Comparative analysis of efficiency limitations in GaN-based blue laser diodes

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Abstract – **Nobel laureate Shuji Nakamura predicted in 2014 that GaN-based laser diodes are the future of solid state lighting. However, blue GaN-lasers still exhibit less than 40% power conversion efficiency, while GaN-based blue light-emitting diodes reach up to 84%. This paper investigates non-thermal reasons behind this difference by comparative numerical device simulation. Fundamental material properties such as poor hole conductivity and high internal absorption are shown to make GaN-lasers inherently less efficient than GaAs-lasers.**

I. INTRODUCTION

Shuji Nakamura predicted in his Nobel lecture that GaN-based laser diodes are the future of solid state lighting (SSL).[1] The main driving force behind the current SSL revolution is the promise of high energy efficiency. GaN-based blue light-emitting diodes (LEDs) achieve up to 84% electrical-to-optical power conversion efficiency (PCE),[2] but the highest PCE reported for GaN-based blue laser diodes (LDs) is still below 40%.[3] This paper analyses the reasons for this PCE difference by comparative numerical simulation of both device types using the same active region design and the same material parameters.

II. MODEL AND PARAMETERS

We employ an advanced commercial device simulation software[4] which self-consistently computes carrier transport, the wurtzite electron band structure of strained InGaN quantum wells (QWs), and photon emission. Schrödinger and Poisson equations are solved iteratively in order to account for the QW 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 radiative and non-radiative recombination mechanisms. For clarity, self-heating is excluded in this study and all results are reported for room temperature (T=300K).

Crucial material parameters are obtained by simultaneously fitting measurements of light output power, bias, and emission wavelength of an industry-grade single-QW blue LED.[5] Fit results are shown in Fig. 1. In particular, the QW interface polarization charge was extracted from reproducing the blue-shift of the photon energy with rising current. Carrier leakage from the QW is found to be negligibly small so that the internal quantum efficiency (IQE) droop is solely caused by QW Auger recombination. The IQE fit is obtained using a Shockley-Read-Hall (SRH) recombination lifetime of 45ns and an Auger recombination coefficient of $C=7\times10^{-31}$ cm^6/s. The bias-current (VI) characteristic reveals a relatively high contact resistance that is not typical for industry-grade LEDs and is therefore neglected in the following.

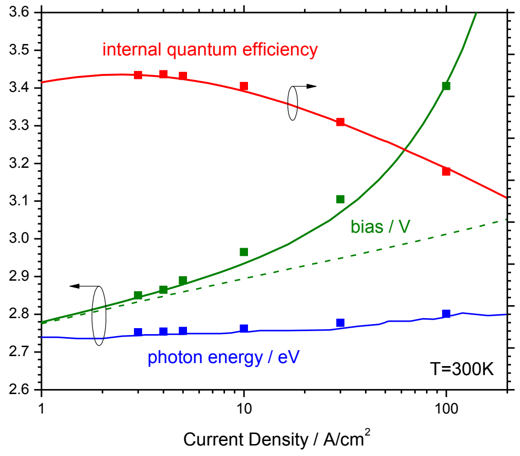

Fig. 1: Comparison between LED measurements (symbols)[5] and simulations (lines). The dashed line gives the bias without contact resistance. The LED chip size is 200µm x 200µm.

III. RESULTS AND DISCUSSION

For laser simulation, we embed the LED layers into a GaN waveguide that is sandwiched between AlGaN cladding layers. Vertical profiles of refractive index and optical mode are shown in Fig. 2. The optical confinement factor is Γ=0.76%. Our broad-area Fabry-Perot laser is 50µm wide and 800µm long so that the active area is the same as in the LED. The facet reflectance is 0.05 and 0.95, respectively.[6] For simplicity, the injection efficiency is 100% in this study. We initially neglect internal absorption (α_i=0), so that the differential quantum efficiency is η_d=100% (slope=2.8W/A). The PCE is calculated as ratio of optical output power to electrical input power and it is shown as red solid line in Fig. 3. The corresponding LED characteristic is plotted as blue solid line, assuming a light extraction efficiency (EXE) of 100%. The dashed lines reflect more realistic internal optical losses with EXE=80% and modal absorption α_i=5/cm (η_d=80%), respectively. The dash-dot lines are calculated by neglecting both internal optical loss and Auger recombination and show

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the lowest lasing threshold as well as the highest PCE. Surprisingly, all cases exhibit efficiency droop at high current, even with C=0, which is caused by the rising bias (see Fig. 4). Since laser diodes operate at higher current than LEDs, their bias is always higher and their peak PCE is always lower. Our GaN-laser exhibits a relatively low series resistance of about $R_s = 0.5\ \Omega$ which is mainly attributed to the poor hole conductivity.

