Philosophy of Approaching a Laser Design Problem: Illustrated by the Design of Ultraviolet Vertical-Cavity Laser Diodes

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The objective of this article is to demonstrate a general approach to the problem of designing a novel laser diode. This involves first understanding prior work in this and related fields (literature survey), and then acquiring a thorough understanding of the relevant physics. This in turn enables the development and/or selection of appropriate models and tools for that problem followed by partitioning the problem into smaller solvable chunks. This involves identifying the key contributing factors affecting poor laser performance (sources of optical loss, poor injection efficiency, high thermal resistance, etc.), quantifying and ranking their relative importance, and finally finding solutions to these problems. The final step involves putting all these pieces back together to arrive at the final laser design. This step is challenging due to the strong coupling between electrical, optical, and thermal physics in a laser diode. Any design changes must be considered through all three lenses. Herein, this approach to laser design will be demonstrated in the context of a novel III–N-based ultraviolet vertical-cavity surface-emitting laser diode (UV-VCSEL).

1. Introduction

Laser diodes (LDs) are among the most complicated semiconductor devices to design, grow, and fabricate. The design is complicated due to the intimate connection between thermal, optical, and electrical physics. An example of such a problem is the design of lateral current spreading layers (CSLs) in vertical-cavity surface-emitting lasers (VCSELs), because its thickness and material properties affect lateral current spreading (gain), Joule heating, and the overall optical loss. This is because higher optical loss leads to increased threshold currents, which in turn causes a higher junction temperature due to self-heating, and thus the laser emits less optical output power for a given injection current. Small design changes can have unexpectedly large impacts if the coupled physics of the problem is overlooked or misunderstood.

The crystal growth of materials for LDs is challenging because it requires the highest grade of epitaxial material. Defects in the active region can make the difference between a laser diode and a light-emitting diode (LED). This is because defects can act as nonradiative recombination centers, which consume injected carriers to produce heat (phonon emission) instead of light. This degrades the internal quantum efficiency (IQE) of the laser diode. Furthermore, LDs have many different III–V material compositions (alloys) grown one on top of another for the purpose of confining light (refractive index contrast), and/or charge carriers (bandgap discontinuities). In some material systems such as III-nitrides, increasing the index contrast or bandgap discontinuity involves increasing the epitaxial strain by increasing the aluminum mole fraction (x) in Al$_x$Ga$_{1-x}$N.\[1,2\]

If the strained layer is grown thicker than its critical thickness, defects will form\[3\] which will degrade the laser’s performance\[4\] and reliability.\[5\] These are some of the factors that make crystal growth for lasers very challenging.

LDs require some unique processing steps, such as the deposition of dielectric distributed Bragg reflectors (DBRs) to serve as high-reflectivity mirrors, or cleaving facets along crystallographic planes to form the optical cavity. Also, lasers operate under conditions of high-level current injection, so during normal operation, the power draw can be heavily influenced by the series resistance of the laser diode.\[6,7\] Thus, it is of paramount importance to have as low contact resistances as possible. Any power dissipated in the series resistances will increase the laser’s junction temperature, thus degrading the laser’s output power and wall-plug efficiency.

Laser design is complicated by the dependency of performance on a great number of factors, and by the constraints imposed on the design space by limitations inherent in growth and processing technologies. A good design should be implementable with current cutting-edge technology. The present
work seeks to demonstrate laser design methodology in the context of a UV-VCSEL LD.\[8\]

\[2\] The Use of Numerical Simulation in Laser Design

Numerical simulation is helpful in the laser design process because it allows us to display and interpret the internal electrical, optical, and thermal processes in the laser which are otherwise unobservable. Band diagrams, charge carrier and photon field distributions, temperature maps, current density vectors, etc., can all be visualized by conventional laser-simulation tools based on Minilase, which was originally developed at the University of Illinois.\[9\] Modern laser-simulation tools use similar equations, and the complete electro-opto-thermal laser simulation framework has been described in our previous work,\[10\] and is pictorially depicted in Figure 1.

Ideally, the Schrödinger and Poisson equations must be solved self-consistently in the active region to account for screening of the fixed sheet charge at the quantum well (QW) and quantum well barrier (QB) interfaces by bound carriers, and this consideration of screening would increase the gain by increasing the electron and hole wavefunction overlap (see Section 3.1.2 for more details) due to a reduced electric field in the active region. However, note that in Figure 1, there is no feedback between the Schrödinger equation (solved by the k.p method with a 6 × 6 Hamiltonian) and the electrothermal charge transport equations. This is because significant problems with convergence occur when the k.p band structure calculations are solved self-consistently with the Poisson, current continuity, and QW scattering equations in the presence of high interfacial sheet charge densities as in c-plane III–N material. The solution of Schrödinger’s equation by the k.p method along with the electrothermal equations are very sensitive to the potential profile in the active region because carrier capture and escape is governed by a thermionic emission type of model,\[9\] and thus the additional feedback between the band structure calculation and the Poison and current continuity equations adversely affects convergence in the presence of high amounts of interfacial sheet charges. The k.p method is advantageous because it accounts for distortions in the parabolic band structure due to band-mixing and strain-related effects.

We used a workaround to get useful simulation results which converge and which are useful for laser design work. Bound carriers that screen the interfacial sheet charge serve to reduce the piezoelectric field in the QWs. By referring to the literature, trying to match experimental data, and by roughly calculating the bound carrier sheet density and subtracting it from the fixed sheet charge density, we can estimate the correct electric field in the QW near the bound carrier density of interest, and then we can directly scale the fixed sheet charge density to 40–60% of its full value, as is common in the simulation of III–N light-emitting devices.\[11\] This workaround roughly reproduces the effect of screening the interfacial polarization charge by the bound carriers without the additional numerical complexity. This screening ratio is further validated by Peng et al.,\[12\] where they found that the electric field reduced from 3.2 to 1.96 MV cm\(^{-1}\) when screening was considered via the solution of the Schrödinger–Poisson equation compared with just solving the Schrödinger equation for carrier densities of interest in lasers. We find that this workaround gives a good match to experimental data around the carrier densities of interest (near and beyond threshold), and the carrier density is then roughly pinned after the threshold current for isothermal simulations.

However, this workaround would not be appropriate for work on specifically designing active regions. Active region design would involve solving the Schrödinger and Poisson equations self-consistently via the k.p method, as demonstrated by Venkatachalam et al.\[13\] and Zhao et al.\[14\] In these cases, they start with a known carrier density, and hence they do not also

![Figure 1. Coupling between equations used in laser diode simulations.](image-url)
need to self-consistently solve the carrier capture/escape and charge transport equations (3D to 2D states and vice-versa) along with the Schrödinger–Poisson equations, as in a full laser simulation. In the work presented here, we focus on designing other layers in the laser, such as CSLs, electron blocking layers (EBLs), and layers for improved thermal performance, which makes this a reasonable approximation for active region modeling and it allows us to use numerical simulation in advanced laser design by overcoming issues pertaining to numerical convergence.

