
Analysis of Efficiency Optimization for InGaN-based Blue Light-Emitting Diode**Phyu Sin Zaw¹, Tin Tin Hla²**phyusinzaw@gmail.com¹, tintinhla99@gmail.com²^{1,2} Department of Electronic Engineering, Mandalay Technological University, Mandalay

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Abstract

Efficiency optimization of an InGaN-based blue light-emitting diode (LED) is performed by analyzing the electron blocking layer (EBL), current spreading layer (CSL), and multiple quantum well (MQW) active region. Analytical calculations and MATLAB simulations are used to evaluate the device performance. Three InGaN/GaN quantum wells are selected for the active region, and an internal quantum efficiency (IQE) of 76% is obtained. The optimized EBL provides an efficiency of 96.57%, while the optimized CSL achieves 99.9962%. The overall LED efficiency is calculated from the efficiencies of the MQW, EBL, and CSL, giving an optimized value of approximately 73.39%. Based on the calculated results, the optimized EBL effectively suppresses electron leakage and improves carrier confinement. The optimized CSL also enhances current spreading, leading to better radiative recombination in the MQW region. The obtained results confirm that the proposed structural optimization improves the efficiency and performance of InGaN-based blue LEDs for solid-state lighting, display technology, and optical communication applications.

A. Introduction

The development of modern solid-state lighting and display technologies has been profoundly shaped by the evolution of wide-bandgap III-nitride semiconductors. Among these materials, Indium Gallium Nitride (InGaN) has emerged as the definitive material system for high-performance visible-light emitters. By adjusting the indium composition within the alloy, the direct energy bandgap can be continuously tuned to cover the entire near-infrared to near-ultraviolet spectrum. This unique physical property makes Indium Gallium Nitride the ideal candidate for fabricating highly efficient blue light-emitting diodes.

Blue light-emitting diodes serve as the essential pump source for phosphor-converted white solid-state lighting, which has replaced inefficient conventional incandescent and fluorescent lamps worldwide. Furthermore, they act as the primary blue light source in high-resolution micro-display technologies and backlighting systems. Despite their widespread commercial success, these devices continue to face physical limitations when operated at high injection currents, where their quantum efficiency progressively declines. Addressing these limitations is crucial for the development of the next generation of high-power optoelectronics [1].

At the microscopic level, the operational physics of an Indium Gallium Nitride-based light-emitting diode is governed by the injection, transport, and recombination of charge carriers. Under forward bias, electrons from the n-type region and holes from the p-type region are injected into the low-bandgap active region, where they become spatially confined. The fundamental goal of efficiency optimization in these structures is to maximize the rate at which these injected electrical carriers are converted into useful, escaping photons. This conversion efficiency is typically categorized into internal and external quantum efficiencies.

The primary physical bottleneck limiting high-power performance is the well-known efficiency droop. This phenomenon refers to the gradual decrease in quantum efficiency as the injection current density is increased beyond a relatively low threshold. To overcome this limitation and maximize the light output power for high-power applications, researchers must focus on engineering the device design to maintain high efficiency across a broad operating current range. This requires a deep understanding of the competing radiative and non-radiative recombination mechanisms within the active region [3].

Under low current injection, the recombination dynamics are dominated by defect-assisted non-radiative recombination, commonly known as Shockley-Read-Hall recombination. This process occurs when a carrier is captured by a deep-level defect state within the bandgap, and its energy is dissipated as heat rather than light. In III-nitride materials, these defects primarily manifest as threading dislocations resulting from the lattice mismatch between the epitaxial layers and foreign substrates. Because this defect-related loss is the dominant mechanism at low currents, the efficiency of the device is initially low [3-5].

As the injection current increases, radiative bimolecular recombination becomes the dominant pathway. This is the productive channel where electrons and holes directly recombine across the bandgap to emit photons of the desired blue wavelength. The radiative recombination rate rises rapidly with increasing carrier density, outcompeting the linear defect-related losses. Consequently, the

internal quantum efficiency of the active region climbs sharply to its peak value under moderate current injection, representing the optimal operating regime for the device[4].

However, at high current densities, a third and highly detrimental mechanism known as Auger recombination takes over. Auger recombination is a non-radiative, three-body interaction where an electron and a hole recombine, but instead of emitting a photon, they transfer their excess energy and momentum to a third carrier. This high-energy carrier eventually relaxes back to its band edge by emitting heat via lattice vibrations. Because this non-radiative process scales aggressively with carrier density, it quickly dominates the recombination dynamics at high currents, causing the efficiency curve to roll over.

