# Energy Efficiency Analysis of GaN-based Superluminescent Diodes

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*Abstract* – **Gallium-nitride-based superluminescent light-emitting diodes (SLEDs) are attractive light sources for augmented or virtual reality devices and other applications. However, the energy efficiency of SLEDs is still far below the peak values reported for LEDs and laser diodes. Utilizing advanced numerical device simulation, this paper investigates the internal physical processes that cause the low SLED efficiency.**

***Index Terms*— superluminescent light-emitting diode, SLED, Gallium Nitride, efficiency**

GaN-based blue light emitters have received tremendous attention in recent years due to various applications in lighting, displays, communication and other fields. Improvement of the electrical-to-optical power conversion efficiency, also called energy efficiency or wall-plug efficiency (WPE), is often a key requirement for these applications. Light-emitting diodes (LEDs) utilize the spontaneous emission of photons and have achieved record WPEs near 0.8. About half that value was reported for the most efficient GaN-based laser diodes (LDs) which are based on internal photon amplification (stimulated photon emission).[1]

Superluminescent light-emitting diodes (SLEDs) produce light by amplified spontaneous emission (ASE).[2] Simply speaking, SLEDs are laser diodes that are operated below lasing threshold by minimizing the optical feedback from one or both facets of the internal waveguide. SLEDs thereby combine the broad emission spectrum of LEDs with the focused light beam of LDs. This is advantageous for applications such as portable or wearable compact projection systems [3] and visible light communication.[4] However, reported SLED wall-plug efficiencies are still much lower than with laser diodes or LEDs.[5]

Based on advanced numerical device simulation,[6] this paper studies the physical mechanisms that cause such severe WPE limitations in GaN-based SLEDs. For comparison, we employ the same model and parameters as in our recent simulation of 405nm InGaN/GaN laser diodes which produced excellent agreement with measurements (Fig. 1).[1] This high-power laser diode featured a reflectivity of 0.95 at the back facet and 0.056 at the front facet. We here reduce the simulated front facet reflectivity to zero and thereby transform this laser into a SLED. Such reflective SLEDs with a single high-reflection facet are commonly used to increase the output power by doubling the photon amplification distance.[2]

Figure 1 compares LD and SLED characteristics calculated for continuous-wave (CW) operation at room temperature. The laser output power P is more than double the SLED power which exhibits and early power roll-off caused by self-heating. As expected, the bias V hardly changes with reduced reflectivity but the internal temperature rise is slightly stronger in the SLED ($\Delta T$=140K at I=4A) than in the laser (120K)[1] due to the difference in light power.

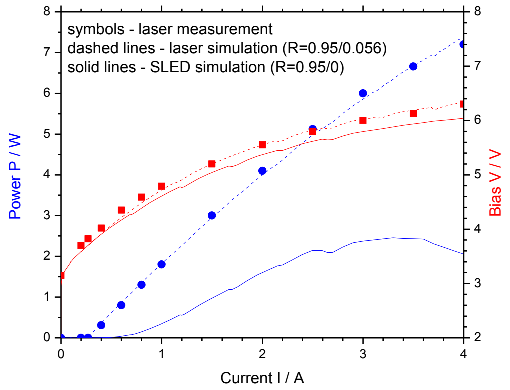


Fig. 1: Output power and bias simulated for the laser diode (dashed lines) and for the SLED (solid lines). Symbols show measured characteristics for a laser with 12µm ridge width and 1.2mm cavity length.

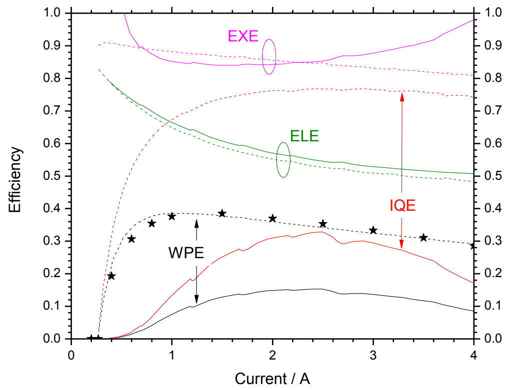


Fig. 2: Calculated efficiencies vs. current for the laser diode (dashed lines) and for the SLED (solid lines). Symbols show the measured laser WPE.

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The wall-plug efficiency WPE = P/IV peaks at 0.38 for the laser and at 0.15 for the SLED (Fig. 2). The SLED efficiency initially increases with SLED power, which is practically limited by the laser threshold, i.e., by the actual reflectivity of the front facet.[7] In other words, the WPE peak is hard to reach experimentally.

