Theoretical Study of the Efficiency Loss in GaN-based Light Emitting Diodes

Hassan Absalan
Department of Physics, Ahar Branch, Islamic Azad University, Ahar, Iran
Email: absalanh@gmail.com

Receive Date: 04 February 2025 Revise Date: 07 February 2025 Accept Date: 22 May 2025

Abstract

In this paper, the efficiency loss in GaN-based light emitting diodes (LEDs) has been studied theoretically. In a LED, as the junction temperature increases, the wavelength of the emission peak shifts. GaN-based LEDs exhibit piezoelectric (PZ) behavior. In InGaN blue/green LEDs, with increasing applied current, a shift to the blue region is observed due to the Quantum Confined Stark Effect (QCSE) caused by PZ fields. At low current density, the efficiency of InGaN/GaN multiple quantum well (MQW) LEDs has the highest value and decreases rapidly with increasing current.

Keywords: light emitting diode, efficiency loss, piezoelectric, blue shift

1. Introduction

Light emitting diodes (LEDs) are p-n junctions that operate based on spontaneous (SP) emission and emit incoherent light at different wavelengths. This radiation can be in the ultraviolet, visible, or infrared regions of the electromagnetic spectrum. LED is a time-incoherent light source that has characteristics such as large form factors and poor coupling efficiency with other optical elements. These diodes are widely used in computers and digital screens. Infrared types of these diodes are used in optical fiber communications.

In a pure semiconductor at a temperature of zero degrees Kelvin, the valence band is initially completely full and the conduction band is completely empty. By irradiating photons, electron-hole pairs are produced in the material. Electrons occupy the distance between the lowest points of the conduction band to level ε_{fn}, and the same number of holes occupy the distance between the valence band to level ε_{fp}. When optical excitation falls on a semiconductor, ε_{fn} and ε_{fp} which are quasi-Fermi levels for holes and electrons appear. In this case, photons with energy greater than ε_g cannot be absorbed. However, such photons can create induced transitions from conduction band-filled states to valence band-empty states. The total SP emission rate per unit volume for transition energy and the optical gain can be calculated [1].

A material that contains atoms in excited states can emit radiation (light) when electrons move from higher energy levels to lower ones. This process usually occurs randomly and is considered SP emission. The emitted radiation is incoherent and can travel in all directions. The energy of the photon depends on the energy band gap between the excited and ground states. This process can also occur inductively (induced emission). This process occurs when a photon causes an electron to transition to a lower state. During this process, another photon is emitted. The two photons have the same phase, frequency, and direction.

2. Characteristics of LEDs

The spectral linewidth of a LED at half maximum intensity (full width at half maximum, FWHM) for a sample operating in the wavelength range of 0.8–0.9 μm and at room temperature is typically between 25 and 40 nm. For materials with smaller band gaps operating in the wavelength range of 1.1–1.7 μm, the linewidth increases to 50–100 nm [2]. As the temperature increases, the output spectra broaden, due to the greater energy spread in the carrier energy distribution. An increase in junction temperature also affects the wavelength of the emission peak and shifts it. Therefore, it may be necessary to use heat sinks in LEDs. These sinks prevent them from heating up due to their high thermal conductivity.

Although researchers are working hard to improve the characteristics of LEDs, their high performance is limited by some issues such as low internal quantum efficiency, low output power, poor cavity injection efficiency, high electron leakage, inefficient radiative recombination, and high dislocations density [3]. Furthermore, when the current injection is high, a drop in efficiency is observed [4]. There are some theories to solve such problems, such as using a hole injection layer to improve the light output power [5], Employing an electron blocking layer [6] to obtain higher densities of electrons and holes in multiple quantum wells (MQWs) and using a composite barrier to reduce lattice mismatch, increasing carrier density, and producing uniform redistribution of carriers [7]. Some specific modifications and theories have been proposed for the structures of the LED. For example, Yang et al. have developed a superlattice hole reservior that further enhances the carrier recombination rate, thereby increasing the luminescence efficiency in an AlGaN-based ultraviolet LED [8]. Sirkeli et al. have stated that InGaN/GaN LEDs with doped GaN quantum barrier can effectively enhance the optical performance due to improve of hole injection and electron confinement, piezoelectric (PZ) field screening, and reduction of the quantum confined stark effect (QCSE) [9]. Li et al. designed a special n-type and p-type doped barrier in LEDs to increase the optical output power by changing the electric field in the active region, which causes more electron confinement and increases the hole injection efficiency [10]. Zhang et al. have studied the enhancement of electron-hole spatial overlap in quantum wells (QWs) in AlGaN ultraviolet LEDs with double electron blocking layers [11].