To mitigate the impact of Auger recombination, background theory suggests that the local carrier density within the active region must be minimized. Since the carrier density is inversely proportional to the active region volume, expanding the physical thickness of the active layer serves as a direct thermodynamic method to dilute the carrier concentration. By increasing the active region volume, the carrier density for any given injection current is lowered, thereby delaying the onset of the severe non-radiative processes and reducing the overall efficiency droop [5].

Despite the benefits of carrier dilution, simply increasing the thickness of an Indium Gallium Nitride active layer introduces severe physical complications due to polarization-induced electric fields. Because wurtzite nitride crystals are highly polar and suffer from lattice mismatch strain, massive spontaneous and piezoelectric polarization charges are generated across the heterojunctions. These combined polarization charges yield intense internal electric fields pointing across the active layer, which bend the energy band profile of the quantum wells. This band bending triggers the Quantum-Confined Stark Effect, which severely deforms the carrier confinement potentials. The internal electric fields force electrons to accumulate on one side of the active layer and holes to pool on the opposite side, physically separating their wave functions. Since the radiative recombination rate is directly proportional to the spatial overlap of the electron and hole wave functions, the Quantum-Confined Stark Effect suppresses the radiative transition rate. This wave function separation ultimately leads to a longer radiative lifetime and a decrease in internal quantum efficiency[5-6].

Therefore, optimizing the thickness of the active region is a delicate balancing act. The active layer must be thick enough to dilute the carrier density and suppress Auger-induced efficiency droop, yet thin enough to prevent severe wave function separation caused by the Quantum-Confined Stark Effect. To explore these competing physical mechanisms and achieve high performance, this study presents a systematic efficiency optimization for an Indium Gallium Nitride-based blue light-emitting diode with a carefully calibrated active zone thickness [9].

B. Research Method

The proposed InGaN/GaN blue light-emitting diode (LED) consists of a multilayer heterostructure grown on a sapphire substrate. The device structure includes a GaN buffer layer, an n-type GaN layer, a three-period InGaN/GaN multiple quantum well (MQW) active region, a p-type AlGaN electron blocking layer (EBL), a p-type GaN layer, and a transparent current spreading layer (CSL).

The MQW active region comprises three InGaN quantum wells with a well thickness of 3 nm separated by 8 nm GaN barrier layers. The EBL thickness is optimized to 14 nm to suppress electron overflow while maintaining efficient hole injection. The current spreading layer is designed to improve lateral current distribution and reduce current crowding.

Figure 1 shows the proposed device architecture which consists of a sequence of epitaxial layers grown on a Sapphire substrate template. The bottom buffer layer deposited on the Sapphire substrate serves to accommodate the substantial lattice mismatch, reducing the threading dislocation density in the active layers. Above this, the n-type Gallium Nitride layer, doped with Silicon, acts as the electron injection and lateral transport channel. Directly above the n-type layer lies the optimized active region, designed with a total accumulated thickness of exactly thirty-nine nanometers. This specific thickness is engineered to strike the perfect balance between carrier dilution and wave function overlap under typical operating conditions.

