

What is the Problem with GaN-based VCSELs ?

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Abstract – In contrast to the impressive progress of GaN-based edge-emitting lasers in recent years, III-nitride vertical-cavity surface-emitting lasers (VCSELs) still exhibit severe performance limitations. Using advanced device simulation, this presentation evaluates design and material issues with different GaN-VCSEL concepts and identifies performance limiting internal mechanisms.

Similar to widely used GaAs-based vertical-cavity surface-emitting lasers (VCSELs), GaN-based VCSELs are expected to show various advantages over their edge-emitting counterparts, including lower manufacturing costs, circular and low-divergence output beam, single longitudinal mode emission, low threshold, high-speed modulation, high-density two-dimensional arrays, wafer-level testing, and longer lifetime. Potential applications of GaN-VCSELs include laser display, solid-state lighting, high-density optical data storage, high-resolution printing, low-cost optical communication, and bio-sampling. However, in contrast to the success of GaN-based edge-emitting lasers in recent years, GaN-VCSELs still face significant challenges.¹ One of the key material problems is the poor quality of AlGaIn/GaN distributed Bragg reflectors (DBRs) due to the large lattice mismatch of GaN and AlN. A possible solution is the use of one or two dielectric DBRs. However, the employment of dielectric DBRs on both sides of the VCSEL cavity requires the removal of the majority of the GaN substrate combined with a precise control of the remaining cavity length.²

This presentation evaluates different current-injected GaN-VCSEL design concepts that show room-temperature (RT) continuous-wave (CW) operation. The design of VCSELs in general is very demanding and numerical simulation is often used for design optimization.³ We here employ the laser simulation software PICS3D⁴ that self-consistently combines the computation of carrier transport, energy band structure, optical gain, optical modes, and self-heating. 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 photon emission, Auger recombination, and defect-related Shockley-Read-Hall (SRH) recombination. For the quantum wells, Schrödinger and Poisson equations are solved iteratively to account for the

quantum-confined Stark effect (QCSE) caused by nitride polarization. Stimulated and spontaneous emission of photons within the quantum well is calculated self-consistently based on the wurtzite energy band structure. More details on model and parameters are given elsewhere.⁵ A similar model was previously employed in the analysis of high-power GaN-based edge-emitting lasers, resulting in very good agreement with measurements.⁶

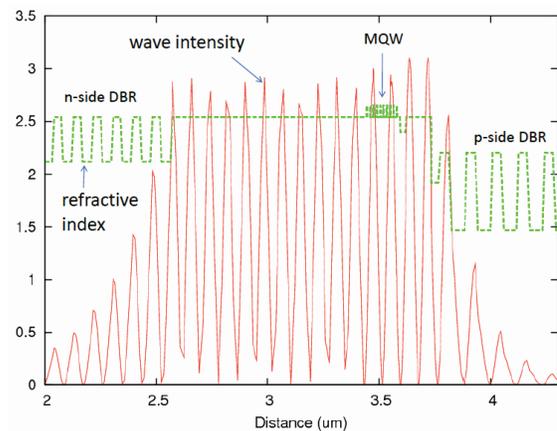


Fig. 1: Vertical profile of refractive index and standing optical wave in the center of the VCSEL from Ref. 9.

The first continuous-wave (CW) operation of a current-injected GaN-VCSEL was demonstrated in 2008 at a low temperature of 77K utilizing an n-side AlN/GaN DBR with superlattice interlayers for strain relaxation and a p-side Ta₂O₅/SiO₂ dielectric DBR.⁷ This hybrid concept was still missing an AlGaIn electron stopper layer (EBL),⁸ which was later added and, together with a much thinner indium-tin-oxide (ITO) current injection layer, led to RT-CW operation with a maximum output power of 37μW at 412nm.⁹ Another key design feature is the thick multi-quantum-well (MQW) active region with 10 quantum wells covering an entire period of the standing wave (Fig. 1) and avoiding the problem of positioning the active layers at an optical intensity peak. However, our simulations reveal that the built-in polarization contributes to a strongly non-uniform QW carrier density. At low current, only the p-side QWs deliver optical gain while the n-side QWs are still absorbing, so that the net modal gain is reduced by using a thick MQW.

