Auger recombination effects on the peak lasing power of InGaN/GaN laser diodes

Joachim Piprek

NUSOD Institute LLC, Newark, DE 19714-7204, United States, E-mail: piprek@nusod.org

Abstract – **The inherently large series resistance of GaN-based lasers causes significant self-heating that leads to the well-known power roll-off at high current. We analyze recently reported measurements using advanced numerical laser simulation and investigate the physical mechanisms restricting the maximum lasing power in continuous-wave operation. Contrary to popular opinion, our analysis reveals a strong influence of Auger recombination.**

Primarily for applications in solid-state lighting, GaN-based light emitting diodes (LEDs) have been widely investigated in recent years and are known to suffer from a declining efficiency with increasing current. Recent research indicates that this efficiency droop is mainly caused by Auger recombination inside the quantum wells (QWs).[1] Auger recombination rises with the third power of the QW carrier density and therefore intensifies with stronger current injection into the LED. In contrast, GaN-based blue laser diodes are believed to suffer less from Auger recombination, based on the popular opinion that the QW carrier density does not rise with increasing current injection above lasing threshold.[2] Shuji Nakamura, who received the 2014 Nobel Prize in physics for his pioneering work on GaN-LEDs, stated in his Nobel lecture that "Auger recombination, with the resulting efficiency droop, does not appreciably occur in blue laser diodes".[3] Our paper investigates this claim by numerical analysis of recently published measurements on high-power InGaN/GaN lasers.[4]

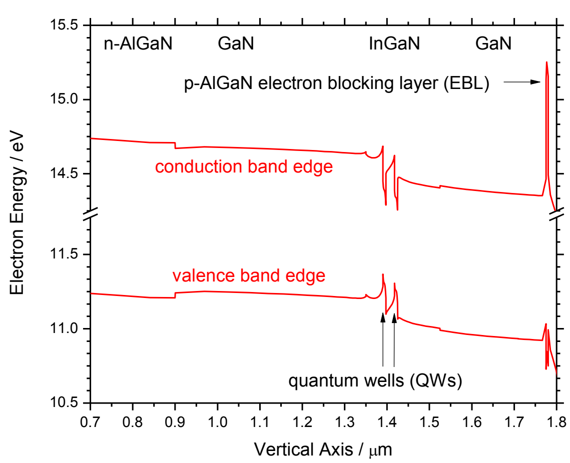

Fig. 1: Energy band diagram of the InGaN/GaN laser near the active layers (QWs) as calculated at high power.

Their active region comprises two InGaN quantum wells embedded in a wide GaN waveguide that is sandwiched between AlGaN cladding layers (Fig. 1). A thin AlGaN layer at the p-side edge of the GaN waveguide serves as electron blocking layer (EBL). Our previous numerical analysis of this laser diode results in excellent agreement with the measurements after careful calibration of material parameters (see blue lines in Fig. 2).[5] We here evaluate the laser performance at elevated ambient temperature (red lines), which is of interest for real-world laser applications.[6]

The simulations employ the PICS3D software[7] which self-consistently combines carrier transport, the wurtzite electron band structure of the strained InGaN quantum wells, photon emission, wave guiding, and heat flow. Schrödinger and Poisson equations are solved iteratively in order to account for the QW deformation with changing device bias. 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.

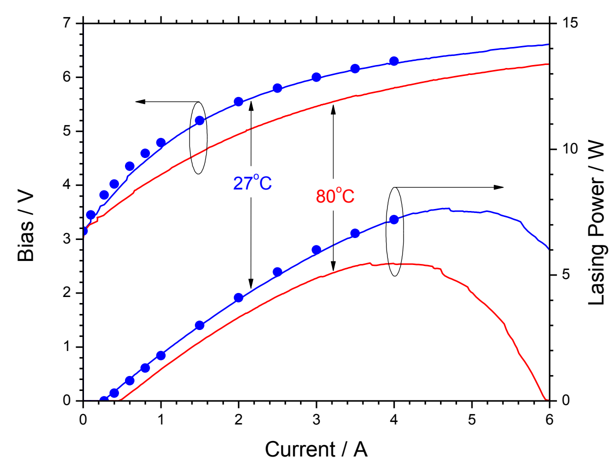

Fig. 2: Laser power and bias simulated at room temperature (blue lines, dots: measurement) and at 80°C stage temperature (red lines).