Furthermore, it is our opinion that the role of simulation should be to inform experiment. Simulation can tell us which design parameters are important, and it can give us an approximate quantitative dependence, which can then be fine-tuned by well-designed experiments, if needed. Numerical simulation can help us perform a Pareto analysis of the design problem by providing logical starting points for the design process of a novel device that has never been demonstrated before. Thus, taking reasonable material parameters from the archival literature, validating simulation with related devices (visible VCSELs, in this case), and using the appropriate physics for the simulation problem should be sufficient to gain initial insight.

Electro-opto-thermal simulations are very time-consuming and can take 1–2 days, and hence, it is not always useful to run full electro-opto-thermal simulations right away. Initially, to get an understanding of the magnitude of a sub-problem, one may only need to run much smaller, faster, and more targeted simulations with better control of variables.

For example, if an aspect of device performance is insensitive to self-heating, we may run faster electro-opto simulations. Such a situation arises in the study of EBLs and p-CSLs at low input currents where self-heating is negligible.[15,16] In this and similar ways, an understanding of both the physics and the software can reduce individual simulation times from days to hours, and dramatically shorten the time required to design a laser. Not all of the physics needs to be considered for every sub-problem.

As another example, when designing the DBRs, one might first only perform a 1D transmission matrix method (TMM) simulation, which takes only a few seconds to simulate the reflectivity spectrum of various types of DBRs.[17] If the reflectivity is too low, there is no need to run an entire laser simulation.

Sometimes, we may want to see the effect of mirror reflectivity on threshold current. In this case, we would simulate the laser diode with a very high loss artificially added in order to obtain the unclamped gain spectrum. Now we can match the new loss values due to various reflectivities to a point on the gain versus input current curve to estimate the threshold current as a function of the mirror reflectivity curves for a given epitaxial stack and device geometry. This can save a lot of time when prototyping devices.

As a rule-of-thumb, the optical problem tends to be the most important, as having lower loss improves the laser in every single way. The thermal problem is usually the easiest and hence it is usually better to deal with it last in the laser design process. The reason for this is shown in Figure 2.

Figure 2 shows a typical plot of the modal gain versus input current (current aperture is 8 μm in diameter). The details of the laser in Figure 2 is not important as the shape of the gain versus f curve is similar for all LDs. Note that d(gain)/df falls monotonically as the operating current increases. This implies that reducing the loss can lead to super-linear reductions in the threshold current. Furthermore, a lower threshold current means that the maximum optical output power increases before thermal rollover. Thus, reducing the loss would allow the threshold current to fall into region 1 in Figure 2, which is far preferable to operating in region 2. This reduces self-heating (more gain) and electron leakage (better injection efficiency) due to a greater energetic barrier height for electrons at lower current densities.

3. Steps in the Laser Design Process

In this section, we shall review the logical sequence of steps needed to design a laser, and provide specific examples pertaining to UV-VCSELs.

3.1. Understanding the Material System and Growth Limitations

Each family of materials (AlGaInAs, InGaAsP, AlInGaN, etc) has certain unique properties such as band alignments, refractive index variations with mole fraction, strain between binary alloys, sheet charges at heterointerfaces for polar materials like the III–N material system, lattice matched alloys, doping efficiency, growth temperatures, etc. The laser designer must understand the material system that they are working with, as that defines their toolbox (materials and processes that they can realistically access). Therefore, we believe that device designers can greatly benefit from working closely with colleagues engaged in materials synthesis and device processing throughout the II–N device design phase.

UV lasers emitting at a free-space wavelength of 370 nm use the AlGaN material system with InGaN (In ≈4%) QWs. The III–Nitride material has some unique characteristics that make it harder to work with than conventional III–V materials (III–AsP material system), such as high lattice mismatch between binary compounds, spontaneous and piezoelectric polarization charges at heterojunctions, poor p-doping efficiency, and optically lossy p-doped layers.
3.1. Strain

The III–N material system is highly strained with AlN grown on GaN experiencing tensile strain of 2.41%,[11] and InN on GaN experiences compressive strain of 11.16%. This strain limits the aluminum mole fraction in the EBL and in the DBR. This leads to poor injection efficiency due to electron leakage and poor DBR reflectivity, respectively. The aluminum mole fraction is limited by the critical thickness of AlGaN on GaN.

3.1.2. Interfacial Polarization Charge

The lack of inversion symmetry along the direction of growth in c-axis material results the formation of electric dipoles within the unit cell, whose magnitude varies with alloy composition. This is referred to as spontaneous polarization. Because this material system is piezoelectric, the presence of strain in epitaxial layers whose in-plane lattice constant differs from that of the substrate creates additional polarization, which may either complement or oppose the spontaneous polarization, depending on whether the strain is tensile or compressive. Interfaces between two dissimilar alloys therefore exhibit a sheet density of fixed polarization charge, whose magnitude depends on the difference in total polarization on either side of the interface, and in a manner consistent with Maxwell’s equations. This interfacial polarization charge has a great impact on the device’s optical and electrical properties. A detailed discussion on the polarization charge in III–N materials can be found by Ambacher et al.[22]

Interfacial polarization charge has deleterious effects on the performance of III–N light emitting devices due to two primary reasons—1) reduction of the QW gain by reducing the overlap between bound electron and hole wavefunctions, and 2) reducing the device’s injection efficiency by exacerbating electron leakage.[15] The Quantum-confined Stark Effect is discussed in more detail by Ryoo et al.[18]

3.1.3. Poor Conductivity in P-Doped Material

Magnesium, the obligatory acceptor in III–N materials, has an activation energy of 166 meV in GaN,[19] and this activation energy further increases with aluminum content in AlGaN,[20] 166 meV corresponds to an energy of 6 kT (at RT), making thermal ionization of the acceptor very inefficient. Thus, the poor free-hole concentration and the low hole mobility makes p-Al0.12Ga0.88N over 50 times more resistive than n-Al0.12Ga0.88N. This leads to high series resistance from the p-side in III–N lasers as well as severe electron leakage caused by the asymmetry in majority carrier conductivities in n- and p-type material.[23]

3.1.4. Optical Loss in P-Contact Layers

p-doped AlGaN has an absorption coefficient that is over three times higher than n-AlGaN based on the model found in ref. [21] and data in ref. [24]. However, the loss in the p++ contact layer is of far greater importance than in the quasi-neutral regions (QNRs), and this point will be discussed in more detail later on in the article. The reason for higher loss in p-doped material is that heavy magnesium doping (>1e18 cm–3) creates optically active defects.[25] The high acceptor activation energy of Mg in AlGaN implies that a much higher concentration of magnesium is required compared with the free hole concentration to achieve a suitably low resistivity. This increases the concentration of the aforementioned optically active defects.

3.2. Understanding the Device and Current State-of-the-Art: Why Are UV-VCSELs So Difficult?

Device-level physics is one layer of abstraction above the material physics and properties that were discussed in Section 3.1.

