PRJ5-3
Invited

Energy Efficiency Comparison of GaN-based Blue Light Emitters

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Keywords: InGaN/GaN, light-emitting diode, super-luminescent LED, laser diode, energy efficiency

ABSTRACT

GaN-based blue light-emitting diodes (LEDs) can reach more than 80% electrical-to-optical power conversion efficiency, but less than 10% are reported for blue super-luminescent LEDs and less than 50% for blue laser diodes. We employ advanced device simulation to investigate the physical mechanisms behind the measured discrepancy in peak energy efficiency.

1 INTRODUCTION

GaN-based light emitters are receiving great attention due to wide-spread applications in displays, lighting, communication, data-storage, medical equipment, and other fields. Three types of GaN-based light sources can be distinguished: light-emitting diodes (LEDs), super-luminescent light-emitting diodes (SLDs), and laser diodes (LDs). Their electrical-to-optical energy conversion rate is equivalent to the commonly given wall-plug efficiency or the power conversion efficiency (PCE). Surprisingly, the maximum PCE achieved with GaN-based LEDs, SLDs, and LDs differs dramatically. Blue LEDs emit up to 83% of the electrical input power.[1] Blue lasers reach about half that efficiency,[2] but less than 10% PCE is reported for blue SLDs.[3] Many publications focus on the so-called efficiency droop, i.e., the relative efficiency reduction with rising current. However, the absolute energy efficiency is usually of greater importance. Our paper analyzes limitations of the peak PCE and explains the strong efficiency discrepancy between the different emitter types. However, the direct comparison of measured efficiencies is difficult due to design and fabrication differences. We therefore employ advanced numerical simulations of identical emitter structures. Simulation results are validated by comparison to experiments.

2 MODEL AND EXPERIMENTAL VALIDATION

Our three-dimensional device simulation self-consistently computes carrier transport, the wurtzite energy band structure of strained InGaN quantum wells, as well as spontaneous and stimulated photon emission spectra. 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 all relevant recombination mechanisms. For clarity, self-heating is excluded in this study and all results are obtained for room temperature. More details on the device models are given elsewhere.[4] For direct comparison of all three emitter types, we employ exactly the same epitaxial layer structure and simulate LED, SLD, or LD operation of that structure. Our model is validated by reproducing the measured performance of a blue LED that comprises a single 3nm thick InGaN quantum well and a 20nm thick Mg-doped $Al_{0.18}Ga_{0.82}N$ electron blocker layer (EBL). The measured external quantum efficiency, electrical bias, and emitted photon energy are simultaneously and almost perfectly reproduced by the simulation after adjustment of several key material parameters (Fig. 1).[5]

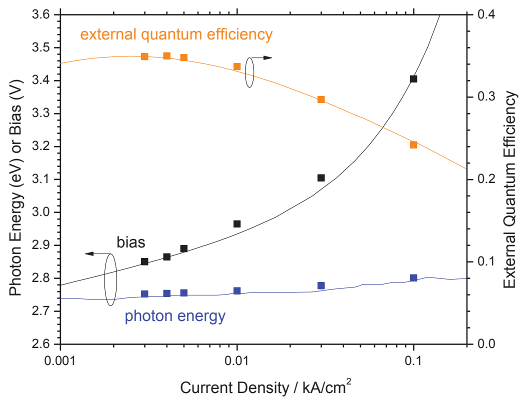

Fig. 1: Comparison of measurements (symbols) and simulations (lines) for the blue LED.

3 RESULTS AND DISCUSSION

For comparison of the three emitter types, we embed the LED layers into a GaN waveguide that is sandwiched between $Al_{0.06}Ga_{0.94}N$ cladding layers. Vertical profiles of refractive index and guided wave are shown in Fig. 2. SLDs employ such waveguides to enable amplified spontaneous emission (ASE) of photons. The ASE power rises exponentially with the length L of the waveguide structure. We here assume L=4 mm as well as the ideal case of zero light reflection at both facets (R=0). For laser simulation, we simply add the cleaved facet reflectivity R=0.18 to the SLED simulation, so that the optical feedback further enhances the internal light amplification.

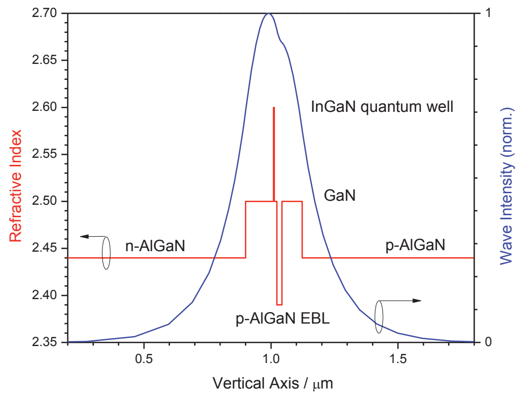

Fig. 2: Refractive index and wave intensity profiles.

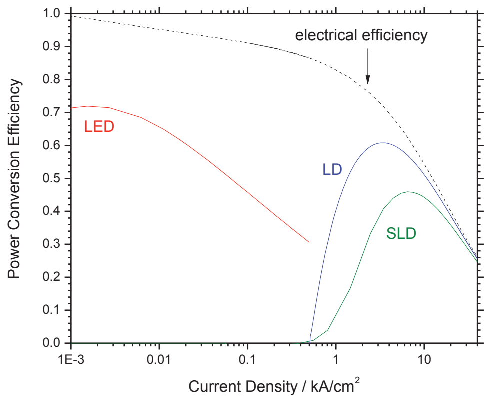

Fig. 3: Comparison of the power conversion efficiency PCE calculated for LED (red), laser (blue) and SLD (green). The top dashed line gives the electrical efficiency.

The calculated power conversion efficiencies are plotted in Fig. 3. For better comparison, results are shown without optical loss and without self-heating. The simulated peak PCE is highest for the LED, somewhat lower for the laser, and lowest for the SLD, in agreement with the experimentally observed trend. The main reason lies in the declining electrical efficiency (dashed line in Fig. 3).[5] The stimulated photon generation in LDs and SLDs requires a much higher injection current density than spontaneous photon emission in LEDs. Higher current causes a higher bias and a lower electrical efficiency, so that the PCE declines even under idealized conditions. Since SLDs need stronger current injection than LDs to reach the same output power, their peak PCE is even smaller. The high bias and low electrical efficiency of LD and SLD is mainly due to the low hole conductivity of the p-doped AlGaN waveguide cladding layer. Waveguide design improvements may include undoped waveguide layers,[6] tunnel junction contacts,[7] or indium-tin-oxide cladding layers.[8] Other options for PCE improvements are explored elsewhere.[9]

4 CONCLUSIONS

Our analysis reveals that the measured energy efficiency discrepancy between blue light emitting LEDs, LDs, and SLDs is mainly caused by the different current density of operation and by the low conductivity of the Mg-doped AlGaN cladding layer required for wave guiding in LDs and SLDs. Both factors dramatically reduce the electrical efficiency of LDs and SLDs, i.e., injected electron-hole pairs suffer major energy loss on their way to the quantum well due to the high electrical resistance.

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