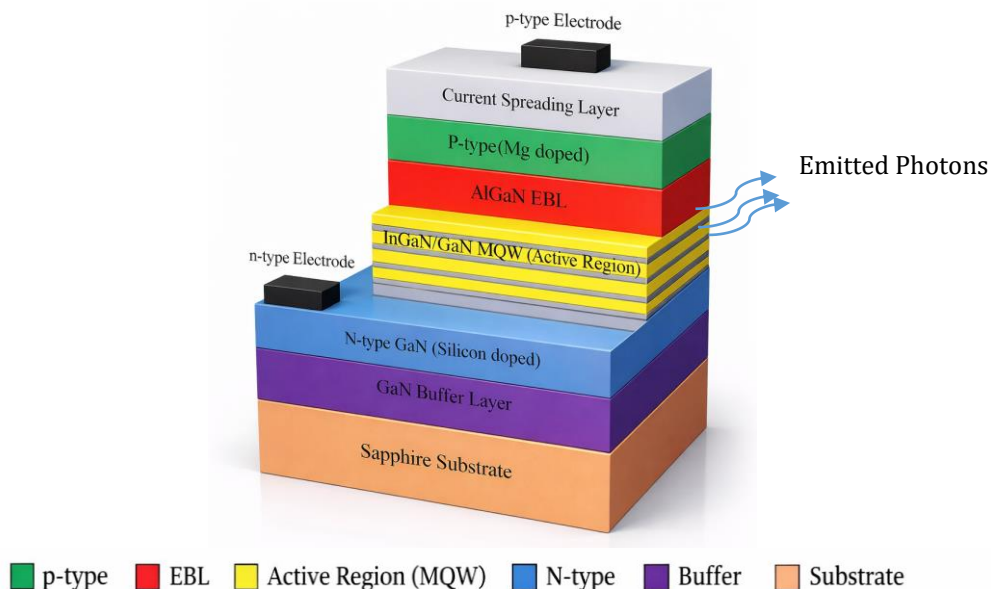


Figure1. Propoese Device Strucuture for InGaN/GaN Blue LED

Immediately following the active region is the Aluminum Gallium Nitride electron blocking layer and the p-type Gallium Nitride layer. Due to the asymmetry in carrier transport properties—where electrons possess a much higher mobility and lower effective mass than holes—electrons easily overshoot the active region. The electron blocking layer introduces a high conduction band barrier that effectively blocks these escaping electrons, redirecting them back into the active wells to undergo radiative transition, while the p-type layer provides the necessary hole injection. To address lateral current crowding, a transparent current spreading layer is deposited on top of the p-type layer, ensuring that the injected current spreads uniformly across the entire active area of the chip. This completed heterostructure is evaluated alongside a highly competitive light extraction efficiency.

Although many studies have investigated the performance of InGaN/GaN blue LEDs by optimizing individual parameters such as the electron blocking layer, current spreading layer, or multiple quantum wells, few studies have evaluated the combined contribution of these three key structures using a unified analytical model. Moreover, limited work has been reported on quantitatively estimating the overall efficiency by integrating CSL efficiency, EBL efficiency, and IQE into a single optimization framework. Therefore, this work proposes a comprehensive analytical approach to investigate the combined influence of these structural parameters on the overall efficiency of InGaN-based blue LEDs.

B.1. Materials and Simulation Parameters

To optimize an InGaN-based blue LED to achieve high performance, the physical mechanisms of the current spreading layer (CSL), the electron blocking layer (EBL), and the internal quantum efficiency (IQE) of the active region are analyzed. Table 1 shows the dimensions of the proposed device structure.

Table 1. Dimensions of Proposed Device Structure

No	Parameter	Symbol	Value
1	Well thickness	L_w	3 nm
2	Barrier thickness	L_b	8 nm
3	Numbers of QW	N_{QW}	3
4	EBL thickness	T_{EBL}	14 nm
5	CSL thickness	T_{CSL}	100 nm
6	Wavelength	λ	470 nm
7	Temperature	T	300 K

B.2. Current Spreading Layer (CSL)

The Current Spreading Layer (CSL) is a highly conductive and optically transparent layer deposited on top of the p-type GaN (p-GaN) layer in an InGaN/GaN multiple quantum well (MQW) blue light-emitting diode (LED). Its primary function is to distribute the injected current uniformly across the entire active region before carriers enter the quantum wells. Because p-GaN has relatively high electrical resistivity and low hole mobility, current injected from the p-electrode tends to concentrate beneath the metal contact, creating current crowding. This non-uniform current distribution reduces radiative recombination, increases Joule heating, and lowers the LED's optical output and efficiency.

The CSL overcomes these limitations by providing a low-resistance lateral conduction path, allowing holes to spread evenly throughout the device and improving carrier injection into all quantum wells. The efficiency of the current spreading layer can be defined as the fraction of injected electrical current that is effectively distributed over the active region. The current spreading layer's equations of the resistivity, length, and efficiency analysis are defined as the following [4]:

$$\rho = \frac{1}{qN_A\mu_h} \quad (1)$$

$$L_s = \sqrt{\frac{t n_{\text{idea}} k T}{\rho J_0 q}} \quad (2)$$

$$\eta_{\text{CSL}} = \frac{L_s}{L_s + t} \times 100\% \quad (3)$$

where ρ is the resistivity of the current spreading layer, q is the elementary charge (1.602×10^{-19} C), N_A and μ_h are the hole concentration in the p-type GaN layer and the hole mobility in the p-type GaN layer, t is the thickness of current spreading layer, J_0 is the reverse saturation current density, n_{ideal} is the diode ideality factor ($n_{\text{ideal}} = 1.2$), k and T are the Boltzmann's constant and the room temperature, 300K.