As usual for LEDs, we split up the WPE into the internal quantum efficiency IQE, the light extraction efficiency EXE and the electrical efficiency ELE: WPE = IQE × EXE × ELE. While this split is not typical for laser diodes,[1] it still helps comparing the two device types. ELE = hν/qV gives the ratio of emitted photon energy hν to injected electron energy qV and it suffers from the low conductivity of p-doped waveguide layers.[1] Both device types employ the same waveguide architecture and the ELE drop with current imposes the strongest WPE reduction in Fig. 2. The light extraction efficiency EXE is relatively high in both devices due to low internal absorption.[1] However, the main efficiency difference is caused by the IQE which gives the fraction of injected current that is consumed by stimulated emission or ASE. In other words, enhanced current loss is the main reason for the low SLED efficiency.

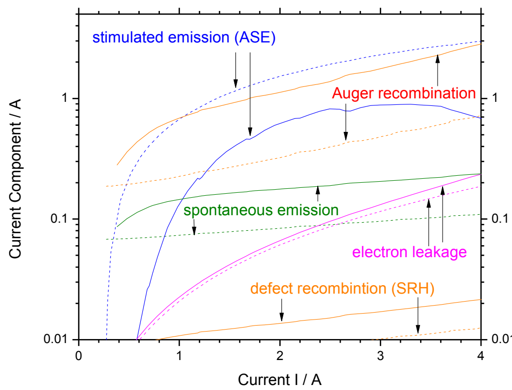


Fig. 3: Current components calculated for the laser diode (dashed lines) and for the SLED (solid lines).

Figure 3 plots the current components consumed by different internal processes. Auger recombination causes by far the strongest current loss in both cases; it even surpasses the ASE current in the SLED. Spontaneous photon emission is also considered a loss because it goes in all directions, only a tiny fraction is coupled into the waveguide. Defect related Shockley-Read-Hall (SRH) recombination is of minor importance here. However, these three current loss mechanisms are much stronger in SLEDs than in lasers due to the higher carrier density in the InGaN quantum wells (QWs). Electron leakage from the QWs is about the same in both devices.

The QW carrier density is affected by the decline of the optical gain with higher temperature.[1] Self-heating reduces the ASE rate and thereby raises the steady-state QW carrier density, leading to enhanced carrier loss. When self-heating is excluded from the SLED simulation, the rise of the QW carrier density is much smaller and the IQE improves significantly (Fig. 4). However, the QW carrier density is still substantially higher than with the laser in pulsed operation, because the latter remains constant above the laser threshold current near 0.3A.

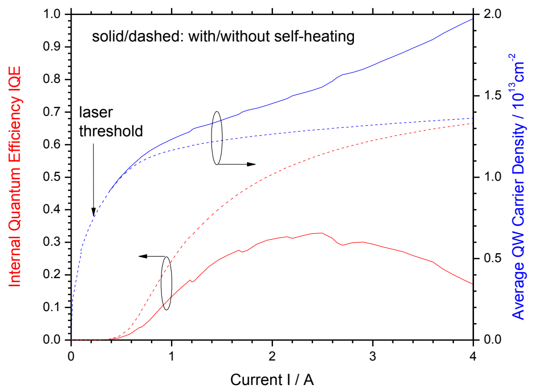


Fig. 4: SLED internal quantum efficiency and average carrier density inside the quantum wells with (solid) and without self-heating (dashed).

Note that our comparison does not include any SLED design optimization for maximum WPE, e.g., by increasing the cavity length.[2] At our violet emission wavelength of 405nm, the highest measured WPE=0.2 was based on a sophisticated waveguide design.[7] However, practical projection systems for augmented or virtual reality applications require somewhat longer wavelengths in the blue and green spectral region, i.e., QWs with higher Indium content and lower band gap. This wavelength shift is accompanied by various challenges.[4,5] QW growth quality and optical gain are severely reduced with longer wavelengths. The lower optical mode confinement leads to larger internal absorption, mainly in p-doped layers. Thus, the highest measured WPE is still only 0.08 for blue light emission.[5]

In conclusion, the wall-plug efficiency of GaN-based SLEDs is severely limited by the low conductivity of p-doped waveguide layers, as in laser diodes. However, due to the higher quantum well carrier density, SLEDs suffer more than laser diodes from carrier recombination losses, in particular from Auger recombination, which are strongly enhanced by self-heating. More details as well as possible remedies will be discussed at the conference.

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