Various non-radiative recombination processes that considered in the active region of a LED QW include Shockley-Read-Hall (SRH) recombination in active QWs, recombination of overflowed electrons in the p-type cladding layer, electron tunneling through defects from the active wells to the p-type layer, and Auger recombination [12]. The efficiency loss occurs only when as the current increases non-radiative recombination processes occur faster than radiative recombination processes.

3. GaN-based LEDs

The optoelectronics industry has been largely dominated by GaAs-based devices, which emit in the infrared region, as well as the use of AlGaAs alloys, which emit in the red region. The compounds GaP, AlP, and AlAs all have an indirect band gap. In an indirect band gap, the minimum of conduction band and the maximum of valence band occur at different points in the reciprocal space, and therefore, during a transition, a phonon and a photon are emitted in order to conserve energy and momentum. Because this is a three-particle process, the half-life of radiative transitions is large compared to non-radiative transitions in indirect band gap structures, resulting in low radiative efficiency. Therefore, commercial devices are made from direct band gap compounds. The active region of GaN-based LEDs is made of InGaN, which can cover a wide range of wavelengths, from violet to red (Figure 1). At room temperature, the band gap wavelengths of GaN and InN are 363 and 657 nm, respectively.

Although early developments with GaN as a blue emitter were promising, but achieving p-type doping was difficult. Therefore, most research in the early 1990s was based on materials such as ZnSe and SiC. Commercial SiC-based devices, due to their indirect band gap, did not have sufficient brightness and were considered as inefficient light emitters. Therefore, research on LEDs was based on ZnSe, because crystal growth was easier in terms of substrate lattice matching and growth temperature compared to GaN.

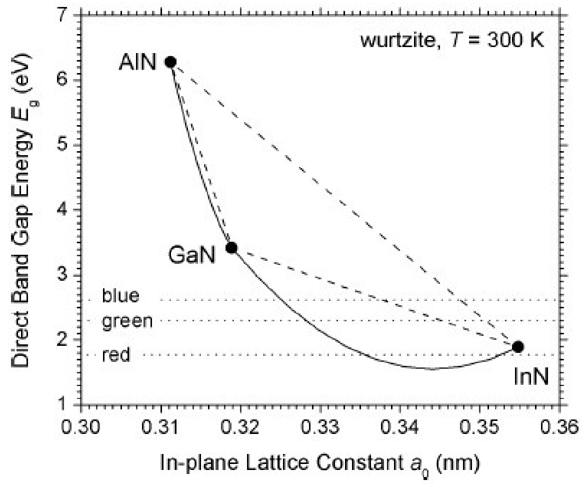

Fig.1. Band gaps and lattice constants for wurtzite nitride compounds [13].

The problem of p-type doping of GaN was solved by Amano et al. using low energy electron beam irradiation [14]. Nakamura and her colleagues at Nicha Corporation commercially manufactured blue GaN LEDs in 1993, green LEDs in 1995, and white LEDs in 1996. As a result of this company's advances, most leading lighting companies focused on GaN as a material for blue LEDs [15]. In recent years, group III nitride semiconductors have shown great potential for advancing optical technologies in a wide range of applications. Furthermore, by doping GaN with InN and AlN, the GaN-based material system has good potential for use in devices with active wavelengths from red to ultraviolet [16]. In the past ten years, GaN-based structures have been the subject of research by many researchers and the expansion of their products.

Recently, major advances in III-V nitride semiconductors have led to commercial production of high efficiency ultraviolet/blue/green LEDs. Due to the difficulty in manufacturing high performance LEDs, all of these light emitting devices use an InGaN active layer instead of a GaN active layer. InGaN LEDs with single quantum well (SQW) or MQW structures and high efficiency in the blue/red region are fabricated directly on a sapphire substrate, despite the high dislocation density resulting from the lattice mismatch between GaN and the substrate [17].

Due to low symmetry, the wurtzite system, like GaN-based materials, exhibits PZ behavior. Macroscopic polarization in materials including the active region of SQW or MQW structures increases the net electric field perpendicular to the well plane, leading to the QCSE. The electroluminescence (EL) blue shift in InGaN blue/green LEDs, accompanied by an increase in operating current, may be explained by the QCSE resulting from PZ fields generated by lattice mismatch. However, high efficiency of LEDs, along with increased strain in the structure, has been observed as soon as the amount of indium in the InGaN well layers increases [18]. This phenomenon cannot be explained only by the QCSE. Localization effects due to composition fluctuations must overcome these inherent limitations due to the PZ field. Localization due to the change in the composition of indium appears to be a major factor in the high efficiency of InGaN-based LEDs.