B.3. Quantum States in Infinite and Finite InGaN Quantum Wells

The optical performance of InGaN/GaN blue light-emitting diodes (LEDs) is strongly influenced by the quantum confinement effect in the multiple quantum well (MQW) active region. The InGaN quantum wells confine electrons and holes within a nanoscale region, resulting in discrete energy levels instead of the continuous energy bands observed in bulk semiconductors. These quantized energy states enhance the overlap of electron and hole wave functions, thereby increasing the probability of radiative recombination and improving the internal quantum efficiency.

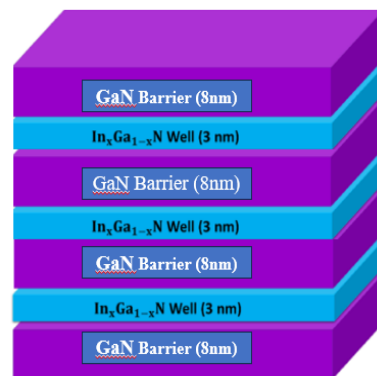


Figure 2. Three Quantum Well Structure of $\text{In}_x\text{Ga}_{1-x}\text{N}$ LED

Figure 2 shows the InGaN/GaN multiple quantum well (MQW) active region of a blue LED. The active region consists of three InGaN quantum wells (QWs) separated by four GaN barrier layers. This region plays an important role in light generation because electron-hole recombination occurs inside the InGaN quantum wells. The InGaN quantum well is the main light-emitting layer in the LED structure. Electrons and holes are confined inside the quantum wells, where they recombine and generate photons.

B.4. Infinite Quantum Well

The infinite quantum well is an ideal model in which the potential barriers surrounding the well are assumed to be infinitely high. Under this assumption,

carriers cannot penetrate the barrier layers, and the wave function is completely confined within the well.

An infinite square well is defined as [3]

$$V(x) = \begin{cases} 0 & \text{for } 0 < x < L \\ \infty & \text{otherwise} \end{cases} \quad (4)$$

where L is the width of the well. Particle cannot exist outside the well ($V = \infty$).

Each wavefunction corresponds to a quantized energy state and is given by the analytical solution,

$$\psi_n(x) = \sqrt{\frac{2}{L}} \sin\left(\frac{n\pi x}{L}\right), 0 < x < L \quad (5)$$

where $\psi(x)$ = wavefunction, $n=1,2,3,4$ is the principal quantum number.

Probability density $|\psi(x)|^2$ is critical for optical transition strength, IQE, and LED performance. Probability density can be affected by well width, indium content, and barrier thickness. The probability density is derived from the square of the normalized wavefunction,

$$|\psi_n(x)|^2 = \frac{2}{L} \sin^2\left(\frac{n\pi x}{L}\right), n=1,2,3,4,\dots \quad (6)$$

Electrons and holes are mostly confined within the InGaN wells. Probability density $|\psi(x)|^2$ has peaks at the well locations and describes where carriers reside in a QW.

B.5. Finite Quantum Well

In practical InGaN/GaN LEDs, the quantum wells are surrounded by GaN barrier layers with finite potential barriers. Consequently, electrons and holes can partially penetrate into the barrier region through quantum tunneling.

The potential profile of a finite quantum well is

$$V(x) = \begin{cases} 0 & x > a \text{ (barrier)} \\ -V_0 & x \leq a \text{ (well)} \end{cases} \quad (7)$$

where 'a' is the well width, V_0 is the well depth.

The time-independent 1D Schrödinger equation is written as the following,

$$\frac{\partial^2 \psi(x)}{\partial x^2} + \frac{2m}{\hbar^2} (E - V(x)) \psi(x) = 0 \quad (8)$$

where $\psi(x)$ is the wavefunction, E and $V(x)$ are the particle energy and potential, m is the particle mass and $\hbar$ is the reduced Planck's constant [3].

The one-dimensional time-independent Schrödinger equation is discretized using the finite-difference method. The Hamiltonian matrix is constructed in

MATLAB and solved using the eigenvalue decomposition technique to obtain the quantized energy levels and wave functions of electrons confined in the InGaN quantum wells.

