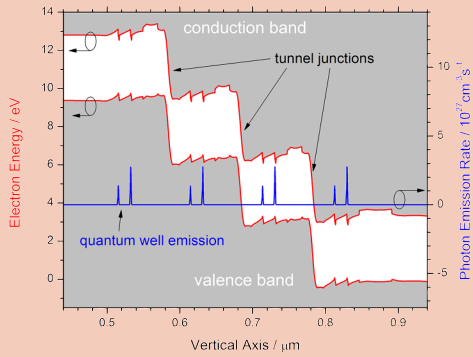
InGaN/GaN light-emitting diodes (LEDs) are known to exhibit a strongly non-uniform vertical carrier distribution within the multi-quantum well (MQW) active region. We propose to eliminate "dark" quantum wells by insertion of multiple tunnel junctions into the MQW which allow for the repeated use of electrons and holes for photon generation. In good agreement with available measurements, we demonstrate by self-consistent numerical simulation that such tunnel junction LED design promises quantum efficiencies as high as 250% as well as a strongly enhanced output power at high input power, compared to conventional LED concepts.



Energy band diagram and photon emission rate for the proposed LED with four sets of two quantum wells separated by three tunnel junctions.

1 Introduction GaN-based light-emitting diodes (LEDs) deliver the desired high efficiency only at relatively low injection current density [1]. At the elevated current densities required in practical high-brightness applications, the efficiency is substantially reduced. This efficiency droop phenomenon has been intensely investigated for a number of years, but the physical mechanisms behind it are still disputed [2]. Among the proposed droop explanations are density-activated defect recombination (DADR) [3], enhanced Auger recombination [4], and electron leakage into the p-doped layers [5]. In all three droop models, the rising quantum well (QW) carrier density causes increasing carrier losses due to non-radiative recombination or leakage. Thus, a possible solution lies in the reduction of the QW carrier density required for a given output power by increasing the number of QWs. But this approach is hampered by the non-uniform vertical carrier distribution commonly observed with thick InGaN multi-quantum well (MQW) active regions, which restricts the relevant light emission to the p-side quantum wells [6]. Alternatively, the QWs may be merged into one thick active layer [7]. However, a more promising approach is the cascading of thin MQW regions with a tunnel junction (TJ) in between, which allows for the repeated use of electrons and holes for photon generation. This concept has been demonstrated experimentally with dual-wavelength LEDs [8, 9]. Based on a simple analytical model, a recent publication predicts LED efficiency improvements for a TJ cascade of up to 50 active regions [10]. But this simple model results in the same improvement without tunnel junctions, i.e., the calculated efficiency enhancement is due to the increasing number of quantum wells. We here demonstrate that tunnel junction insertion promises significant performance improvements even without adding more quantum wells.

2 Models and parameters Our analysis utilizes a customized version of the APSYS simulation software [11] which self-consistently computes the semiconductor carrier transport equations, coupled with a quantum-mechanical model for the photon emission from the strained quantum wells. The built-in polarization is calculated using a recently published second-order model [12]. Schrödinger and Poisson equations are solved iteratively in order to account for the QW deformation with changing device bias and the quantum-confined Stark effect. The carrier transport model considers drift and diffusion of electrons and holes, Fermi statistics, thermionic emission at hetero-interfaces, as well as band-to-band tunneling. Both Auger recombination and electron leakage are included in our LED model as possible droop mechanisms. The coefficients for Shockley–Reed–Hall (SRH) recombination ($A = 5 \times 10^6$/s) and Auger recombination ($C = 2.4 \times 10^{-30}$ cm^6/s) are adjusted to find agreement with measurements (see below). Further details of our LED model can be found elsewhere [13].

GaN-based tunnel junctions including GdN nano-islands were recently demonstrated to exhibit a reverse resistivity as low as 5.7×10^{-4} Ω cm^2 [10]. The corresponding tunneling process is difficult to simulate accurately, not only because of incomplete knowledge about the GdN islands, but also because the tunnel probability is generally very sensitive to the actual doping profile. To still achieve a sufficiently realistic TJ representation in our model, we assume a step-doped GaN homo-junction and adjust the effective tunneling mass in the common WKB approximation [14] to reproduce the measured reverse TJ resistivity for the given density of 5×10^{19} cm^{-3} donors and acceptors.

3 Results and discussion For comparison and model validation, we first simulate a conventional blue LED according to published design specifications [15]. The reference device includes a 3 µm-thick 5×10^{18} cm^{-3} n-doped GaN layer, followed by eight 2-nm-thick $In_{0.12}Ga_{0.88}N$ QWs and nine 15-nm-thick GaN barriers. The 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, doped with 12×10^{18} cm^{-3} Mg. Figure 1 demonstrates the good agreement between simulated LED performance and published measurements. Fit parameters are the photon extraction efficiency of 80% and the p-contact resistivity of 5×10^{-3} Ω cm^2, respectively. Neither of these two numbers is reported for the reference device and they are hard to predict theoretically. Figure 2 plots the band diagram and the radiative recombination profile. The eight quantum wells are strongly deformed by the built-in polarization. Only the two p-side quantum wells deliver a relevant photon emission rate because of the higher carrier density in those wells. Holes have a high effective mass and travel across the MQW less rapidly than electrons.

