Blue Laser Diodes

Numerical Simulation Helps to Understand Physics and Performance Limitations

The first demonstration of a GaN-based blue laser diode by Shuji Nakamura [1] was followed by a tremendous research and development effort around the world. Gallium nitride technology enables a range of novel applications with vast consumer markets. Examples are full-color video displays, solid-state lighting, and high-definition DVD players. However, there still remains a strong need for a more detailed understanding of microscopic physical processes in nitride devices. Advanced models and numerical simulation can help to investigate those processes and to improve the device performance. This article reviews practical examples of GaN-laser simulation, analysis, and optimization [2, 3].

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Joachim Piprek received his Ph.D. in theoretical physics from Humboldt University in Berlin, Germany. For more than two decades, he worked in industry and academia on design, simulation, and analysis of optoelectronic devices. He has taught graduate courses at universities in Germany, Sweden, and in the United States. Most recently, he was a professor at the University of California at Santa Barbara, where his research focused on long-wavelength vertical-cavity lasers and on GaN-based light emitters.

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Unique Material Properties

The troubled history and the recent success of nitride semiconductor devices are both very much related to the unique material properties of GaN and its most relevant alloys InGaN and AlGaN. Depending on the alloy composition, the direct bandgap varies from about 0.7 eV to 6.2 eV, covering a wide wavelength range from red through yellow and green to blue and ultraviolet (Fig. 1). For many years, there was no suitable bulk-crystal technology for producing GaN substrates and epitaxy was done on highly lattice- and thermal-expansion-mismatched substrates. The resulting heteroepitaxial films exhibited high dislocation densities, more than 5 orders of magnitude higher than in other compound semiconductor devices. The surprisingly small impact of these defects on the performance of GaN-based light emitters is still not fully understood.

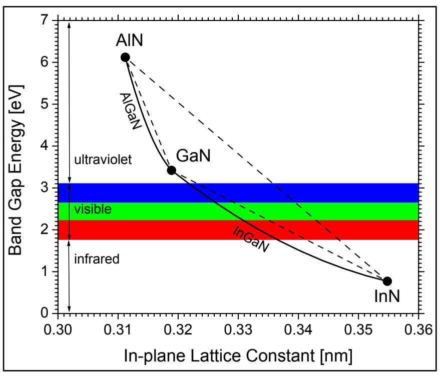

FIGURE 1: **Electron energy bandgap vs. lattice constant for GaN, AlN, InN, and their alloys.**

While other compound semiconductors such as GaAs and InP belong to the zinc blende crystal system, nitride devices are grown in the hexagonal (wurtzite) crystal system. This leads to unique material properties, such as built-in electric fields due to spontaneous and piezoelectric polarization. The polarization varies with the alloy composition so that net charges remain at every interface between semiconductor layers. This can have dramatic effects on the thin active layers (quantum wells) which are used to transform electrical current into light, i.e., electron energy into photon energy. Figure 2 shows the energy band diagram of a quantum well. The built-in polarization field leads to a strong deformation of the usually rectangular quantum well diagram. As a consequence, the electrons are moved to one side and the holes are moved to the other side of the quantum well. Since the photon emission rate depends on the overlap of the wave functions, the carrier separation reduces the light emission intensity. In addition, the photon energy, i.e., the light wavelength is changed by the built-in field, as electron and hole energy levels are less separated. The wider the quantum well, the stronger the effect of built-in polarization. However, it is often believed that the high density of quantum well carriers in GaN laser diodes compensates for the built-in field.

Another unique property of nitrides is the high activation energy for acceptor (Mg) doping of about 170 meV. It requires high

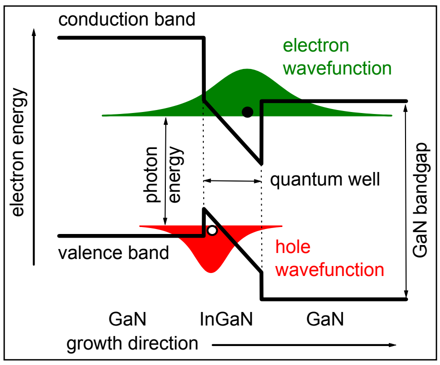

FIGURE 2: **Energy band diagram for an InGaN/GaN quantum well with built-in polarization field.**