B.6. Electron Blocking Layer (EBL)

The Electron Blocking Layer (EBL) is a thin p-type AlGa_N (Al_xGa_{1-x}N) layer inserted between the InGa_N/Ga_N multiple quantum well (MQW) active region and the p-GaN layer in an InGa_N/Ga_N blue light-emitting diode (LED). The primary purpose of the EBL is to prevent electrons from overflowing out of the MQW active region into the p-GaN layer while allowing holes to be injected efficiently into the quantum wells. Since electrons have much higher mobility than holes, a significant number of electrons can escape from the active region under high current injection, leading to non-radiative recombination, efficiency droop, and reduced optical output [10-15].

The EBL introduces a higher conduction band potential barrier that confines electrons inside the MQWs, thereby increasing the probability of electron-hole radiative recombination and improving the overall efficiency of the LED. Electron overflow from the active region toward the p-GaN layer is modeled as an exponential decay process governed by both Al composition and EBL thickness:

$$L_e(t, x) = e^{-\alpha x t} \quad (9)$$

where L_e is the normalized electron leakage probability, t is the EBL thickness (nm), x is the Al composition, α is an attenuation coefficient representing carrier blocking strength. This equation indicates that electron leakage decreases exponentially with increasing EBL thickness and Al content.

Hole transport efficiency due to increased potential barrier and scattering effects. This behavior is modeled as:

$$H(t) = e^{-\beta(t-t_0)^2} \quad (10)$$

where $H(t)$ is the hole injection efficiency, t_0 is the optimal EBL thickness, β is a fitting parameter representing sensitivity to thickness variation. This Gaussian-type behaviours indicates that hole injection is maximized at an optimal thickness. The effective carrier concentration in the MQW is modeled as:

$$n(t, x) \propto (1 - L_e(t, x)) \cdot H(t) \quad (11)$$

This expression indicates that carrier accumulation increases when electron leakage is suppressed and hole injection is enhanced. Substituting the leakage and hole injection terms, the final analytical expression becomes:

$$IQE(t, x) = (1 - e^{-\alpha x t}) \cdot e^{-\beta(t-t_0)^2} \quad (12)$$

This equation captures the trade-off between electron confinement and hole injection efficiency.

For the optimized InGaN/GaN blue LED structure investigated in this work, the EBL thickness of 14 nm provides the best balance between electron confinement and hole injection. At this thickness, electron leakage is significantly suppressed without introducing severe resistance to hole transport, leading to enhanced carrier accumulation inside the MQW active region, increased radiative recombination probability, higher IQE and EQE, and improved overall device efficiency. These results confirm that careful optimization of the EBL is an effective approach for mitigating efficiency droop and improving the performance of high-power InGaN/GaN blue LEDs.

B.7. Active Region Layer

The active region is the light-generating part of an InGaN/GaN blue light-emitting diode (LED). It is composed of one or more InGaN/GaN multiple quantum wells (MQWs), where electrons and holes recombine to emit blue photons with wavelengths typically between 450 and 470 nm. In a typical InGaN/GaN blue LED, the active region consists of InGaN quantum wells (QWs) separated by GaN barrier layers. The quantum wells confine electrons and holes in a very thin region (typically 2–4 nm), increasing the overlap of their wavefunctions and enhancing the probability of radiative recombination. Consequently, the active region determines the optical output power, emission wavelength, and internal quantum efficiency (IQE) of the LED. The Internal Quantum Efficiency (IQE) is the fraction of injected electron–hole pairs that recombine radiatively within the active region. It is defined as the following [7]:

The radiative recombination rate within the MQW is given by:

$$R_{rad} = Bn^2 \quad (13)$$

where B is the radiative recombination coefficient and n is the carrier concentration.

The total recombination rate including non-radiative processes is expressed using the ABC model:

$$R_{total} = An + Bn^2 + Cn^3 \quad (14)$$

where A represents Shockley–Read–Hall recombination, B represents radiative recombination, C represents Auger recombination.

$$\eta_{IQE} = \frac{R_{rad}}{R_{rad} + R_{non-rad}} = \frac{Bn^2}{An + Bn^2 + Cn^3} \quad (15)$$

where R_{rad} and R_{nonrad} are the radiative and non-radiative recombination rates, A is the Shockley–Read–Hall (SRH) non-radiative recombination coefficient (defect-

related), B is the radiative recombination coefficient, C is the Auger recombination coefficient and n is the carrier concentration.

