Numerical Simulations of Blue and Green GaN SLEDs

Nicolai Matuschek, Marco Rossetti, Jerome Napierala, Marcus Duelk, Christian Velez
EXALOS AG, Wagistrasse 21, CH-8952 Schlieren, Switzerland
Tel.: +41-43-444 60 90, Fax: +41-43-444 60 99, E-mail: matuschek@exalos.com

Abstract-**Numerical simulations are inevitable for the development and optimization of GaN-based superluminescent light-emitting diodes (SLEDs) for the blue and green spectral region. Depending on their application the devices have to be optimized with respect to given specifications. We discuss the simulation of various device performance parameters as well as the basic calibration of the full 3D device simulator. We use well-characterized SLED devices realized with standard epitaxial structures for the calibration procedure. A comparison between simulated and measured data allows the extraction of important simulation parameters such as the screening factor.**

I. INTRODUCTION

Nowadays, superluminescent light-emitting diodes (SLEDs) are well-established optical light sources for wavelengths ranging from the red to the near-infrared spectral region (650-1700 nm). Major research and development work on violet and blue (405-450 nm) GaN SLEDs over the past years [1, 2] resulted recently in first commercialization of such broadband light sources and is now shifting towards the development of cyan and green SLEDs to further replace laser diodes (LDs) in, e. g., speckle-sensitive applications. The successful realization of robust and reliable SLEDs for the short-wavelength region relies strongly on results obtained from numerical simulations that match real device characteristics.

The SLED chip design is based on an edge-emitting waveguide structure similar to LDs. It combines the beam directionality of LDs (high spatial coherence) with the broadband emission spectrum of LEDs (low temporal coherence). SLEDs operate in the amplified spontaneous emission (ASE) regime, i. e. spontaneously emitted photons are amplified by stimulated emission within a single pass in the optical waveguide. However, in contrast to LDs, SLEDs do not exhibit an intrinsic resonant cavity, which would allow the build-up of longitudinal cavity modes. Hence, the output spectrum is smooth and continuous. The suppression of resonant cavity modes is achieved by tilting the waveguide by a few degrees and by applying anti-reflection coatings on the output facets of the SLED chip.

In this presentation, we show that vertical power leakage into the substrate due to a low optical confinement factor and/or the occurrence of substrate modes is a severe problem for III-nitride structures. Guidelines for the optimization of the vertical epitaxial structure are given. Moreover, we discuss the basic calibration of a full 3D-simulator in detail. Unknown simulation parameters, as for example the internal loss coefficients or the screening factor, are extracted from a comparison between simulated and measured data. The screening factor is an important parameter for the simulation of *c*-plane nitride structures. It determines the percentage of interface charges that contribute effectively to polarization-induced built-in electric fields.

II. EPITAXIAL DESIGN

A. Guided mode vs. substrate mode

SLEDs for the blue and green spectral region are based on InGaN/AlGaN epi layers, which are grown on a free-standing GaN substrate. It is well known that such epi structures tend to produce substrate modes instead of guided modes [3]. The reason is the higher refractive index of the substrate material compared to the AlGaN material that is typically used for the cladding layers.

Substrate modes suffer from a leakage of optical power out of the waveguide region into the substrate which might be reflected at the bottom of the substrate back into the waveguide. As a result, undesired asymmetric side lobes occur in the vertical far-field spectrum of the SLED. Therefore, the vertical epi structure has to be designed carefully in order to avoid substrate modes or, if not possible, to allow substrate modes still having a high optical confinement factor. The production of a high amount of ASE output power requires a minimum level for the confinement factor. Even guided modes may have a low confinement factor for an unfavorable choice of the epi structure.

We use a one-dimensional mode solver for the fast simulation of the vertical epi structure. This allows us to vary the material parameter space for the cladding-, waveguide-, and active-region layers over the entire reasonable range of material compositions. As an example, Figure 1 shows the vertical near-field distribution as well as the refractive-index profile obtained for (a) a guided mode and (b) a substrate mode. It should be noted that for this particular example the substrate mode has a greater confinement factor than the guided mode. Hence, this structure might be preferable depending on the other design constraints.

B. L-I characteristics and polarization field effects

A realistic full 3D-simulation of an SLED requires knowledge of several parameters, which enter into the simulation such as Auger recombination coefficients, carrier lifetimes, internal loss coefficients, and many others. Moreover, the gain model has to be specified precisely, which includes the definition of the line-shape and broadening function. A particular problem for the simulation of III-nitride structures is the occur-

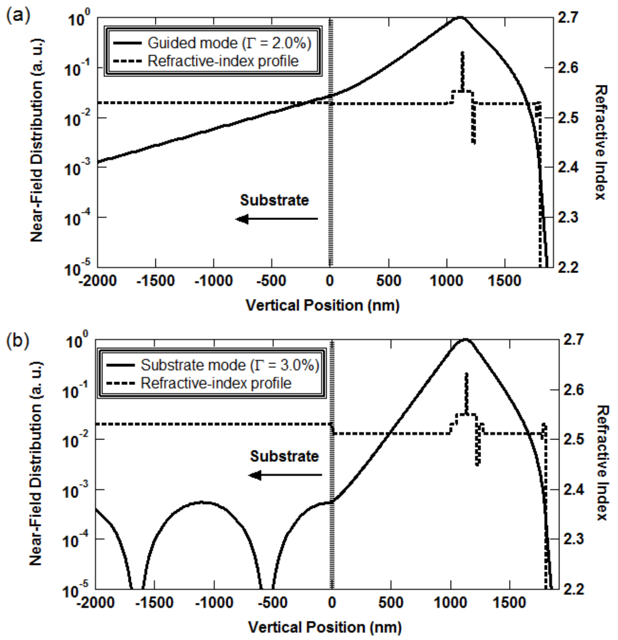

Fig. 1. Vertical near-field distribution and refractive-index profile for an epi structure, where the mode with highest gain is (a) a guided mode or (b) a substrate mode. Here, the confinement factor for the guided mode is lower than for the substrate mode.