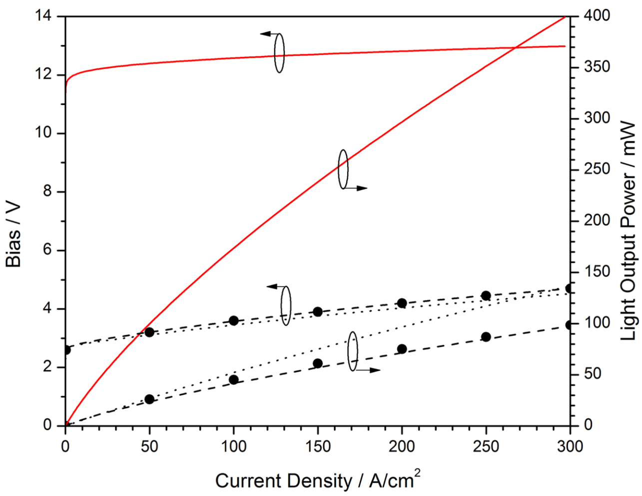


Figure 1 Light power and bias vs. current density: dots: measurement, lines: simulation (dashed: reference LED, dotted: LED with a single 16 nm thick active layer, solid: tunnel-junction LED).

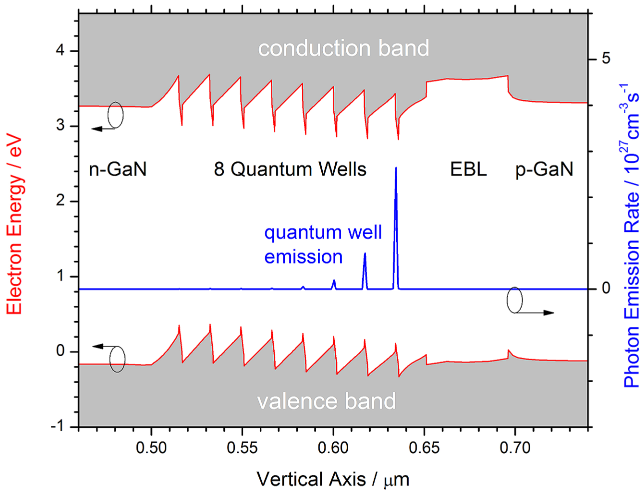


Figure 2 Energy band diagram and photon emission rate for the reference LED at a current density of 200 A/cm^2.

Since the top two QWs emit most of the light in the reference LED, we now separate the eight QWs into pairs of two QWs by insertion of three 30-nm-thick p-GaN/n-GaN tunnel junctions. A 20-nm-thick p-$Al_{0.15}Ga_{0.85}N$ EBL is also included on the p-side of each TJ to suppress electron leakage from each QW pair. The photon generation in this structure works as follows (see Abstract figure). Conduction band electrons are injected from the left-hand side and recombine with valence band holes inside the first QW pair. The influx of new holes into these QWs can also be seen as electrons moving inside the valence band to the first tunnel junction. The TJ transfers these electrons into the conduction band of the second active region. This photon generation process is repeated in the second QW pair, and so on. The emission profiles of each QW pair are almost identical. The light output power is plotted in Fig. 1 (solid lines) and it is about four times larger than before. However, the bias is also about four times higher. For comparison, Fig. 1 also shows the simulation results for an LED with a single active layer having the same total thickness of 16 nm (dotted lines).

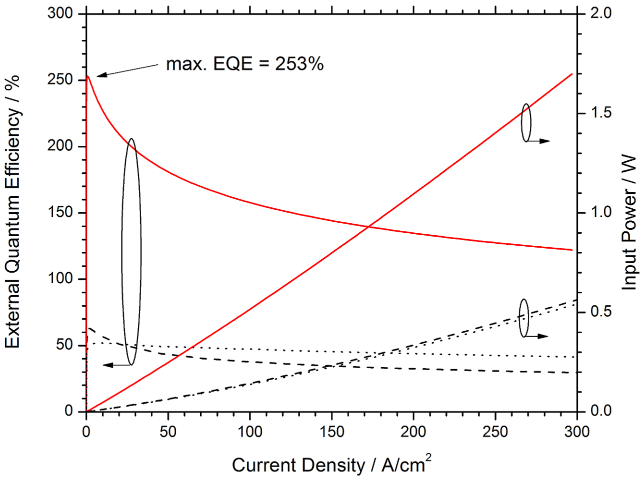


Figure 3 Quantum efficiency and input power vs. current density (dashed line: reference LED, dotted line: LED with 16 nm thick active layer, solid line: tunnel-junction LED).