UV-VCSELs have several unique challenges, and to date, there is no demonstration of electrically pumped UV-VCSELs operating in CW at a wavelength less than 400 nm at RT. III–N-based VCSELs emitting at visible wavelengths have been demonstrated by several groups and will be briefly reviewed in this section. In our experience, the primary challenge to the realization of III–N VCSELs is obtaining a bottom (n-side) mirror whose reflectivity exceeds 99%. This is unlike edge-emitting lasers which can get by with low reflectivity (~30%) cleaved facets as mirrors. In edge-emitting LDs, light propagates in the plane of the active region, thus enabling high round-trip gains. VCSELs, in contrast, have a much smaller round-trip gain due to the fact that the light propagates perpendicular to the active region, and hence only sees the gain material in only 2–3% of the optical cavity.

3.2.1. Review of State-of-the-Art III–N VCSELs

The first electrically pumped VCSEL based on the III–N material system was demonstrated in 2008 by Nichia,[26] with a lasing wavelength of 414 nm, under room-temperature (RT) continuous-wave (CW) operation. It was grown on a sapphire substrate and used dielectric DBRs on both sides. To deposit a dielectric mirror on the bottom (n-side), the substrate was removed by laser lift-off after bonding the p-side to a support substrate. Subsequently, Nichia managed to increase the maximum output optical power under RT CW operation and reduce the threshold current by using a native GaN substrate[27,28] which has a reduced dislocation density on the order of 10⁶ cm–2 (compared with 10⁸–10¹⁰ cm–2 on sapphire). The GaN substrate could not be removed by laser lift-off, and hence had to be thinned by chemical mechanical polishing (CMP). This caused an increase in the variation of the VCSEL’s cavity length (and hence the lasing wavelength), leading to reduced yields compared with VCSELs grown on sapphire. Furthermore, the cavity length fluctuation due to imprecise polishing can deviate the peak of the optical mode’s antinode from the location of the MQW active region. This detuning can lead to significant reductions in the modal gain as the gain region is no longer near the peak of the optical mode profile; and this effect manifests as a reduced optical confinement factor. A similar approach was used by Panasonic to fabricate a VCSEL emitting light with wavelength of 408 nm under RT CW operation. All these devices extracted heat from the p-side as a result of the flip-chip process. The primary disadvantages of this method are related to the difficulty in precisely controlling the cavity length as polishing lacks the precision of epitaxy by metal organic chemical vapor deposition (MOCVD) or molecular beam epitaxy, and the necessity of obtaining a smooth surface after
polishing in order to minimize scattering losses at the cavity and dielectric DBR interface.

An alternative approach to achieving III–N VCSELs with double dielectric DBR stacks was demonstrated by Sony, who made use of epitaxial lateral overgrowth (ELOG) to overcome the drawbacks mentioned earlier pertaining to the device yield. The ELOG method has been effectively used by Sony to obtain milliwmatt class blue VCSELs.[30, 31] In this process, the SiO$_2$/SiN$_x$ bottom dielectric DBR stack is embedded in n-GaN grown by ELOG.[31] This method allows more precise cavity length control than that obtained by CMP, thus increasing the yield.

GaN is highly absorptive in the UV spectrum, and hence a tensile strained AlGaN cavity (on a GaN substrate) is needed in UV VCSELs. ELOG is easier to do with GaN than with AlGaN due a reduced lateral growth rate for AlGaN and because the AlGaN polycrystals tend to stick to the dielectric masks.[12] The advantages of using double dielectric DBRs over hybrid DBRs include higher reflectivity and wider stopbands obtained due to the increased refractive index contrast between the two dielectric materials. This leads to lower threshold currents (due to higher reflectivity), and the wider stopband improves the VCSEL’s robustness against fluctuations in material composition and thickness by ensuring that the lasing wavelength is always within the DBR’s stopband while simultaneously extending the VCSEL’s operating temperature range.

The three groups discussed earlier (Nichia, Panasonic, and Sony) all used double dielectric DBRs. Another class of VCSELs use hybrid DBRs, which means that the p-side DBR is a dielectric DBR whereas the bottom n-side AlInGaN DBR is grown epitaxially. All three types of VCSELs are shown in Figure 3. The use of epitaxial DBRs allows precise cavity length control and it reduces the complexity of the fabrication process by eliminating the laser-liftoff and/or polishing steps. However, the primary challenge in achieving indium-free epitaxial DBRs is in managing the biaxial tensile strain when AlGaN is grown on GaN. The III-nitride material is highly strained, with AlN grown on GaN experiencing tensile strain of 2.41%.[32] This makes it challenging to grow crack-free AlGaN-based DBRs with a sufficient number of pairs needed to overcome the low refractive index contrast and achieve 99% reflectivity. The only report to date of an electrically-pumped VCSEL operating CW at RT which uses an indium-free AlGaN/GaN or AlGaN/AlGaInN DBR is by Lu et al. at a wavelength of 412 nm,[33] in which the bottom DBR consisted of 29 pairs of AlN/GaN.[34] They claim that the insertion of superlattice layers every 5.5 pairs helps to suppress defect generation.

Another class of epitaxial DBRs are made of lattice-matched AlGaN/AlInN, which solves the aforementioned problems associated with the high tensile strain. These materials have high refractive index contrasts and are hence able to attain reflectivities exceeding 99%, at wavelengths extending from the UV to the visible portion of the electromagnetic spectrum by tuning the aluminum mole fraction. EPFL obtained DBRs whose reflectivity exceeded 99% at $\lambda = 340$ nm with as few as 35 pairs,[35] and a reflectivity of 99.6% at $\lambda = 424$ with 42 pairs.[36] Meijo University and Nagoya University[37] have also demonstrated blue VCSELs with a record high optical output power of 15.7 mW at 20 °C and 2.7 mW at 110 °C.[38] Using these mirrors, EPFL obtained an electrically pumped VCSEL operating at RT in pulsed mode,[39] whereas Nagoya University and Meijo University obtained a VCSEL which lased at RT under CW operation.[40] However, the growth of high-quality AlInN layers is challenging due to different optimum growth temperatures of InN and AlN, and the compositional inhomogeneity in AlInN alloys which results from the large disparity in the covalent bond lengths between the two binary compounds.[41] In our experience, the ability to grow AlInN (with more than 6% indium) also strongly depends on the geometry of the MOCVD reactor.

### 3.2.2. Why Are UV-VCSELs More Difficult than Visible VCSELs?

All the VCSELs cited previously are at visible wavelengths (406–500 nm). This is because UV light-emitters have several drawbacks over their visible (violet-green) counterparts, such as poorer conductivity in p-layers, reduced IQE of the QWs, high tensile strain of the AlGaN epitaxial layers on a GaN substrate, and higher optical losses at UV wavelengths. The activation energy for Mg (acceptor species) increases with the bandgap of $\text{Al}_x\text{Ga}_{1-x}\text{N}$.[30, 31] Visible III–N light-emitters use GaN-based cavities, which have more conductive and more transparent p-layers than the AlGaN-based cavities used in UV devices.

