# GaN-based bipolar cascade laser exceeding 100% differential quantum efficiency

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*Abstract* – **Worldwide research efforts have been focusing on quantum efficiency enhancements of GaN-based light emitters. A promising approach is the separation of multiple active regions by tunnel junctions, enabling electron-hole pairs to generate more than one photon. Utilizing advanced numerical device simulation, we here analyze internal physics and performance limitations of such InGaN/GaN bipolar cascade laser which recently demonstrated superior slope efficiency.**

***Index Terms* — semiconductor laser, multi-junction laser, bipolar cascade laser, stacked active regions, tunnel junction, quantum efficiency**

In recent years, countless publications have been devoted to efficiency improvements of GaN-based light emitters.[1] Among the most intriguing proposals is the cascading of multiple active regions with tunnel junctions in between. Such multi-junction devices were already demonstrated for several types of light emitters, including GaAs-based lasers[2] and GaSb-based light-emitting diodes (LEDs).[3] Dual-wavelength GaN-based LEDs combined two different active regions based on the same concept.[4] In all these cases, electrons and holes are recycled by tunneling and used repeatedly for photon generation. Thus, the ratio of emitted photon number to injected number of electrons, the so-called quantum efficiency, should exceed 100%.[5] But the AlGaInN material system makes it difficult to fabricate multi-junction devices with traditional growth methods so that the expected high quantum efficiencies have not been reported yet. However, an alternative growth method recently led to GaN-based lasers with more than 100% differential quantum efficiency, which is the quantum efficiency above lasing threshold.[6]

We here analyze the internal physics of this novel device by numerical simulation. Our laser model is based on the PICS3D simulation software.[7] It self-consistently computes carrier transport, the wurtzite electron band structure of strained InGaN quantum wells (QWs), stimulated photon emission, multi-mode wave guiding, and self-heating. The transport model includes drift and diffusion of electrons and holes, Fermi statistics, built-in polarization and thermionic emission at hetero-interfaces, interband tunneling, as well as all relevant radiative and non-radiative recombination mechanisms. Schrödinger and Poisson equations are solved iteratively in order to account for the QW deformation with changing device bias (quantum-confined Stark effect). Field-enhanced partial ionization of Mg acceptors is included in the simulation as well as doping-related absorption. More details on the employed laser models can be found elsewhere.[8]

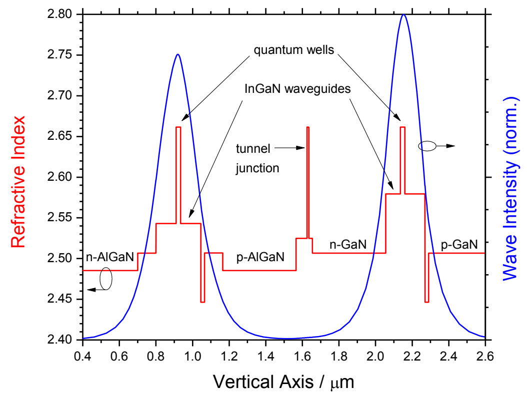


Fig. 1: Vertical profiles of refractive index (red) and lasing modes (blue).

Our experimental reference device is a blue light emitting laser diode featuring two InGaN single-quantum well active regions that are separated by an InGaN tunnel junction.[6] The cleaved-facet cavity is 1mm long and the 15μm wide ridge is etched through both QWs. The vertical waveguide structure and the two lasing modes are illustrated in Fig. 1. For characterization purposes, the two lasers were designed slightly different which results in two independent lasing modes. A rather unique feature of this laser is the 25nm thick quantum well, which leads to the screening of interface polarization charges by low-level QW carriers, while carriers at higher QW energy levels provide most of the optical gain.[9] This somewhat surprising phenomenon is indicated in Fig.

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2 which shows the electron energy band diagram together with the gain profile calculated at 2A injection current. The QW band edges are almost flat in the center where maximum gain originates from higher-order QW wave functions.