Figure 2(a) shows the dependence of EL on operating current in green LEDs. As the current increases, due to the band-filling effect, a shift to the blue region is observed in the substituted energy states created by changes in the indium composition in the InGaN well layer.

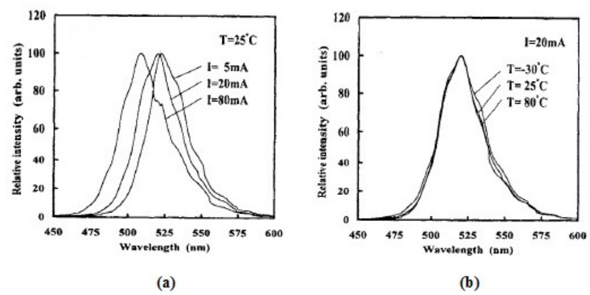

Fig.2. Dependence of (a) operating current and (b) ambient temperature of the electroluminescence of green InGaN SQW LEDs [18].

Figure 2(b) also shows the ambient temperature dependence of EL. No change in EL is observed with changing ambient temperature. This is a strange result, because the band gap energy of semiconductor materials should become smaller as temperature increases. Also, the peak wavelength of emission should become larger with increasing temperature. Blue LEDs with a peak emission wavelength of 475 nm exhibit the same EL variations as green LEDs. As the current increases, a blue shift of the peak emission wavelength is observed, while no change in EL is observed with increasing temperature. By employing the QCSE, the shift to the blue region with increasing current in Fig. 2(a) may be explained by carrier cloaking by the PZ field. Also, the constant peak wavelength of the emission with increasing temperature in Fig. 2(b) may be explained by the neutralization of the shift to the blue region due to the reduced QCSE resulting from the reduction in strain and the shift to the red region due to the narrowing of the band gap.

Under ambient conditions, GaN has a blue wurtzite structure, which is thermodynamically stable and has the lowest free energy [19]. Figure 3 shows a view of a wurtzite structure. This structure consists of two interlocking hexagonal sublattices, for example, of Ga and N atoms. In this structure, all three valence bands are strongly coupled and a combined valence band (three band model) must be considered. The three valence bands mentioned are the heavy-hole (HH), light-hole (LH), and crystal-field split-hole (CH). The spin-orbit interaction results in a slight separation at all three band edges.

One of the fundamental problems that can limit the expansion of InGaN devices is the lack of a suitable substrate material. Ideally, for growth a layer on a substrate, there should be zero percent lattice mismatch between them. This causes the crystal growth of materials to be dislocation-free. In the growth of II-VI or III-V material with narrow band gap, where GaAs is used as the substrate, the lattice mismatch is almost zero. In materials with wider band gaps, such as GaN, lattice mismatch is a significant issue. At high pressures ($2\times10^{19}\,Pa$) and high temperatures (1800°C), GaN vaporizes and disintegrates. Therefore, GaN substrates cannot be prepared by this method.

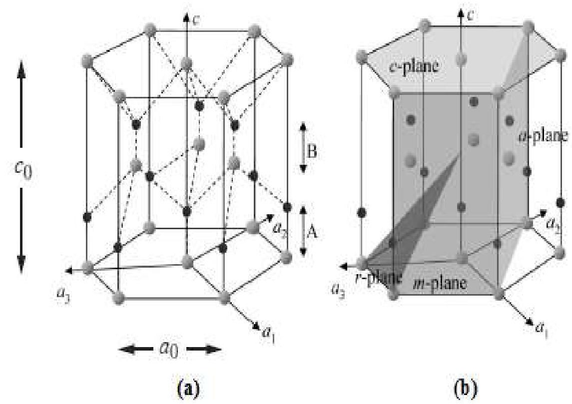

Fig.3. Wurtzite crystal structure with lattice constants c_0 and a_0 [13].