Visible devices’ GaN-based cavities are lattice-matched to free-standing GaN substrates or GaN templates, but growing AlGaN-based cavities on GaN leads to large tensile strain which leads to cracks and extended defects being formed on the wafer. Several groups have reported that InGaN QWs have the highest IQE for the violet-blue portion of the electromagnetic spectrum, and the Shockley–Read–Hall (SRH) recombination lifetime reduces with the reduction in the indium content in the QWs used in UV devices.[44, 45] This enables increased gain for visible LDs compared with UV LDs.

![Figure 3. Schematics of the three types of VCSELs: a) hybrid DBR VCSEL, b) flip-chip VCSEL, and c) ELOG VCSEL. Reproduced with permission.[10]](Image)

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InGaN QWs show strong violet-blue light emission despite threading dislocation densities (TDDs) exceeding $10^7 \text{cm}^{-2}$. The prevailing explanation for this observation is indium fluctuations in the QW, which generates localized excitons in regions with higher indium, thus preventing those bound carriers from recombining nonradiatively at a defect site.\textsuperscript{46–48} As the indium content reduces for UV light emitters, so does the potential barrier height due to reduced indium fluctuations, leading to increased nonradiative recombination at defects due to an increase in the effective diffusion length of bound carriers in the plane of QW. However, this theory for indium segregation increasing the IQE has no conclusive supporting evidence at present.

Finally, materials commonly used in visible VCSELs are far more optically absorptive at $\lambda = 370$ nm than at $\lambda = 420$ nm. Typically, the difference between the QNR material’s bandgap and the photon energy $h\nu$ is smaller for UV devices than for visible-light emitters. This is because the aluminum mole fraction is limited by the critical thickness of AlGaN grown on GaN. The absorption loss in ITO (hole CSL in GaN VCSELs) approximately doubles from 2900 to 5800 cm$^{-1}$ as the wavelength reduces from 410 to 370 nm, as seen in \textbf{Figure 4}.\textsuperscript{49,50}

However, despite these drawbacks, UV edge-emitting LDs have been demonstrated by PARC,\textsuperscript{51,52} Nichia,\textsuperscript{53} and Hamamatsu.\textsuperscript{54–56} PARC got around the problem of growing a crack-free thick AlGaN cladding by using a 100 nm thick $\text{In}_{0.02}\text{Ga}_{0.98}\text{N}$ compliance layer on top of the GaN substrate/template. Hamamatsu created an AlGaN template on a GaN substrate by hetero-facet controlled epitaxial lateral overgrowth (hetero-FACELO).\textsuperscript{57–59} This relaxed AlGaN template allowed them to grow thick Al$_x$Ga$_{1-x}$N claddings with $x > 0.2$.

### 3.3. Identifying the Key Bottlenecks for the Realization of the Laser

The foregoing literature survey and review of the materials and device architectures greatly facilitate an efficient laser design process, as it helps explain why current state-of-the-art methods and design techniques have failed when applied to UV VCSELs. This line of thinking naturally leads to a partitioning of the key problems that must be overcome.

Four primary challenges have been identified, and they are: 1) insufficient reflectivity from the n-side DBR, 2) lack of conductive and transparent hole current spreading and p-contact layers, 3) electron leakage, and 4) high thermal resistance.

Greater optical loss increases the operating current, which reduces the peak output optical power and the wall-plug efficiency. Electron leakage due to asymmetry in electron and hole injection reduces the injection efficiency, and high thermal resistance limits the peak output optical power by determining the current at which thermal rollover (slope efficiency drops to zero) occurs. Each of these issues will be discussed in more detail in the next section.

#### 3.3.1. Higher Optical Loss in UV Light Emitters

A prototypical UV-VCSEL is shown in \textbf{Table 1}, with DBR reflectivities of 99.8%, and we have identified the main sources of optical loss in \textbf{Table 2}. UV-VCSELs have greater optical loss than visible VCSELs primarily due to the p++ contact layer and the ITO CSL, as shown in \textbf{Figure 4}.

Assuming 10 pairs of HfO$_2$/SiO$_2$ as the top and bottom DBRs, calculations suggest that about 40% of the loss can be attributed to the mirrors, and 50% of the total loss can be attributed to the p-contact layers (a 15 nm thick ITO CSL and a 20 nm thick p++ AlGaN cap layer). \textbf{Table 2} shows all the key contributors to the optical loss, which helps determine efficient focus for design resources.

| Layer | Material | Thickness [nm] | Layer |
|-------|----------|----------------|-------|
| Top DBR | $\text{HfO}_2/\text{SiO}_2$ | 10× 42/63 | Top DBR |
| Spacer | $\text{HfO}_2$ | 32 | Spacer |
| ITO | ITO | 15 | ITO |
| p++ AlGaN | Al$_{0.06}\text{Ga}_{0.94}\text{N}$ | 20 | p++ AlGaN |
| p-QNR | Al$_{1.12}\text{Ga}_{0.88}\text{N}$ | 114 | p-QNR |
| Taper | Inverse Taper Al$_{0.3}\text{Ga}_{0.7}\text{N}$-Al$_{0.68}\text{Ga}_{0.32}\text{N}$ along c-axis | 10 | Taper |
| EBL | Al$_{0.5}\text{Ga}_{0.5}\text{N}$ | 5 | EBL |
| MQW | $6\times$ Al$_{0.12}\text{Ga}_{0.88}\text{N}/5\times$ In$_{0.04}\text{Ga}_{0.96}\text{N}$ | 6/2.5 | MQW |
| n-QNR | Al$_{0.12}\text{Ga}_{0.88}\text{N}$ | 291 | n-QNR |
| Bottom DBR | $\text{HfO}_2/\text{SiO}_2$ | 10× 42/63 | Bottom DBR |

| Layer | Optical loss [cm$^{-1}$] | % of total loss | Layer |
|-------|--------------------------|----------------|-------|
| ITO | 6.1 | 10.9 | ITO |
| p++ AlGaN | 21.3 | 38.2 | p++ AlGaN |
| p-AlGaN | 5.9 | 10.6 | p-AlGaN |
| Mirrors | 22.5 | 40.3 | Mirrors |
Strategies to reduce the optical loss in the contact layers are reviewed in Section 3.4.1, where a modulation-doped short-period superlattice (MD-SPSL) has been proposed as a lateral hole CSL instead of ITO for UV-VCSELs.\cite{23,60} Alternative strategies to obtain a high reflectivity bottom DBR are discussed in Section 3.4.2, where a hybrid epitaxial and metal mirror is proposed—an epitaxial DBR to provide a reflectivity of >90% and a planar metal mirror underneath provides the remaining 90% reflectivity.\cite{15,68}

3.3.2. Electron Leakage

Electron leakage reduces the injection efficiency of the laser and leads to poor high-temperature performance (high $T_d$). Verzellesi et al. demonstrated by numerical simulation that when p-type conductivity is lower than n-type conductivity, holes are not supplied to the active region at the same rate as electrons, causing electrons to leak out of the active region and recombine nonradiatively in the p-QNR and at the anode, resulting in efficiency droop in LEDs and reduced gain in LDs; however, by making the electron and hole conductivities equal, electron leakage was reduced and efficiency droop was suppressed.\cite{60}