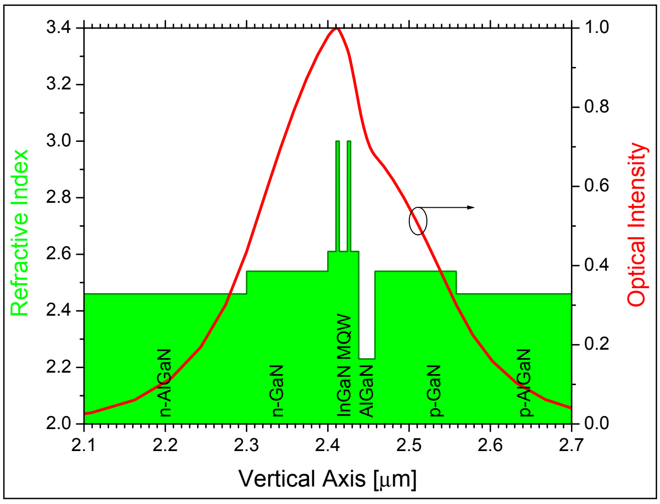

FIGURE 3: **Vertical profiles of refractive index (green) and optical intensity (red) in the center of the laser.**

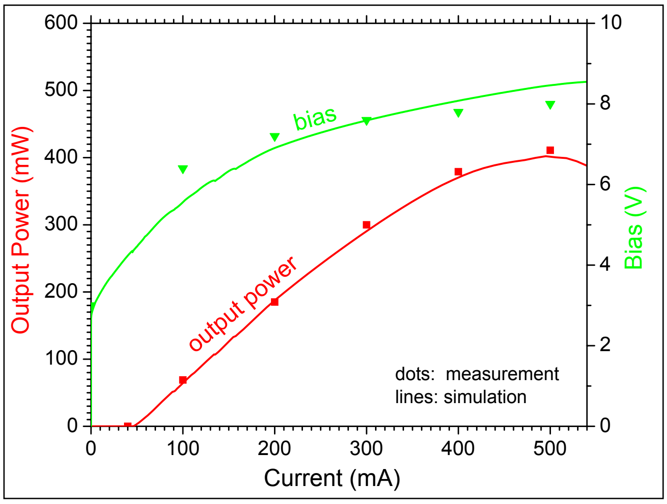

FIGURE 4: **Comparison of measured and simulated laser characteristics.**

doping densities near 1020 cm-3 to achieve free hole concentrations of about 1018 cm-3. This causes an extremely low hole mobility on the order of 10 cm^2/Vs. On the other hand, the high GaN electron mobility of up to 2000 cm^2/Vs and the large critical breakdown field of more than 3 MV/cm are advantageous in high-speed and high-power electronics. The thermal conductivity in GaN is more than three times higher than in GaAs.

Edge-Emitting Lasers

Our first simulation example is an InGaN/GaN high-power laser diode as demonstrated by S. Nakamura [4]. The layer structure is illustrated in Figure 3 which plots the refractive index profile and the optical intensity in the center of the device. The active region consists of two InGaN/InGaN quantum wells that are embedded in a GaN waveguide layer. The AlGaN blocker layer on top of the quantum wells is supposed to reduce the electron leakage into the p-side of the device.

For numerical simulation, the LASTIP software package by Crosslight Software is employed here, which self-consistently combines wurtzite band structure and gain calculations with two-dimensional (2D) simulations of wave guiding, carrier transport, and heat flux [2]. Figure 4 shows good agreement between measured and simulated light-current (LI) and current-voltage (IV) characteristics. This agreement was achieved by calibration of several device parameters that were not exactly known: the internal modal loss (12 cm^{-1}), the non-radiative recombination lifetime within the quantum wells (0.5 ns), and the total thermal resistance (75 K/W). The modal loss controls the slope efficiency of the LI curve, the lifetime affects the threshold current, and the thermal resistance has a strong impact on the power roll-off. All three numbers found are reasonable and confirm the accuracy of the laser model. The IV characteristic depends on the carrier mobility as well as on the contact resistance [2]. Its accurate simulation is essential for a correct calculation of the internal heat power generated during laser operation.