Recently, new methods have been developed using vapour phase techniques [20]. In this method, GaN crystal is grown on a substrate made of a material other than GaN. Sapphire (Al_2O_3) and SiC are two materials commonly used as substrates for III-V nitrides. These two materials have advantages such as suitable hexagonal symmetry and high temperature stability. Due to the high cost of SiC, most GaN-based LED structures are grown on sapphire substrates. Due to the 13.5% lattice mismatch between GaN and sapphire, the use of sapphire as a substrate is not completely satisfactory hence the initial GaN crystals grown on sapphire were of poor quality. The researchers solved the lattice mismatch between the substrate and GaN by placing an AlN buffer layer on the sapphire substrate before the GaN. This layer prevents crystal dislocations from affecting the active region [21] and as a result, the devices can operate effectively despite the presence of large lattice mismatches.

4. Efficiency loss in GaN-based LEDs

At low current densities (less than 10 A/cm^2), the efficiency of InGaN/GaN MQW LEDs reaches its maximum value and decreases rapidly with increasing current [22]. This phenomenon, known as efficiency loss, is a major obstacle to achieving high-power LEDs for illumination applications. Several reasons for the efficiency loss have been proposed, including non-radiative Auger recombination, electron leakage, lack of carrier delocalization, and lack of hole injection, but the origin of the efficiency loss is still under investigation. In the electron leakage state, there are three pathways for electrons to escape from QWs: thermionic emission, defect tunneling, and electron filling. It has been found that leakage due to drift at high current densities can be the main reason for the efficiency loss [23].

To further compare the effects of reducing of Auger recombination at different injection currents, the Auger recombination rate inside the active region of the $In_{0.2}Ga_{0.8}N$/GaN LED at injection currents of 30 and 480 mA is plotted in Figure 4 [24]. The reason for choosing these current values is to compare the effects of the Auger recombination rate under low and high current injection, and consequently to investigate how this mechanism affects the efficiency loss. The left part of the figure is the n-side of the device. In Figure 4, at current of 30 mA, the Auger recombination rate obtained using $3.0\times10^{-30}cm^6s^{-1}$ is much larger than the Auger recombination rate obtained using $3.0\times10^{-34}cm^6s^{-1}$. Furthermore, the highest Auger recombination rate is always observed in wells close to the p-side. Given these conditions, it is expected that a large number of carriers are located within these wells. It is found that this condition is caused by the non-uniform hole distribution inside the MQW region, leading to a larger effective hole mass and lower hole injection.

The results show that in addition to the Auger recombination effect, there are three effects that may influence the wavelength-dependent efficiency loss in InGaN/GaN LEDs [24]. The first effect is carrier localization due to lateral fluctuations in potential due to the inhomogeneous continuity of indium. Although localization effects improve the radiative efficiency by preventing the presence of carriers in non-radiative centers, the increased input current may lead to the escape of carriers from the substituted states and reduce the radiative efficiency. Furthermore, as the indium composition increases, strain effects and indium phase separation decrease the crystal quality, which it may be a reason for the efficiency loss. However, Yang et al. have shown that the crystal quality has a small effect on light emission and is not responsible for the efficiency loss behaviors in green InGaN/GaN LEDs [25]. However, experimentally indium heterogeneity has been observed in InGaN QWs and may be the source of the wavelength-dependent efficiency loss.

The second effect is that the energy band of the QW is influenced by the composition of the indium and the SP and PZ polarizations in the wells. Since the lattice mismatch between the GaN barrier and the InGaN QW increases with increasing indium content, increasing the PZ polarization leads to a tilting of the QW potential. The electric field created by these polarizations leads to the QCSE and consequently causes a decrease in the internal quantum efficiency and efficiency loss [22].