B.8. Overall Efficiency

The overall efficiency of an InGaN/GaN blue light-emitting diode (LED) is governed by a sequence of carrier transport and optical conversion processes, including current injection, electron confinement, radiative recombination within the multiple quantum wells (MQWs), and photon extraction from the semiconductor structure. Since the performance of each process directly affects the subsequent stage, the overall efficiency of the LED can be represented as the product of the individual efficiency components. Therefore, the overall efficiency is expressed as;

$$\eta_{\text{EQE}} = \eta_{\text{CSL}} \times \eta_{\text{EBL}} \times \eta_{\text{IQE}} \times \eta_{\text{LEE}} \quad (16)$$

where η_{EBL} is the electron blocking layer efficiency, η_{CSL} is the current spreading layer efficiency, η_{IQE} is the internal quantum efficiency of the active region [9].

C. Results and Discussions

The simulation results of the InGaN/GaN blue LED structure. The electrical and optical characteristics of the current spreading layer (CSL), electron blocking layer (EBL), and MQW active region are studied using analytical models and MATLAB simulations. The dependence of device efficiency on injection current, light extraction efficiency, active region thickness, and efficiency droop behavior is investigated. The simulation outcomes clarify the role of each layer in enhancing carrier confinement, improving light generation, and achieving higher overall efficiency.

Figure 3 shows the relationship between external quantum efficiency (EQE) and injection current for the InGaN/GaN blue LED. The EQE increases rapidly at low injection current and reaches a maximum value of 57.24% at 38.5 mA. After reaching the peak value, the EQE slightly decreases with increasing current due to efficiency droop caused by carrier leakage and non-radiative recombination. The high EQE value is obtained due to effective electron confinement by the EBL, improved current spreading by the CSL, and efficient light extraction from the LED structure.

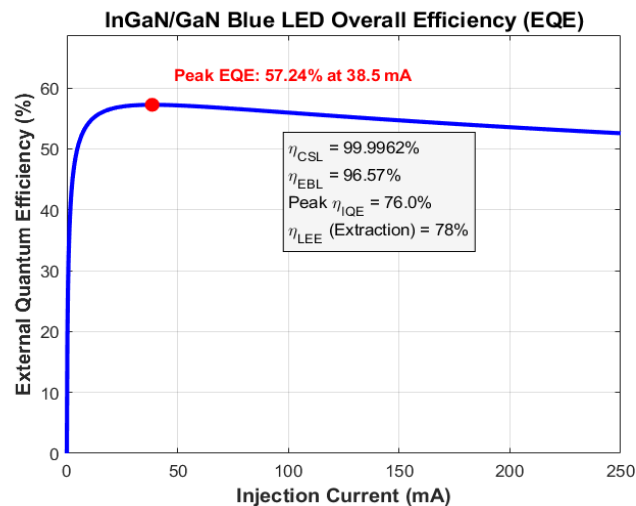


Figure 3. Overall Efficiency with Injection Current for InGaN/GaN Blue LED

The EQE of the InGaN/GaN blue LED reaches a peak value of 57.24% at 38.5 mA injection current. The high efficiency results from the optimized CSL, EBL, and MQW active region. The CSL provides efficient current distribution with an efficiency of 99.9962%, while the EBL reduces electron leakage with an efficiency of 96.57%. The IQE and LEE values are 76.0% and 78%, respectively, which improve the overall optical performance of the LED.

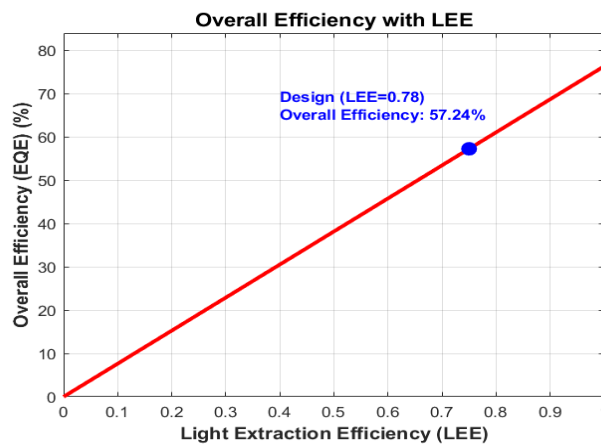


Figure 4. Overall Efficiency with Light Extraction Efficiency for InGaN/GaN Blue LED

Figure 4 illustrates the overall efficiency with light extraction efficiency for InGaN/GaN Blue LED. The optimization of Light Extraction Efficiency (LEE) serves as a critical performance multiplier in InGaN quantum well blue LEDs, directly dictating the proportion of generated photons that successfully escape the semiconductor matrix rather than being reabsorbed. As illustrated by the linear dependency characterization curve, the overall External Quantum Efficiency (EQE) exhibits a direct proportional scaling with changes in light extraction, highlighting that advancements in surface texturing, photonic crystals, or chip geometry yield immediate dividends in optical output. Within this specific design configuration, achieving a high LEE value of 0.78 (78%) successfully translates the device's

internal radiative performance into a commanding overall efficiency (EQE) of 57.24%.