Figure 3 plots the calculated QW temperature rise with increasing current. The strong self-heating is attributed to the low wall-plug efficiency of GaN-based lasers.[5] The rising temperature reduces the optical gain available at a given QW carrier density. Thus, this density needs to rise in order to

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maintain the threshold gain required for lasing. A higher carrier density triggers an even stronger increase in Auger recombination, thereby diverting injected current into non-radiative recombination. Such current diversion intensifies with higher ambient temperature. This is visualized in Fig. 4 by plotting the currents that feed the different recombination mechanisms. Stimulated recombination creates the laser beam but it competes with various loss mechanisms, among which Auger recombination clearly dominates. Electron leakage from the QWs into the p-side waveguide layers rises strongly with the injection current but it is dampened by the EBL (Fig. 1). Spontaneous photon emission and defect-related Shockley-Read-Hall recombination are less important in this laser. Ambient temperature elevation enhances Auger recombination (Fig. 4) which leads to a decline of the stimulated recombination current and to the earlier power roll-off as shown in Fig. 2.

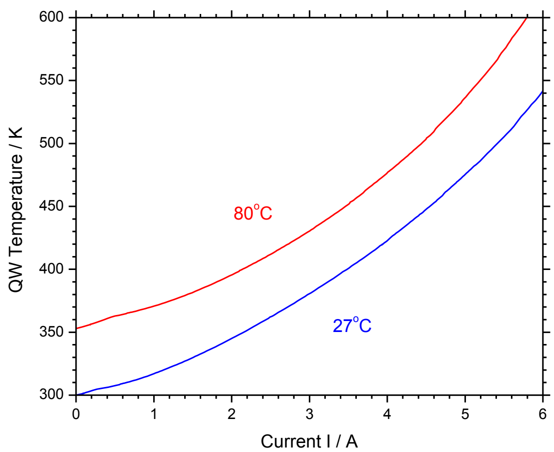

Fig. 3: QW temperature vs. injection current calculated for both stage temperatures.

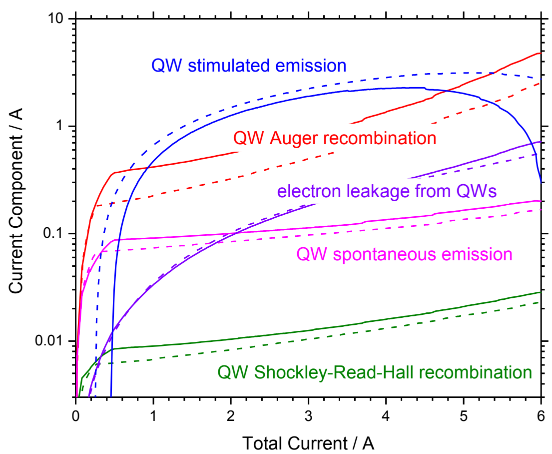

Fig. 4: Current components feeding the different carrier recombination mechanisms of the laser (dashed: 27°C, solid: 80°C).

However, the carrier budget analysis in Fig. 4 is missing the influence of Joule heating and of internal absorption, which both reduce the laser output power. Figure 5 shows the power components of the laser and it reveals that Joule heat generation consumes even more power than Auger recombination. This is attributed to the inherently poor conductivity of p-doped layers as well as to the p-contact resistance.[5] The internal absorption of laser light has a much smaller influence on the emitted power. Thus, the peak output power is mainly limited by Joule heating and by Auger recombination. Removing Auger recombination from the simulation raises the peak power at 80°C from 5W to 12W.

Somewhat surprisingly, the generated Joule heat is reduced at higher ambient temperature because the series resistance shrinks due to the larger hole density in p-doped layers,[5] as illustrated by the bias characteristics in Fig. 2. In contrast, Auger recombination rises with the temperature (Fig. 4) so that its influence on the output power grows relative to the resistive heating. As a consequence, the peak output power declines with increasing stage temperature despite the lower resistance, as shown in Fig. 2. This finding is validated by recent measurements.[6]

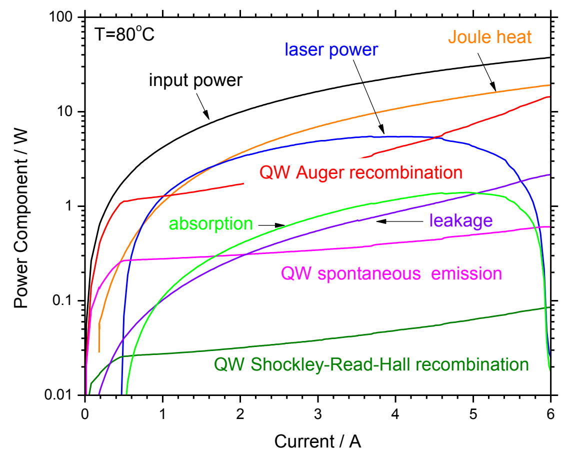

Fig. 5: Power components of the laser vs. injection current (at 80°C stage temperature).

In summary, advanced numerical analysis of laser measurements reveals a strong influence of Auger recombination on the peak output power of InGaN/GaN lasers.

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