The main task of this simulation was to understand the physical mechanism behind the power roll-off shown in Fig. 4. The simulation reveals that the high injection current causes strong self-heating which reduces the quantum well optical gain substantially. Consequently, the carrier concentration within the two InGaN quantum wells increases dramatically (Fig. 5a). This leads to enhanced non-radiative carrier recombination at defects and to an escalation of electron leakage from the quantum wells into the p-side of the diode, despite the AlGaN blocker layer (Fig. 5b). The simulation clearly shows that electron leakage is the main reason for the power roll-off.

The next task is the evaluation of possible counter measures. Leakage may be reduced by increasing the bandgap of the AlGaN

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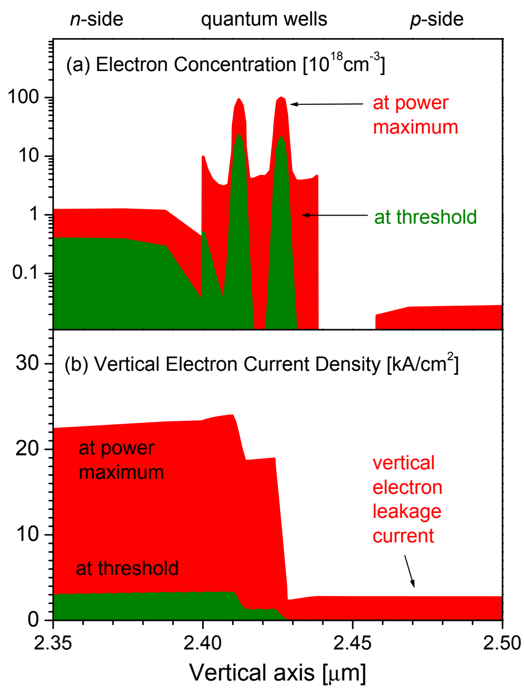

FIGURE 5: **Vertical profiles of (a) electron density and (b) electron current in the center of the laser at lasing threshold (50 mA, green) and at maximum power (500 mA,**

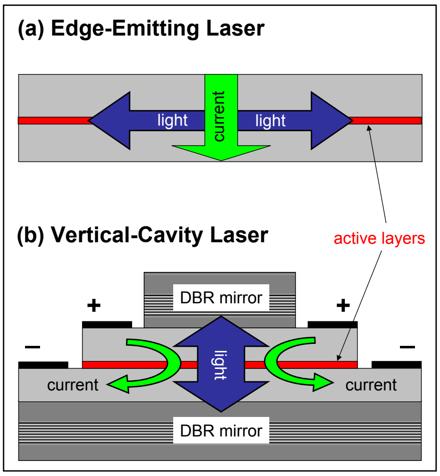

FIGURE 6: **Design illustration of edge-emitting and vertical-cavity lasers.**

blocker layer. However, as the internal self-heating represents the root cause for this mechanism, it is more efficient to reduce the temperature rise. This can be done by limiting the heat production (less contact resistance, higher electrical conductivity) and/or by improving the heat removal. The latter approach is easily implemented by using a better heat sink. Simulations predict double the laser output power for an ideal heat sink with negligible thermal resistance (for more details see Chapter 9 in [2]).

Vertical-Cavity Lasers

Vertical-cavity surface-emitting lasers (VCSELs) are a relatively new type of laser diodes. They exhibit several advantages over their edge-emitting counterparts, including lower manufacturing costs, circular output beams, and longer lifetime. The optical cavity of VCSELs is formed by two mirrors above and below the active region (Fig. 6). Contrary to edge-emitting lasers, the VCSEL laser light propagates in vertical direction and the photons pass the active region in perpendicular direction. Optical gain is produced over a short propagation distance only and the amplification per photon round trip is small. Therefore, the mirrors need to be highly reflective so that photons make many round trips before they are emitted. To achieve high reflectivity, distributed Bragg reflectors (DBRs) are used with two alternating layers of high refractive index contrast. With quarter-wavelength layer thickness, the reflected waves from all DBR interfaces add up constructively, allowing for DBR reflectivities above 99%.