Figure 5 shows the efficiency performance of different layers in the InGaN/GaN blue LED structure. The current spreading layer provides a very high efficiency of 99.9962%, which helps to achieve better current distribution in the active region. The electron blocking layer reaches an efficiency of 96.57% by reducing electron leakage toward the p-side layer. The quantum well structure provides an internal quantum efficiency (IQE) of 76%, while the light extraction efficiency (LEE) is 78%. By combining these efficiency factors, the LED device achieves an overall external quantum efficiency (EQE) of 57.24%. These results indicate that the optimized layer design improves both carrier management and photon extraction performance.

The optimized AlGaN electron blocking layer effectively increases the conduction band barrier between the active region and the p-GaN layer. Consequently, electron overflow into the p-region is significantly suppressed, increasing the electron concentration inside the quantum wells. At the same time, the optimized current spreading layer distributes the injected current uniformly across the active region, reducing localized current crowding. These improvements enhance electron-hole overlap, resulting in higher radiative recombination and improved internal quantum efficiency.

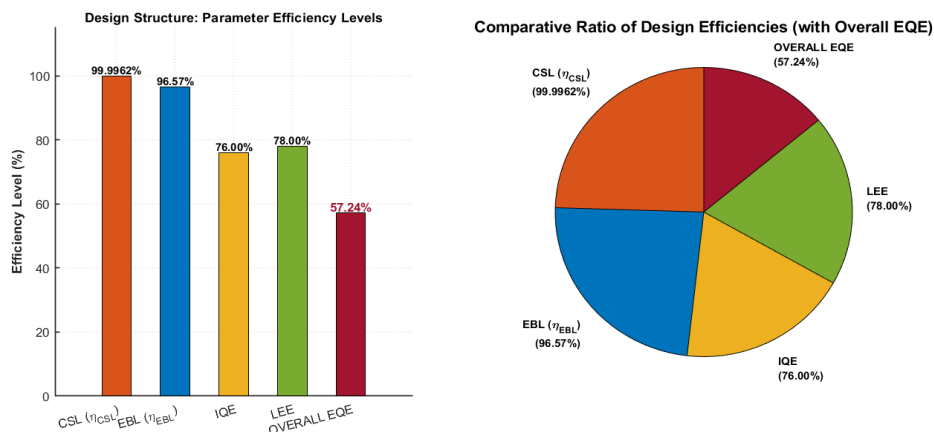


Figure 5. Comparison with Efficiencies for InGaN/GaN Blue LED

Figure 6 illustrates the efficiency droop behavior of the InGaN/GaN blue LED under high injection current conditions. The device reaches a maximum External Quantum Efficiency (EQE) of 57.24% at an injection current of 38.5 mA. When the injection current increases to 250 mA, the EQE decreases gradually due to enhanced non-radiative recombination and carrier overflow effects. However, the efficiency degradation remains limited, with an efficiency droop of only 10.21% at the highest operating current. Consequently, the EQE value remains above 51% even at 250 mA injection current. The optimized quantum well structure, current spreading layer, and electron blocking layer reduce carrier loss mechanisms and enhance carrier confinement within the active region, resulting in stable light emission under high current operation. The designed InGaN/GaN blue LED structure maintains improved efficiency stability, making it suitable for high-

brightness applications that require reliable performance at elevated driving currents. Efficiency droop mainly originates from electron leakage, Auger recombination, carrier delocalization, and polarization-induced electric fields. The optimized EBL suppresses electron overflow, whereas the optimized active region reduces carrier density inside each quantum well. Consequently, Auger recombination is reduced, resulting in a drop of only 10.21%, which is significantly lower than conventional blue LEDs operating under similar injection conditions.