The three tunnel junctions give each carrier four opportunities to generate photons. The external quantum efficiency (EQE) is defined as ratio of the emitted number of photons to the number of injected carriers and it could be as high as 400% if there were no losses of carriers or photons. The EQE characteristics simulated for our devices are shown in Fig. 3. The quantum efficiency peaks at 52% for the single active layer, at 63% for the reference device, and at 253% for the TJ-LED, the latter remaining above 100% beyond 300 A/cm^2 current density. The price for the higher quantum efficiency of the TJ-LED is paid in form of a higher bias (Fig. 1). Electron leakage from each active region is very small, i.e., the efficiency droop is mainly caused by Auger recombination in our devices. However, a comparison of efficiency droop vs. current density characteristics is misleading since the TJ-LED current density is accompanied by a much higher input power (Fig. 3) and a much higher output power (Fig. 1) than with the other devices. A better comparison is provided in Fig. 4 which plots output power (P_{out}) and wall plug efficiency (WPE) vs. input power (P_{in}) with WPE = P_{out}/P_{in}. Due to the more uniform QW emission in the TJ-LED, both numbers double at 800 mW input power, compared to the reference device (800 mW correspond to a current density of 392 A/cm^2 for the reference device and 152 A/cm^2 for the TJ-LED). The tunnel-junction concept also outperforms the merger of all QWs into one thick active layer. The TJ-LED produces the desired output power not only at lower current than the other LEDs, due to the higher bias, but also at lower input power, due to the higher efficiency. As expected, the efficiency enhancement is caused by the lower carrier density required to achieve high output power. The lower carrier density leads to reduced non-radiative recombination and to a significant droop mitigation in the WPE vs. input power characteristic.

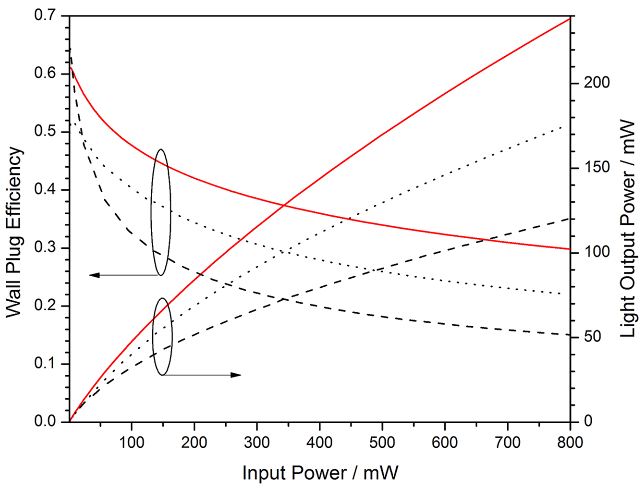


Figure 4 LED output power and wall plug efficiency vs. input power (dashed line: reference LED, dotted line: LED with a single 16 nm thick active layer, solid line: tunnel-junction LED).

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 eliminates inefficient quantum wells and promises a significant output power enhancement compared to the same active layer thickness without tunnel junctions. The proposed tunnel-junction LED design enables a repeated use of electrons and holes for photon generation and leads to high-power quantum efficiencies well above 100%.

References

[1] J. Piprek, Phys. Status Solidi A **207**, 2217 (2010).
[2] J. Piprek, Proc. 13th NUSOD Conf., Vancouver, Canada, 2013 (IEEE, Piscataway, 2013), pp. 107–108.
[3] J. Hader et al., Appl. Phys. Lett. **96**, 221106 (2010).
[4] Y. C. Shen et al., Appl. Phys. Lett. **91**, 141101 (2007).
[5] M. H. Kim et al., Appl. Phys. Lett. **91**, 183507 (2007).
[6] A. David et al., Appl. Phys Lett. **92**, 053502 (2008).
[7] N. F. Gardner et al., Appl. Phys. Lett. **91**, 243606 (2007).
[8] I. Ozden et al., Appl. Phys. Lett. **79**, 2532–2534 (2001).
[9] C. H. Chen et al., Phot. Technol. Lett. **14**, 908 (2002).
[10] F. Akyol et al., Appl. Phys. Lett. **103**, 081107 (2013).
[11] APSYS by Crosslight Software Inc. (www.crosslight.com).
[12] J. Pal et al., Phys. Rev. B **84**, 085211 (2011).
[13] J. Piprek and S. Li, in: Optoelectronic Devices: Advanced Simulation and Analysis, edited by J. Piprek (Springer, New York, 2005), chap. 10.
[14] J. Piprek, Semiconductor Optoelectronic Devices (Academic Press, San Diego, 2003), p. 56.
[15] Y. Y. Lin et al., Phot. Technol. Lett. **24**, 1600 (2012).