rence of polarization-field effects, which are caused by spontaneous polarization and strain-induced polarization. However, it is well known that high carrier densities in the quantum wells lead to a reduction of polarization fields because of a charge screening effect [4].

We use well-characterized SLED devices realized with standard epi structures for the experimental determination of most of the relevant simulation parameters, i. e. we calibrate our simulator by a detailed comparison between measured and simulated data. In this way, the number of free fit parameters is strongly reduced. The gain model can be fixed by analyzing the photoluminescence spectrum, the ASE output spectrum, or by measuring the gain spectrum directly using a Hakki-Paoli or a similar set-up. Other parameters are extracted from the SLED's *L-I* characteristics (*L* = light output power, *I* = injection current). In particular, the screening factor can be determined from the ASE threshold behavior. We found that a reasonable value for blue SLEDs is ≈ 0.3. This means that only 30% of the theoretical interface charges contribute to built-in electric fields.

As an example, Figure 2 shows results obtained for a blue SLED after the basic calibration procedure. The chips under investigation have a length of 1 mm and exhibit a ridge-waveguide structure with a ridge width of 2 µm. Obviously, there is a good agreement between simulated and measured curves. Hence, the simulator can be considered well-calibrated such that results, which are obtained from the simulation of new epi structures, are reliable. We use the calibrated simulator twofold: First, we use it for the optimization of existing blue SLED structures. Second, it can be directly used for the simulation of new SLED structures shifted to the green spectral region just by changing material compositions.

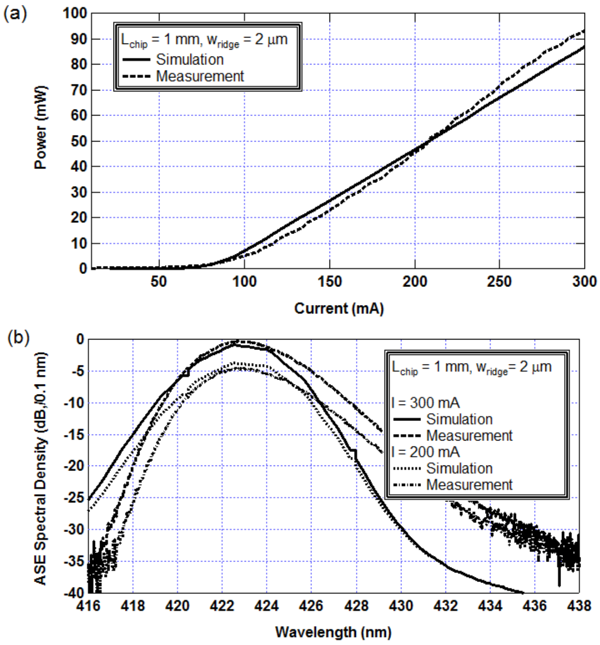

Fig. 2. Comparison of measured and simulated (a) *L-I* characteristics with *L* being the ex-facet output power and (b) ASE output spectra for a blue SLED with a chip length of 1 mm and a ridge width of 2 µm. The ASE spectra with their peak wavelengths at around 423 nm are shown for two different injection currents.

III. SUMMARY

We have demonstrated that the application of simulation tools is very helpful and necessary for the development and optimization of blue and green SLED devices.

A particular problem for III-nitride SLEDs is the possible occurrence of substrate modes. Thus, the design of an epi structure with high modal gain and the avoidance of substrate modes is a demanding task. We use a one-dimensional mode solver as a fast and proper design tool to investigate the vertical mode behavior.

Due to the complex physics behind SLEDs a well-calibrated full 3D-simulator is the basis for the reliable simulation of the electro-optical device performance. We reduce the number of free fit parameters in the simulator by extracting most of the relevant input parameters from a comparison of simulated with experimental data. After the successful calibration procedure, the simulator is applied to the optimization of existing blue SLED devices as well as for the design of new devices in the green spectral region.

REFERENCES

[1] E. Feltin, *et al.*, "Broadband blue superluminescent light-emitting diodes based on GaN," *Appl. Phys. Lett.*, vol. 95, 081107, 2009.

[2] M. Rossetti, *et al.*, "High power blue-violet superluminescent light emitting diodes with In GaN quantum wells," *Appl. Phys.Epress.*, vol. 3, 061002, 2010.

[3] V. Laino, *et al.*, "Substrate modes of (Al,In)GaN semiconductor laser diodes on SiC and GaN substrates," *IEEE J. Quantum Electron.* , vol. 43, pp. 16-24, 2007.

[4] F. D. Sala *et al.*, "Free-carrier screening of polarization fields in wurtzite GaN/InGaN laser structures", *Appl. Phys. Lett.*, vol. 74, pp. 2002-2004, 1999.