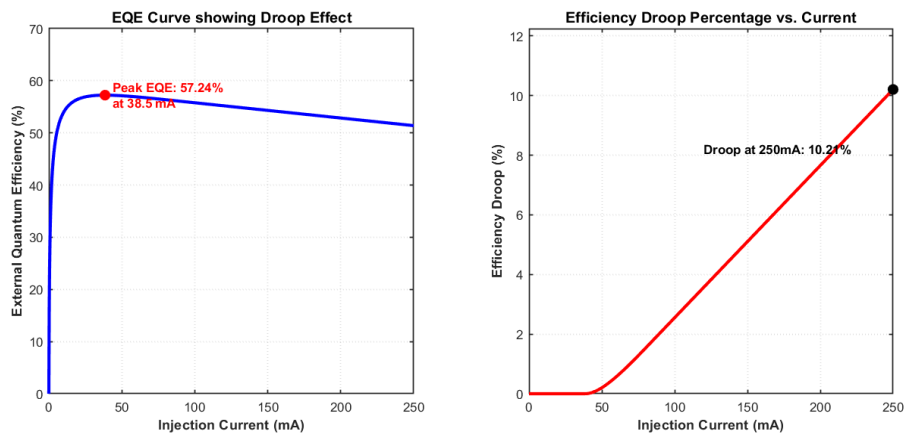


Figure 6. Efficiency Droop Effect for InGaN/GaN Blue LED

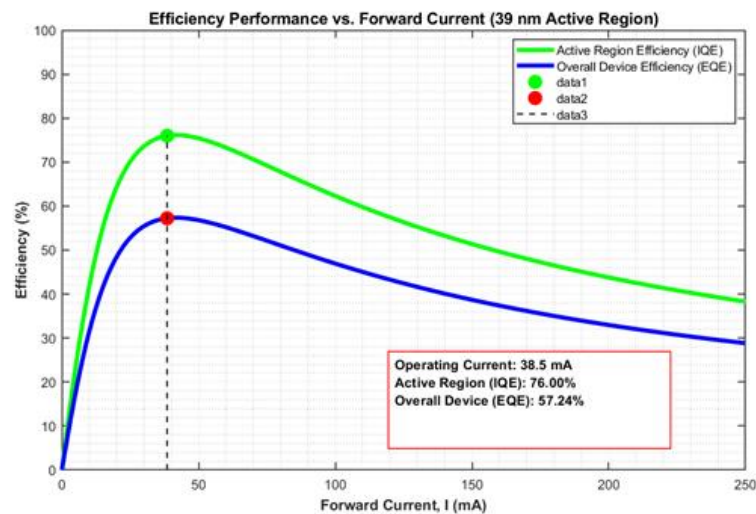


Figure 7. Efficiency Performance for InGaN/GaN Blue LED

Figure 7 shows the efficiency performance as a function of injection current for the InGaN/GaN blue LED with a 41 nm active region thickness. The optimized active region thickness maintains a balance among carrier confinement, carrier capture, and carrier distribution within the quantum wells. At an injection current of 38.5 mA, the active region reaches a peak internal quantum efficiency (η_{IQE}) of 76%, resulting in an overall External Quantum Efficiency (η_{EQE}) of 57.24%. The 41 nm active region thickness suppresses carrier overflow and reduces the effect of polarization-induced spatial separation in the quantum wells. The enhanced electron-hole wave function overlap increases radiative recombination efficiency

within the active region and maintains stable device efficiency under high injection current conditions.

D. Conclusion

In conclusion, the research is optimized the efficiency performance of InGaN-based blue LEDs by improving the active region structure. The thickness and volume of the active layer were adjusted to obtain better carrier distribution and stronger carrier confinement. The optimized structure reduced electron overflow and improved carrier recombination in the quantum wells. It also helped to reduce non-radiative recombination processes, such as Shockley–Read–Hall (SRH) and Auger recombination, which are major causes of efficiency droop at high current injection. Simulation results showed that the optimized InGaN/GaN LED structure achieved a peak internal quantum efficiency (η_{IQE}) of 76% and a maximum external quantum efficiency (η_{EQE}) of 57.24% at an injection current of 38.5 mA. The improvement in efficiency was mainly attributed to enhanced carrier injection, effective carrier confinement, and increased radiative recombination within the active region. The results explain the relationship between carrier transport and efficiency loss in InGaN-based blue LEDs. The optimized active region structure can be used to improve LED efficiency and reliability for high-power lighting, micro-LEDs, and display applications.

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