An industry perspective on the optimization of InGaN lasers and LEDs via modeling

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***Abstract*—In this paper, we illustrate the role of modeling in the development of commercial nitride-based lasers and LEDs. Aside from optimizing device performance, joint analysis of simulations and experimental results can shed light into the intrinsic properties of the InGaN/GaN material system.**

Nitride-based light sources are currently the subject of extensive research all over the world, mostly due the growing solid state lighting market demand for brighter and more efficient InGaN LEDs. Also, the race is on to produce the first commercial direct green laser diode for mobile projection applications.

The performance of InGaN light emitters degrades significantly as wavelengths shift towards the green and the indium concentration in the active region is increased. In the case of LEDs, the internal quantum efficiency (IQE) peaks at small current densities and subsequently drops as the operating point is approached. The fraction of input power not converted into light (green area in Fig. 1) grows for longer wavelengths. On the other hand, green InGaN lasers exhibit larger threshold currents and smaller slope efficiencies than their blue analogues [1].

Both for nitride LEDs and lasers, the root causes of this performance penalty with indium concentration are still controversial. With increasing pressure to reduce the “time to market”, modeling plays here a key role by improving our understanding of the existing problems and speeding up product development.

Good carrier transport is essential to device performance. In this front, drift diffusion transport simulations show that the existing piezofields in c-plane GaN grown epistructures may lead to non uniform carrier distribution across the different quantum wells (QWs). Carrier overcrowding in turn favors non-radiative Auger-like processes which would explain the reduction in IQE for LEDs. Modeling allows to quickly assessing the potential of optimized epidesigns in which a more uniform pumping of the multiple QW (MQW) region is achieved.

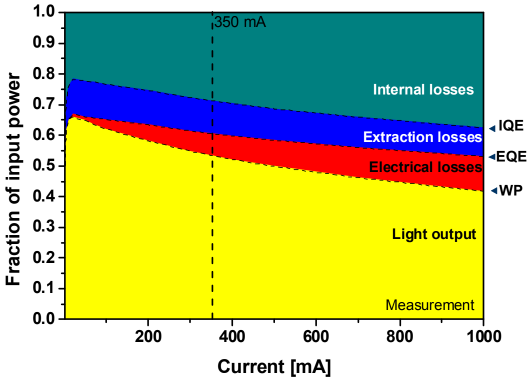

Figure 1. Loss analysis of a ThinGaN LED emitting at 435nm. The dashed line marks the typical operating point.

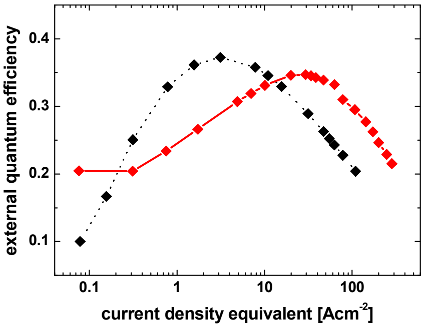

Figure 2. EQE of optically pumped green 40xMQW (red curve) in comparison with that of a reference LED at the same wavelength (black curve).

However, transport alone does not tell the whole story. To

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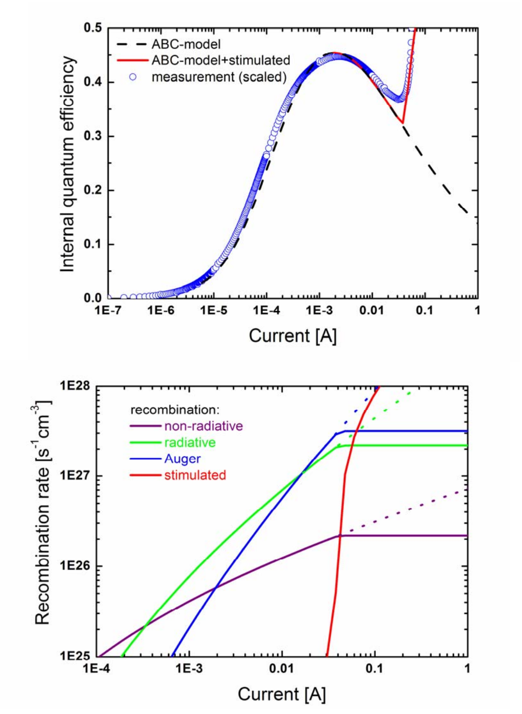