The problem of efficiency droop in III–N LEDs is often falsely represented as a dichotomy between either Auger recombination or electron leakage,\cite{61,62} whereas actually it is more likely that both occur simultaneously.\cite{60} Electron leakage is a natural and undeniable consequence whenever there is a large asymmetry in majority carrier conductivities in p–n diodes, as unambiguously demonstrated in three cases: 1) UV-LEDs with three different EBL barrier heights of 0, 80, and 140 meV were fabricated by Hirayama,\cite{63} and it was shown that the optical power increased by a factor of 10 and 15 for devices with 80 and 140 meV barriers, respectively, as compared to the one without an EBL. 2) Vampola et al., observed luminescence from a p-doped QW above the EBL which is indicative of electron leakage,\cite{64} and 3) an 80% degradation in the external quantum efficiency of violet LEDs grown on the c- and m-planes was observed by Lee et al. for devices without an EBL.\cite{65} Thus, regardless of the exact magnitude of the Auger coefficient, electron leakage has been experimentally proven to be severe in GaN-based light-emitting devices, and thus implementing strategies to stem the leakage can only be advantageous. Furthermore, proponents of the Auger hypothesis for droop still use EBLs in every single laser diode and almost every LED that they fabricate.

We find that the optimum EBL design strongly depends on the device’s intended operating current density, and thus we find different optimum EBL designs for LEDs, edge-emitting LDs, and VCSELs.\cite{15} Section 3.4.3 briefly describes epitaxial design techniques to stem electron leakage, and provides general guidelines on optimum EBL design for a III–N light-emitting device.

3.3.3. Thermal Resistance

The thermal resistance ultimately limits the maximum optical power output of a VCSEL due to self-heating under current injection. Self-heating degrades the laser’s performance for three reasons: 1) increased carrier leakage by thermionic emission, 2) reduction in the maximum gain due to gain-broadening by carrier–carrier and carrier–phonon scattering, and 3) increased nonradiative recombination rates. Our simulations\cite{60} only account for point (1), which is a good first-order approximation as that is the largest contributor to gain reduction at high temperatures.\cite{66,67}

Section 3.4.4 compares the thermal performance of the most common VCSEL architectures (Figure 3), identifies the key geometrical parameters affecting the thermal resistance, and then optimum designs are suggested based on self-consistent electro-opto-thermal simulations of VCSELs for each of these three categories.

3.4. Solving the Aforementioned Key Device Design Problems

Now that the key factors holding back the development of the laser have been identified, the next step is to formulate solutions to these problems through the creative application of physical principles and numerical simulation. This section discusses solutions to the problems described in Section 3.3 for UV-VCSELs.

3.4.1. Design of Transparent Lateral Hole CSLs

As seen in Figure 3, III–N VCSELs need a lateral hole current injection scheme as the DBR is comprised of insulating dielectric materials, unlike GaAs-based VCSELs which have conductive p-DBRs. A lateral hole CSL is needed to efficiently pump the optical mode. The black curve in Figure 5 shows the radial profile of the lasing TE01 mode. To make an efficient laser, it is desirable to preferentially inject current in regions of high optical mode intensity. Various optical modes were computed, such as HE11, EH11, HE21, EH12, TE01, and TM01 modes, and we found that the TE01 mode lased first. Current crowding in the thin ITO layer makes pumping the fundamental mode (HE11) very inefficient. This is consistent with experimental results showing multi-transverse mode operation in visible wavelength VCSELs.\cite{28,30}

![Figure 5. Vertical component of the hole current density vector (left axis) for different CSLs in the p-Al$_{0.12}$Ga$_{0.88}$N QNR near the EBL at an input current of 3 mA, and the radial profile of the TE01 mode (right axis). Reproduced with permission. Copyright 2019, IEEE.](image)
Figure 5 compares the lateral current spreading performance of various CSLs in UV-VCSELs with a current channel radius of 4 μm. Thus, an effective hole CSL increases the overlap between the optical mode and the vertical hole current density.

The hole CSL should ideally be transparent at the lasing wavelength and be electrically conductive with low bulk and contact resistances. However, these two properties are usually at odds with each other because higher doping (conductivity) increases the optical loss by increasing the number of optically active defects and free carrier absorption.

For visible wavelength VCSELs, a 20–50 nm thick ITO is typically used as a CSL. However, as previously shown in Figure 4, the absorption coefficient of ITO approximately doubles from 2900 to 5800 cm\(^{-1}\) as the wavelength reduces from 410 nm (violet) to 370 nm, thus making ITO unsuitable for UV-VCSELs.

From our prior work,[16] we recommend using MD-SPSLs as lateral hole CSLs. Typically, doped material has lower mobility than undoped material due to ionized impurity scattering. Ideally, we would like the free carrier density of doped material and the carrier mobility of undoped material. Despite limitations to the abruptness of practically realizable doping profiles and the influence of remote impurity scattering, modulation doping is a step in this direction.

Modulation doping involves doping a wider bandgap material adjacent to an unintentionally doped (UID) narrow bandgap material. This offset in band edges in combination with selective doping allows for a transfer of free carriers from the doped material into the UID material. This creates laterally conductive channels in the UID material, which is good for hole current spreading in laterally-contacted VCSELs.

The SPSLs discussed here consist of 25 pairs of Mg-doped Al\(_{0.12}\)Ga\(_{0.88}\)N (2.5 nm) and UID- Al\(_{0.08}\)Ga\(_{0.92}\)N (1.5 nm). 25 pairs of this SL add up to a total thickness of 100 nm for the CSL. Figure 6 shows the L–I–V simulation data for UV-VCSELs with various types of CSLs—MD-SPSLs, bulk AlGaN, uniformly doped p-SPSL (both layers in the SL are doped), and MD-SPSLs with different hole mobilities in the UID-layer.

![Figure 6](image-url) Simulated optical power (solid lines) and voltage (dotted lines) versus current for LDs with different CSLs: MD-SPSL (red circles), uniformly doped p-SPSL (green squares), bulk AlGaN (blue triangles), and 20 nm thick ITO (magenta stars). Reproduced with permission.[16] Copyright 2018, IEEE.

Figure 5 in combination with Figure 6 tells a very interesting story. Figure 5 suggests that the ITO VCSEL has the best lateral current spreading, but Figure 6 shows much worse L–I characteristics for the ITO VCSEL compared to the MD-SPSL VCSEL. The reason for this is the high optical loss in the ITO layer. A high-performance laser requires both low optical loss and high lateral conductivity. ITO only checks one of the boxes, whereas the MD-SPSL satisfies both requirements.

A discussion on growth techniques to obtain the MD-SPSL and the performance sensitivity to the hole mobility in the narrow bandgap material, as well as the technical details of the simulation have been further described in our prior work,[16] where we also find that the performance is not very sensitive to the period of the SPSL, and the performance hit is small when the period is increased from 4 to 10 nm. Increasing the period makes the growth easier.