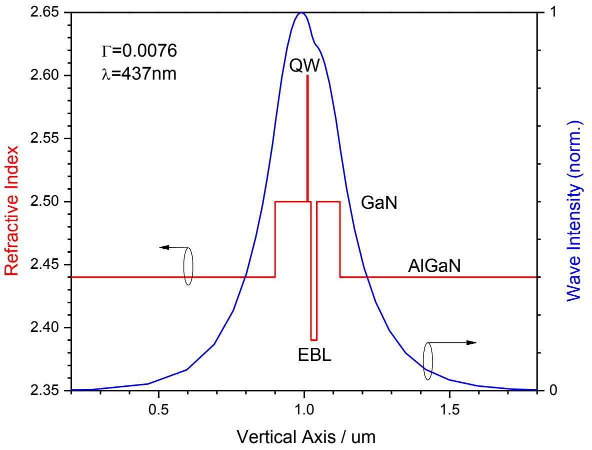

Fig. 2: Vertical profiles of refractive index and wave intensity for the laser diode using the same InGaN quantum well (QW) and AlGaN electron blocking layer (EBL) as the LED.

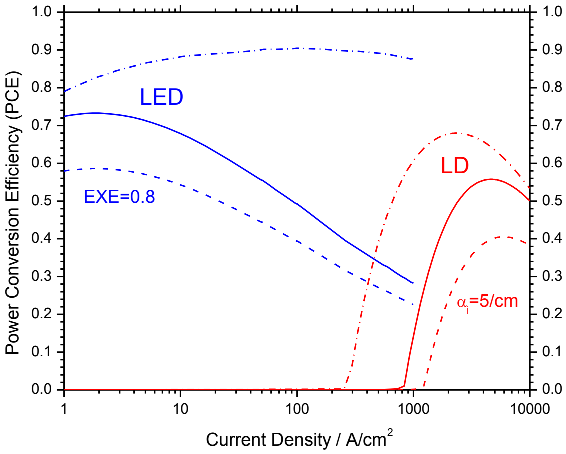

Fig. 3: Efficiency comparison (dashed: realistic optical loss; solid: no optical loss; dash-dot: no optical loss and no Auger recombination).

This somewhat idealized comparison overestimates the efficiency by neglecting the effects of self-heating, vertical carrier leakage, and lateral carrier spreading. It thereby reveals more fundamental PCE limitations that are rooted in III-nitride material properties. Auger recombination in the InGaN QWs strongly contributes to the high threshold current but the underlying physics is not fully understood.[7] The high series resistance is related to the high ionization energy of Mg acceptors. Sufficient densities of free holes require extremely high Mg doping densities which limit the hole mobility by scattering. The high Mg doping density also enhances absorption losses.

There are several options for laser performance optimization.[6,8] As example, Fig. 4 plots simulation results with longer cavity length L which reduces the threshold current but also the differential quantum efficiency. The bias is smaller but the resulting PCE remains almost unchanged. However, the optimum design for practical applications depends not only on the exact values of α_i and R_s but also on the thermal resistance R_{th} which is controlled by laser mounting and packaging. Record numbers of $R_{th} = 6.6$K/W and $\alpha_i = 2.5$/cm were recently reported for 405nm GaN-lasers with 7.2W output power at I=4A and V=6.3V in continuous wave (CW) operation at room temperature, but the measured PCE remains below 40%.[6, 9]

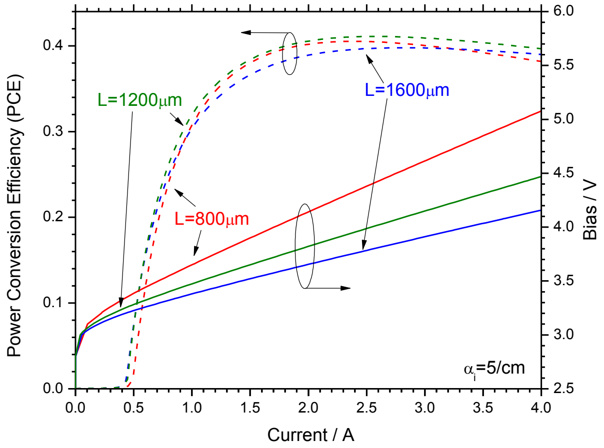

Fig. 4: Efficiency (dashed) and bias (solid) for cavity length L = 800μm (red), 1200μm (green), and 1600μm (blue). The dashed red curve is the same as in Fig. 3.

The most efficient laser diodes today are based on GaAs and reach close to 70% PCE in CW operation at room temperature. Their thermal resistance is similar to GaN-lasers, but their internal absorption loss and series resistance are about one order of magnitude smaller.

In conclusion, the record PCE values reported for GaN-LEDs and for GaAs-lasers seem out of reach for GaN-lasers due to detrimental III-nitride material properties such as low conductivity and high absorption in p-doped layers.

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