Figure 3. Above: IQE curve of a blue laser diode up to laser threshold fitted with a rate equation model taking stimulated emission into account. Below: corresponding recombination rates.

cancel out the influence of non-uniform pumping of the wells and potential carrier leakage, we have grown monolithically 40 electrically inactive green QWs on top of an UV LED. When comparing the external quantum efficiency curve to that of a reference green LED in Fig. 2, one can observe that the optically pumped QWs exhibit a similar droop behavior, only shifted in the current density axis due to the larger number of QWs. This leads us to believe that the droop is a fundamental material property that can be minimized but not completely avoided.

Despite of being grown with essentially the same materials as the LEDs, InGaN lasers have their own critical issues which must be properly addressed by modeling tools. Above threshold, for example, carrier density clamping in the active region should suppress the relevance of nonradiative recombination mechanisms (see Fig. 3. Note, however, that typical threshold current densities lie already in the droop region of the IQE curve). Another focus in the laser optimization is waveguide design, having an impact on both threshold and slope efficiency. This can be done by conducting optical simulations with, e.g., a 1D transfer matrix method.

In InGaN ridge lasers, a significant part of the operating current for 50mW of light output goes into reaching threshold. It is therefore important to understand which properties are modified by increasing the indium concentration in the wells. In this respect the available material gain is one decisive parameter. We have investigated the differences between blue and cyan lasers on c-plane GaN by combining Hakki-Paoli measurements performed at the Fraunhofer IAF with microscopic gain spectra calculations from Marburg University

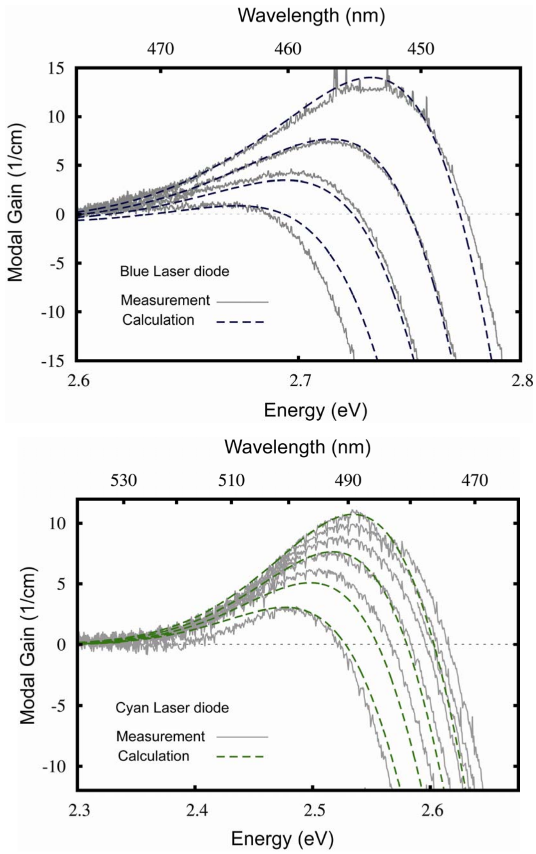

Figure 4. Above: measured intensity gain spectra of a 450 nm LD for currents of 3,7,11,15 and 19 mA, and simulation with a gaussian inhomogeneous broadening of 32 meV. Below: measured intensity gain spectra of a 490 nm LD for currents of 10, 25, 35, 45, 50, 55, and 65 mA, and simulation using an inhomogeneous broadening of 70 meV.

[2]. The latter take into account the optical excitation, the Coulomb interactions as well as the Fröhlich type interaction of the electrons with LO-phonons, and thus leave the inhomogeneous broadening as a free parameter. Fitting of the experimental data, as shown in Fig. 4, reveals a significantly larger broadening for cyan devices (70meV compared to 32meV in blue lasers), therefore suggesting material quality and homogeneity as a decisive factor in the smaller values of differential gain measured.

In conclusion, we have discussed how modeling can address some of the key issues in the development of nitride lasers and LEDs, as well as improve our understanding of the ultimate causes of the InGaN droop.

ACKNOWLEDGMENT

Part of this work was funded by the German Federal Ministry for Education and Research BMBF under Contract No. 13N9373.

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