3.4.2. Design of a High Reflectivity Bottom UV-DBR

As mentioned earlier, obtaining a bottom mirror whose reflectivity exceeds 99.5% is the biggest obstacle to realizing GaN VCSELs, and this problem is greatly exacerbated for UV-VCSELs. A DBR is typically used in VCSELs to achieve the desired reflectivity, and it consists of multiple pairs of alternating high refractive index and low refractive index material, in which each layer is a quarter-wavelength thick. The reflections from each pair add up in phase leading to large overall reflectivities. If the refractive index contrast (Δn) between the layers is larger, then the same reflectivity can be reached with fewer DBR pairs than needed for a lower Δn DBR. The DBR with a greater Δn also has a wider stopband in the reflectivity spectrum. In other words, a high reflectivity can be obtained by either a large number of pairs for a low Δn DBR (if bulk absorption is small), or else with fewer pairs by a higher Δn. In this section, we discuss some innovative applications of known physics to solve this problem by employing judicious material choices and doping profiles to increase Δn and using the unique wideband mirror properties of silver and aluminum metals at a wavelength of 370 nm.

![Figure 7](image-url) Total modal loss (α + α_m) for the VCSEL as a function of the bottom mirror reflectivity.
Achieving a high reflectivity bottom DBR is crucial for the successful demonstration of a VCSEL, because the round-trip gain in VCSELs is lower than in edge-emitting LDs, as discussed in Section 3.2. The total modal loss nearly doubles in our prototypical VCSEL as the reflectivity drops to 99.5% from 100%, as seen in Figure 7.

**Excitonic Resonances to Increase the Refractive Index:** As mentioned in Section 3.1, the high strain between AlN and GaN limits the amount of Al we can incorporate into an AlGaN-based mirror on a GaN substrate. This places a hard limit on $\Delta n$. However, in ref. [17], we theoretically and experimentally demonstrate methods to increase $\Delta n$ without increasing the tensile strain. By correctly choosing the high-index material’s aluminum mole fraction, we can exploit the near-bandedge excitonic resonances to enhance the refractive index of the material. These excitonic resonances and their effect on the refractive index, and on the refractive index contrast with GaN and AlN are shown in Figure 8. However, we must be judicious, as large absorption losses occur near the excitonic resonances, as seen by the dotted lines in Figure 8. In ref. [17], we have found the optimum balance between the high index contrast and low loss for AlGaN compositions in DBRs with center wavelengths of 370 and 226 nm.

**Heavy Doping to Reduce the Refractive Index:** Furthermore, heavily doping a layer can reduce its refractive index by increasing the material’s plasma frequency, and due to band filling effects (Burstein–Moss effect). Recent experiments at Georgia Tech[17] reproduce the results of Perlin et al., with $n^{++}$ GaN showing an index contrast of 1.5–2% with UID-GaN.

**Use of Metal Mirrors:** Metals have a very low refractive index in certain wavelength ranges (Figure 9a), where the real part of the dielectric function is negative. Thus, the reflectivity of an AlGaN-silver interface exceeds 90% in the UV-A to the...
infrared portion of the electromagnetic spectrum, whereas aluminum is preferred for UV-C to UV-A wavelengths (180–350 nm). 

*Putting It All Together:* The three aforementioned techniques can be combined to create a hybrid epitaxial-metal mirror, as shown in Figure 10a. If it takes “x” number of pairs in the DBR to obtain 90% reflectivity, then it takes 2x to get 99%. Furthermore, we know that achieving epitaxial DBRs with 90% reflectivity is fairly straightforward,\(^\text{76–78}\) so simply depositing a metal film on the backside yields a mirror whose overall reflectivity exceeds 99%.

As the backside must be exposed to deposit the mirror, we show in Figure 10b that this mirror is very robust against fluctuations in the unpolished substrate thickness. Figure 10b shows that the reflectance spectrum is good enough for a VCSEL even if 3\(\mu\)m of material is left unpolished between the epitaxial DBR and the metal film. A negative “t” means that some of the epitaxial DBR has been removed. Removing 427 nm of the DBR is about six pairs, which only drops the reflectivity from 99.25% to 99%. Thus, it is preferable to be conservative in polishing. As “t” gets higher, there are transmission peaks in the spectrum that correspond to the second cavity formed between the reflective metal and the epitaxial DBR.

This DBR design overcomes the primary drawback of VCSELs with double dielectric DBRs—that of controlling the cavity length. In VCSEL’s of the type in Figure 3b, the yield is very poor as the polishing precision sets the cavity length, and hence the lasing wavelength. Our hybrid epitaxial-metal mirror circumvents this problem as the cavity length is instead set by the precisely controlled epitaxial DBRs and is not left up to the precision of the polish.

One might argue that the roughness of the polish may adversely influence mirror reflectivity due to diffractive losses at the metal–semiconductor interface, but Kim et al.\(^\text{75}\) show that the interface reflectivity is remarkably robust against interface roughness, as shown in Figure 9b for blue wavelengths (450 nm). Furthermore, the state-of-the-art in polishing technology shows an RMS roughness of 0.3 and 0.8 nm when polished with colloidal silica and diamond powder, respectively for a 2\(\times\)2\(\mu\)m\(^2\) atomic force microscopy (AFM) scan area.\(^\text{79}\) Hu et al.\(^\text{80}\) also demonstrate an RMS roughness of \(\approx\)0.6 nm with an AFM scan area of 2\(\times\)2\(\mu\)m\(^2\), which suggests that current polishing technology may be smooth enough for our application.

As per our experience, and the work of Hamaguchi et al.\(^\text{30}\) and Zhang et al.,\(^\text{81}\) controlling the cavity length by polishing is a far more challenging problem than obtaining a smooth polished surface. Our proposed hybrid epitaxial-metal mirror partially
3.4.3. Mitigating Electron Leakage

Section 3.3.2. describes the motivation for stemming electron leakage, which is a natural consequence of the asymmetry between the conductivities of p- and n-doped material. Simply put, electrons are supplied to the active region at faster rate than holes, so the electrons without a hole to radiatively recombine will leak out of the active region. Many cutting-edge lasers today use the same type of rectangular EBL that was used in the first electrically pumped blue laser diode in 1996,[82] which is EBL (A) in Figure 12. In this section, we will discuss the drawbacks of the conventional rectangular EBL, and find that the optimum EBL design is a function of the device’s operating current density. This suggests that the optimum EBL design for VCSELs, edge-emitting lasers, and LEDs are all fundamentally different.

We find by simulation that the optimum EBL for VCSELs is EBL (D), and we show by both experiment and simulation that EBL (C) is optimum for edge-emitting LDs, and in the latter case, the correct EBL can reduce the threshold current by as much as 54%. The reason for this massive improvement can be better explained here using the simulation and experimental data for edge-emitting LDs, and the equivalent analysis for VCSELs can be found in ref. [15].