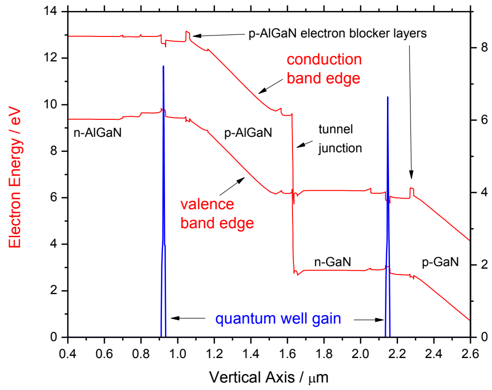


Fig. 2: Electron energy band edges (red) and quantum well gain (blue) calculated at 2A input current.

Key material parameters are extracted from the simulation by reproducing the light vs. current (LI) characteristic measured in pulsed laser operation (see dots in Fig. 3). Self-heating is neglected in this case. The threshold current is mainly controlled by the QW Auger recombination coefficient near $6 \times 10^{-30} cm^6/s$ which lies within the range of published numbers.[1] Defect-related QW Shockley-Read-Hall (SRH) recombination has negligible impact assuming a SRH lifetime of 20 ns. The LI slope is often limited by internal absorption. We here adopt a first-principle model[10] resulting in an absorption cross section of about $0.6 \times 10^{-18}$ $cm^2$ for free electrons. Hole-related absorption including non-ionized acceptors exhibits a cross section of about $0.9 \times 10^{-18}$ $cm^2$ for GaN. Alloy scattering raises the hole-related absorption cross-section to about $1.2 \times 10^{-18}$ $cm^2$. In our case, this doping-related absorption model yields a total modal loss of about 3/cm. The highly doped tunnel junction contributes only a small fraction to this loss because it is located at minimum wave intensity (Fig. 1). However, the predicted absorption of 3/cm is far too small to explain the measured slope efficiency, as illustrated by the dashed line in Fig. 3. Reproducing the measurement requires a total modal loss of 15/cm (solid line in Fig. 3) which is mainly attributed to absorption between band tails caused by alloy disorder within the InGaN waveguide layers (Fig. 1).[11] The calculated LI slope of 1.47 W/A translates into a differential quantum efficiency of $\eta_d$ = 52% per facet, i.e., $2\eta_d$ = 104% from both facets. Without any internal photon loss, we obtain $2\eta_d$ = 197% (dash-dot line in Fig. 3). In good agreement with measurements,[11] we find that $\eta_d$ is limited by internal photon loss and not by electron leakage, which is successfully suppressed by the AlGaN electron blocker layer (EBL, see Fig. 2). Without EBL, the efficiency would be much smaller (blue line in Fig. 3).

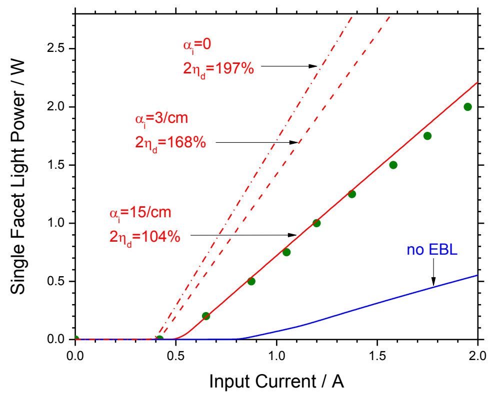


Fig. 3: Simulated output power vs. current with varied modal absorption $\alpha_i$ (red lines, $\eta_d$ – differential quantum efficiency). Symbols show measured data.[6] The blue line is calculated without electron blocker layer (EBL).

The calculated bias of 13V at 2A is lower than measured because the simulation assumes a perfect tunnel junction with rectangular doping profiles that are impossible to achieve in reality. However, the bias is more than twice the value expected with a single-junction laser due to the tunnel-junction cascade. The total power conversion efficiency is the ratio of optical output power to electrical input power and it exhibits a peak value of 17% in our simulation, which is mainly limited by the high resistance of the p-side waveguide cladding layers (cf. Fig. 2).[8]

In summary, our simulations explain internal physical mechanisms of novel GaN-based bipolar cascade lasers and reveal origins of efficiency limitations.

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