In contrast to the great success of GaAs-based VCSELs in recent years, GaN-based VCSELs face significant challenges and only optically pumped devices have been reported thus far. Discussed reasons for the failure of current-injected GaN-VCSELs include the high threshold carrier density (which is typical for all GaN-based lasers), the high optical loss (due to insufficient reflectance of native AlGaN/GaN DBRs), and the low electrical conductivity of p-GaN. We here analyze a current-injected GaN-VCSEL that was manufactured by T. Margalith at the University of California at Santa Barbara [5].

First, the PICS3D laser software by Crosslight Software is employed to investigate polarization effects. The built-in polarization strongly deforms the energy band diagram of the InGaN multi-quantum well (MQW) active region. Figure 7 plots the MQW band diagrams with and without built-in polarization. Without polarization, the quantum wells are almost rectangular and the AlGaN layer imposes a considerable energy barrier on electrons trying to leak out of the MQW active region. With polarization, the energy band diagram is significantly deformed, leading to enhanced leakage and reduced gain. This deformation is even more remarkable considering the high current density assumed in this calculation, which is 16 times higher than the threshold current density of the edge-emitting lasers discussed in the previous section. Surprisingly, even with strong carrier injection, the built-in polarization field is not completely screened as often assumed for laser operation. The polarization charge densities at the MQW interfaces translate into a built-in quantum well field of 1.8 MV/cm. The actual electrostatic field within the quantum wells is about 0.5 MV/cm due to partial screening by electrons and holes. The electrostatic field leads to a separation of electrons and holes within the quantum wells and thereby reduces the laser gain (Fig. 2). This is one of the reasons that no lasing operation was achieved with this device.

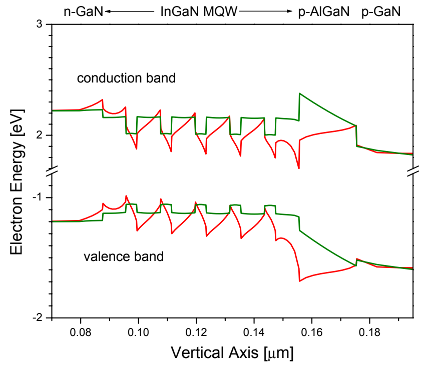

FIGURE 7: **VCSEL active region band diagram with (red) and without (green) built-in polarization (room temperature, 50 kA/cm^2 current density).**

Pulsed laser operation is often used to prevent any significant self-heating of the VCSEL and to enable lasing at room temperature. Practical current pulse lengths are between 50 ns and 500 ns. Thermal simulations with the multi-physics software FEMLAB by COMSOL are employed in the following to investigate the VCSEL self-heating [5]. Under continuous-wave conditions, 10 mA injection current lead to a steady-state temperature rise of 110 K in the active region. This strong heating is mainly due to the high voltage drop measured (20 V) and it translates into a thermal resistance of 550 K/W. As expected, this resistance is about one order of magnitude higher than in GaN-based edge-emitting lasers due to the smaller volume of the heat source in VCSELs. The transient temperature rise during pulsed laser operation is often considered negligible. Surprisingly, our simulations show that even a very short pulse of 50 ns causes a temperature rise of 26 K in the active region. More than half of the steady-state temperature rise is reached after 500 ns (Fig. 6). The temperature rise causes a reduction of the quantum well gain leading to a higher threshold current. This strong self-heating during short current pulses is another possible reason for the failure of these VCSELs.

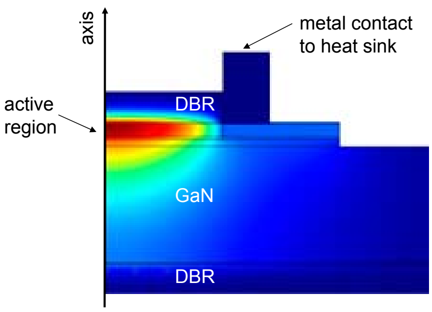

FIGURE 8: **VCSEL temperature distribution T(r,z) after 500 ns current pulse of 10 mA with T_{min} = 300 K (dark blue) and T_{max} = 360 K (dark red).**

Summary

These examples demonstrate how advanced laser simulation can help to understand internal physics and to improve device performance. Various software tools are available which facilitate the design and analysis of sophisticated device structures (see software directory at www.nusod.org). Following the trend observed with other semiconductors, physics-based nitride device simulation is expected to gain importance in coming years.

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