Blue Edge-Emitting Laser Diode: Figure 13 shows that step-grading the EBL/QB interface has a significant impact on the L–I characteristics of edge-emitting LDs, with a 34% lower threshold current compared to the rectangular EBL (A). The reason for this is clearly seen in Figure 14a. The positive polarization charge at the EBL/QB interface causes the conduction band edge to dip below the quasi-Fermi level at the interface, which causes an accumulation of electrons, thus reducing the injection efficiency. The band bending exacerbates the carrier leakage over the EBL by reducing the energetic barrier for electron escape (Ec–Ev). This positive interfacial sheet charge also causes an electrostatic redistribution of bound charge carriers in the QWs due to Coulombic forces, particularly in the QW on the
When the number of bound electrons greatly exceeds the number of bound holes, the excess electrons cannot recombine radiatively, leading to a reduction in the injection efficiency and IQE. The middle and n-side QWs have much lower carrier mismatch than the p-side QW because they are screened from the sheet charge at the QB/EBL interface by the p-side QW’s bound electrons.

Furthermore, the band offsets at the p-QNR and EBL (A) interface present a barrier to hole injection by thermionic emission, and the negative sheet charge at that interface causes a pileup of holes at the interface, which electrostatically facilitates electron leakage over the EBL.

EBL (B) solves the problem originating due to the sheet charge at the EBL/QB interface by splitting up the polarization charge into three steps. This ensures that the electron quasi-Fermi energy stays below the conduction band edge, and that the last QB remains relatively flat, as seen in Figure 14b. This removal of the parasitic inversion layer leads to the tremendous reduction in threshold current, as demonstrated by simulation and experiment in Figure 13.

The problem pertaining to hole injection can be solved by EBL (C), which yields further improvement over EBL (B) by compositionally grading the p-QNR/EBL interface to remove the barrier to hole injection. Thus, EBL (C) is the optimum EBL design for edge-emitting III-N LDs.

Vertical-Cavity Surface-Emitting Lasers: EBL (B) and EBL (C) fail for VCSELs. This is because there is a big difference between the hole current injection profile for edge-emitting LDs and VCSELs. As previously shown in Figure 5, VCSELs suffer from severe current crowding at the edge of the current aperture, so only the edge of the optical mode is pumped. This causes very high peak current densities near the aperture, often above 10 kA cm$^{-2}$ at threshold. At this increased current density, $E_C$ is pushed above $E_B$ near the EBL/QB interface, and this leads to the formation of parasitic inversion layers, in both abrupt and step-graded EBLs in the case of VCSELs.

Edge-emitting LDs, in contrast, have very uniform current profiles, and hence much lower peak threshold current densities. For example, an input current of 4 mA corresponds to a uniform current density of 7.95 kA cm$^{-2}$ across an 8 μm aperture. However, in our VCSEL simulation, the current density at 4 mA is 13 kA cm$^{-2}$ just 0.5 μm away from the aperture edge! Thus, the improvement obtained with a step-graded EBL in edge-emitting LDs does not translate to VCSELs due the latter’s nonuniform vertical hole current density profile.

Thus, we cannot solve the problem of the inversion layer at the QB/EBL interface for VCSELs but grading the p-QNR/EBL interface is always beneficial, and hence EBL (D) is optimum for VCSELs. These results and the underlying theory are discussed in more detail in our article on the theory of EBL design.¹⁵

3.4.4. Thermal Design of III–N VCSELs

This section demonstrates the correct way to use numerical simulation in device design. When there are so many key
parameters in the device design space, there are many permutations of simulation parameters which may be adjusted to “match” experimental data. Searching for such permutations is not a good use of the designer’s time, and any “results” so obtained ultimately inspire no confidence among those familiar with physics-based numerical simulation. Instead, it is desirable to work with one set of best possible simulation parameters in the pursuit of predicting trends and isolating the key design variables. The more complex the simulation, as this one (coupled electro-opto-thermal), the more unknowns and unreported parameters there are, such as diameters of various layers, heatsink material, interfacial thermal resistances, etc. Also, several studies suggest that the thermal conductivity of GaN depends on the growth conditions and defect concentrations, with values ranging from 130 to 220 W/(m K)\(^{-1}\) [86] a range of over 40%!

Thus, simulation should instead be used to gain physical insight and get ballpark estimates which can then be verified by experiment, instead of being overly concerned with perfectly matching experimental data. Consensus values for key parameters can be used.

As shown in Figure 3, there are three primary VCSEL architectures, and in ref. [10], we found the key geometric variables affecting each of these VCSEL types. This allowed us to identify the optimum VCSEL design for hybrid VCSELs, flip-chip VCSELs and ELOG VCSELs from a thermal point of view. In this section, we shall discuss only the thermal design of ELOG VCSELs, and would refer the reader to ref. [10] for a more detailed thermal analysis of all three types of VCSELs.

This VCSEL design (ELOG) is best demonstrated by Sony [30,31]. Reducing the radius of the dielectric DBR to improve the thermal resistance is obvious, and hence will not be discussed. The n-side DBR’s diameter is fixed at 10 μm. In this section, the effect of the cavity length and the device (III–V mesa) diameter will be studied. The design splits are shown in Table 3, and the L–I–T data in Figure 16.

It is readily apparent from Figure 16 and Table 3 that the diameter of the overgrown n-GaN makes the largest difference in the overall thermal resistance (ELOG-A versus ELOG-C), followed by the cavity length (ELOG-B, ELOG-C, and ELOG-D). Increasing the cavity length from 0.37 to 3 μm led to a reduction in the thermal resistance by about 27%, and changing the n-GaN diameter from 20 to 30 μm reduced the thermal resistance at threshold by 47%. The right axis of Figure 16a shows the maximum temperature in the active region.

There are a couple of features in Figure 16 that are worth noting: 1) there is a kink in the \( R_{\text{thermal}} \) versus \( I \) plot at threshold, and 2) \( R_{\text{thermal}} \) monotonically increases with injection current.

**Table 3.** Device descriptions and thermal resistance of the various ELOG VCSELs. Reproduced with permission [10].

| VCSEL ID | Cavity length [μm] | n-GaN QNR diameter [μm] | Thermal resistance at threshold [K W\(^{-1}\)] |
|----------|-------------------|------------------------|-----------------------------------------------|
| ELOG-A   | 1.8               | 20                     | 705                                           |
| ELOG-B   | 0.37              | 30                     | 453                                           |
| ELOG-C   | 1.8               | 30                     | 371                                           |
| ELOG-D   | 3                 | 30                     | 330                                           |

The kink appears because of the abrupt increase in the rate of stimulated recombination at threshold once the nonradiative recombination rates are relatively pinned.

\( R_{\text{thermal}} \) is the temperature rise per Watt of input electrical power and it monotonically increases with injection current. At low current densities, a larger fraction of the current is converted to light, which suppresses carrier leakage. This improves the injection efficiency.

As the current density increases, the electron quasi-Fermi energy shifts upward with respect to the conduction band edge, leading to enhanced electron leakage, which in turn results in increased nonradiative recombination and the emission of phonons (heat). Thus, now a smaller fraction of the injected carriers recombine radiatively, causing a greater fraction (than the previous low-\( J \) case) of carriers to recombine by SRH processes. This manifests as a higher thermal resistance at higher input current densities.