Another group achieved RT-CW operation employing dielectric Nb₂O₅/SiO₂ DBRs on both sides of the VCSEL cavity.¹⁰ This approach features much thicker quantum wells and delivered thus far the highest CW output power of 0.7mW at 451nm, when using a GaN substrate for the epitaxial growth.¹¹ The 9-nm-thick quantum wells allow for an almost complete QCSE elimination under lasing operation.⁸ However, the design does not incorporate an EBL. The calculated current profile within the p-GaN layer above the MQW is plotted in Fig. 2. The sharp peak of the electron current at the ITO aperture edge reveals strong electron leakage into the p-GaN layer. Leaking electrons capture holes before they reach the active region and reduce the efficiency of the laser.

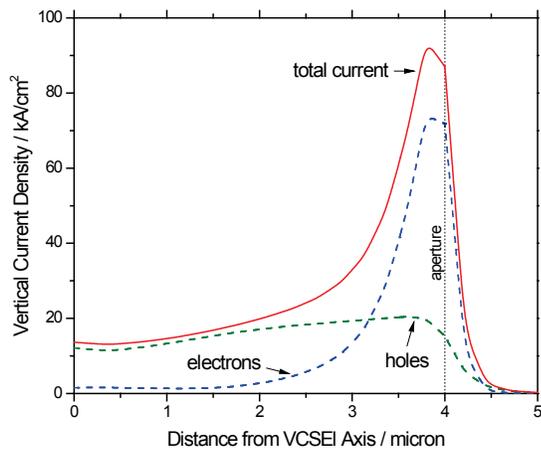


Fig. 2: Lateral current density profile in the p-GaN layer above the MQW for the VCSEL from Ref.10.

GaAs-based monolithic VCSELs typically feature a very short cavity length to obtain single-longitudinal mode operation. The VCSEL emission wavelength is directly linked to the cavity length and precise thickness control is required during the manufacturing process to align the cavity wavelength with the MQW gain wavelength.¹² The remaining difference is called gain offset. The alignment difficulty partially arises from the different temperature sensitivity of both wavelengths. The thermal shift of the gain peak of 0.066 nm/K was extracted from measurements on in-plane InGaN/GaN lasers.¹³ The temperature sensitivity of the GaN-VCSEL emission wavelength (0.01 nm/K)¹⁴ originates in the temperature dependence of the refractive index. Figure 3 plots the thermal shift of both wavelengths and illustrates the temperature sensitivity of the gain offset. Even with zero gain offset at room temperature, the strong self-heating of the VCSEL leads to an increasing detuning. In contrast, Fabry-Perot lasers always emit near the wavelength of maximum gain, due to their small longitudinal mode spacing.

Thus, some GaN-VCSEL concepts utilize a relatively thick cavity which allows for a narrow spacing of longitudinal modes and alleviates the need for precise thickness control. A recent example employs a 6μm cavity, sandwiched between two dielectric ZrO₂/SiO₂ DBRs, and emits multiple longitudinal modes in CW operation (cf. Fig. 3).¹⁵ But this VCSEL exhibits a very low output power (3μW), which is partially attributed to strong absorption inside the cavity, e.g., by the thick ITO layer.

In summary, many of the GaN-VCSEL problems are related to III-nitride material peculiarities such as lattice mismatch, built-in polarization, and low p-conductivity, as well as to severe technological issues, e.g., with cavity length control and lateral confinement, which do not exist with GaAs-based VCSELs.

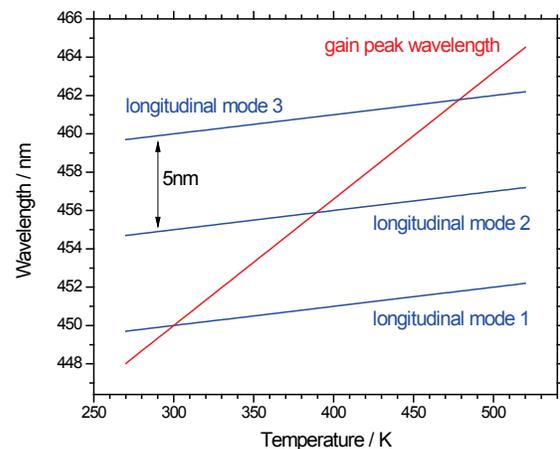


Fig. 3: Thermal shift of gain peak wavelength and cavity wavelength for different longitudinal modes.

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