Also, the high series resistance of the p-QNR leads to a significant potential drop across the “QNR” (which may in fact may no longer be strictly quasi-neutral), leading to Joule heating. Thus, the temperature in the active and p-doped layers increases due to SRH recombination and Joule heating, which causes thermal runaway (indicated by high dT/dI in Figure 16b).
4. Conclusion

In this article, we have gone through the series of steps involved in designing a laser diode and provided examples on how to effectively use numerical simulation in the design process (simulation-aided design). Understanding the material system (Section 3.1) places hard bounds on the design space (such as doping concentration, polarization charge, optical loss, etc.) and provides clues as to what the main challenges could be. Section 3.2 then reviews the literature for related devices (visible VCSELs) to understand why currently known techniques would not work for this specific problem (UV VCSELs), such as unique problems with AlGaN ELOG, higher strain due to the AlGaN cavity, higher optical loss in ITO, lower IQE QWs at UV wavelengths, and poorer electrical and thermal conductivity of AlGaN alloys compared to GaN.

Once the background is understood, the key bottlenecks for the development of the laser have been identified in Section 3.3. The key contributors to the overall optical loss were identified (hole CSL and the bottom mirror) and roughly quantified, problems with electron leakage and thermal resistance were identified due to the asymmetry between the conductivities of p- and n-doped material, and the poor thermal conductivity of a dielectric or AlInN-based bottom DBR, respectively. The nonuniform current density and small device dimensions exacerbate the thermal issues.

Finally, Section 3.4 discussed solutions to the aforementioned problems using technology that is available today. An AlGaN-based MD-SPSL was proposed as a transparent hole CSL, and it had superior performance to ITO at UV-wavelengths. A novel hybrid epitaxial-metal bottom mirror was proposed to reduce the strain and the thermal resistance of the DBR, and to decouple the cavity length (lasing wavelength) from the polishing precision during substrate removal.

Then, the underlying physics behind electron leakage was briefly discussed, and we found through experiment and simulation that the optimum EBL design is a strong function of the device’s peak operating current density as it determines the location of the electron quasi-Fermi energy relative to the band edge. Edge-emitting LDs and VCSELs were found to have different optimum EBL designs. Finally, the key geometric parameters influencing the VCSEL’s thermal resistance were identified by self-consistent electro-opto-thermal numerical simulations.

It is also worth noting that each of these problems was tackled by different simulation techniques. The CSL and EBL design was done with only electro-opto VCSEL simulations as we were only interested in the device’s performance near threshold, before self-heating becomes significant. However, the thermal analysis required self-heating to be accounted for, as we were interested in the VCSEL’s maximum power (near roll-over), and hence electro-opto-thermal simulations were needed. The design of bottom hybrid metal-AlGaN DBR used a 1D-TMM solver with complex impedances to simulate the reflectivity spectra of DBRs comprising of lossy materials.

The objective of this article is to provide a general framework with which to approach a laser design problem.

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Conflicts of Interest

The authors declare no conflict of interest.

Keywords

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[1] I. Vurgaftman, J. R. Meyer, Nitride Semiconductor Devices: Principles and Simulation, Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim, Germany 2007, pp. 13–48.
[2] F. Bernardini, V. Fiorentini, Phys. Status Solidi A 2002, 190, 65.
[3] D. Holec, Y. Zhang, D. V. S. Rao, M. J. Kappers, C. McAleese, C. J. Humphreys, J. Appl. Phys. 2008, 104, 123514.
[4] S. J. Rosner, E. C. Carr, M. J. Ludowise, G. Girolami, H. I. Erikson, Appl. Phys. Lett. 1997, 70, 420.
[5] S. Tomiya, T. Hino, S. Goto, M. Takeya, M. Ikeda, IEEE J. Sel. Top. Quantum Electron. 2004, 10, 1277.
[6] J. Piprek, IEEE J. Quantum Electron. 2017, 53, 1.
[7] Y. Liu, K. D. Choquette, K. Hess, Appl. Phys. Lett. 2003, 83, 4104.
[8] K. Mehta, Ph.D. Thesis, Georgia Institute of Technology (Atlanta) 2019.
[9] M. Gruppen, K. Hess, IEEE J. Quantum Electron. 1998, 34, 120.
[10] K. Mehta, Y.-S. Liu, J. Wang, H. Jeong, T. Tetchprohm, R. D. Dupuis, P. D. Yoder, IEEE J. Quantum Electron. 2019, 55, 1.
[11] C.-K. Li, M. Piccardo, L.-S. Lu, S. Mayboroda, L. Martinelli, J. Peretti, J. S. Speck, C. Weisbuch, M. Filoche, Y.-R. Wu, Phys. Rev. B 2017, 95, 144206.
[12] L.-H. Peng, C.-W. Chuang, L.-H. Lou, Appl. Phys. Lett. 1999, 74, 795.
[13] A. Venkatachalam, B. Klein, J. H. Ryou, S. C. Shen, R. D. Dupuis, P. D. Yoder, IEEE J. Quantum Electron. 2010, 46, 238.
[14] H. Zhao, R. A. Arif, Y. K. Ee, N. Tansu, IEEE J. Quantum Electron. 2009, 45, 66.
[15] K. Mehta, Y.-S. Liu, J. Wang, H. Jeong, T. Tetchprohm, Y. J. Park, S. R. Alugubelli, S. Wang, F. A. Ponce, S.-C. Shen, R. D. Dupuis, P. D. Yoder, IEEE J. Quantum Electron. 2018, 54(6), 1.
[16] K. Mehta, Y.-S. Liu, J. Wang, H. Jeong, T. Tetchprohm, Y. J. Park, S. R. Alugubelli, S. Wang, F. A. Ponce, S.-C. Shen, R. D. Dupuis, P. D. Yoder, IEEE J. Quantum Electron. 2018, 54(4), 1.
[17] K. Mehta, T. Tetchprohm, Y. J. Park, Y.-S. Liu, O. Moreno, S. R. Alugubelli, S. Wang, F. A. Ponce, S.-C. Shen, R. D. Dupuis, P. D. Yoder, IEEE J. Quantum Electron. 2017, 53(6), 1.
[18] J.-H. Ryou, P. D. Yoder, J. Liu, Z. Lochner, H. Kim, S. Choi, H. J. Kim, R. D. Dupuis, IEEE J. Sel. Top. Quantum Electron 2009, 15, 1080.
[19] K. KumaKura, T. Makimoto, N. Kobayashi, J. Appl. Phys. 2003, 93, 3370.
[20] M. Imura, N. Kato, N. Okada, K. Balakrishnan, M. Iwaya, S. Kamiyama, H. Amano, I. Akasaki, T. Noro, T. Takagi, A. Bandoh, Phys. Status Solidi Curr. Top. Solid State Phys. 2007, 4, 2502.
[21] J. Piprek, H. Wenzel, M. Kneissl, Proc. SPIE 2007, 6766, 67660H.
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