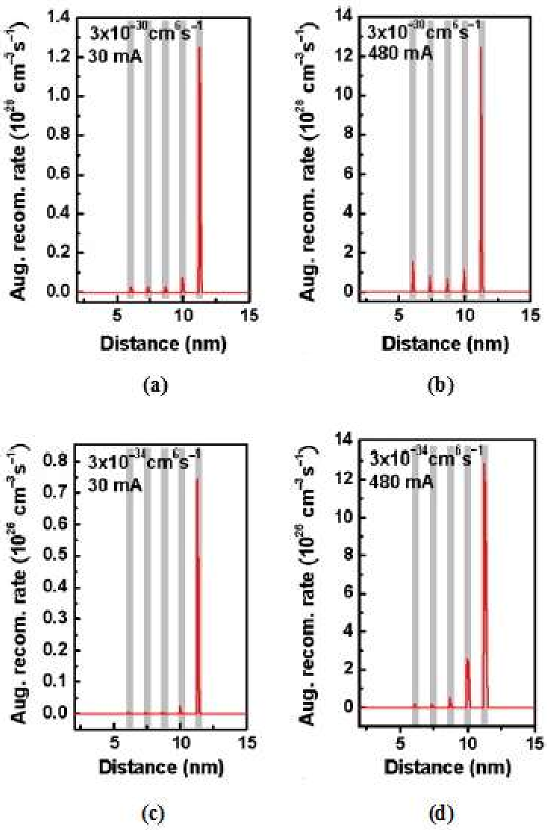

Fig.4. Auger recombination rate inside the active region of $In_{0.2}Ga_{0.8}N$/GaN LED at 30 and 480 mA [24].

The results show that PZ polarization in the wells plays a critical role in preventing of efficiency loss in GaN-based LEDs. The significant improvement in internal quantum efficiency in the InGaN/GaN SQW structure is due to the reduction of PZ polarization in the QW. Internal polarization fields can cause efficiency loss by increasing electron leakage current. It has been shown that the efficiency loss can be significantly reduced by using LED structures with low internal polarization fields, such as polarized MQW active layers or non-/semi-polar substrates [26].

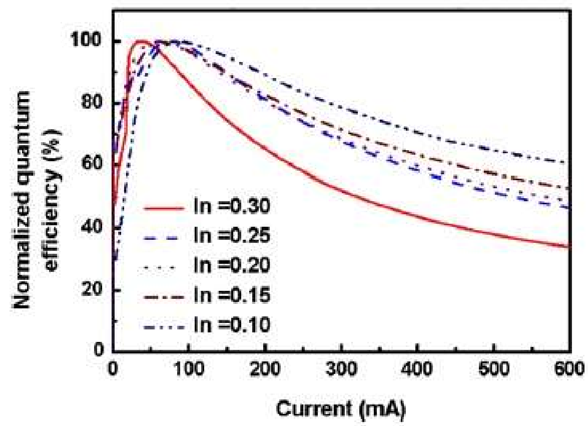

Fig.5. Normalized quantum efficiency of InGaN/GaN LEDs versus input current [24].

The third is that the Auger coefficient can depend on the indium density of the InGaN alloy. This could be more likely to cause wavelength-dependent performance degradation. However, experimental measurements of the dependence of Auger coefficients on the amount of indium have hardly been reported in the literature. Figure 5 shows the normalized quantum efficiency of InGaN/GaN LEDs with different indium compositions in the QWs as a function of input current.

5. Conclusion

In LED, as temperature increases, the width of the output spectra increases, and this is due to the greater energy width in the energy distribution of the carriers. As the current injected into the active region of

LED increases, the rate of non-radiative recombination processes becomes greater than the rate of radiative recombination processes, leading to a decrease in diode efficiency. The active region of GaN-based LEDs is made of InGaN, which covers a wide range of wavelengths. By increasing the injection current, the QCSE caused by PZ fields leads to a shift to the blue region in InGaN blue/green LEDs.

References

[1] G. P. Agrawal, and N. K. Dutta, Semiconductor Lasers, (van Nostrand Reinhold, New York, 1986).

[2] J. M. Senior, Optical Fiber Communications, Principles and Practice, (Prentice Hall, 1985).

[3] X. Wanga, H. -Q. Suna, X. Yanga, X. -Y. Yia, J. Suna, X. Zhanga, T. -Y. Liua, Zh. -Y. Guoa, and L. -Z. Zhaoa, “Performance enhancement of AlGaN-based UV-LEDs inserted with a pindoped AlGaN layer between the active region and electron-blocking layer,” Mat. Sci. Semi. Proc. 83, 133-138 (2018).

[4] T. -H. Wang, J. -L. Xu, “Advantage of InGaN-based light-emitting diodes with trapezoidal electron blocking layer,” Mater. Sci. Semicond. Process. 29, 95-101 (2015).

[5] M. Xu, Q. Zhou, H. Zhang, H. Wang, X. Zhang, “Improved efficiency of near-ultraviolet LEDs using a novel p-type AlGaN hole injection layer,” Superlattices Microstruct. 94, 25-29 (2016).

[6] Y. Li, S. C. Chen, W. Tian, Z. H. Wu, Y. Y. Fang, J. N. Dai, C. Q. Chen, “Advantages of AlGaN-Based 310-nm UV Light-Emitting Diodes With Al Content Graded AlGaN Electron Blocking Layers,” IEEE Photon. J. 5, 8200309 (2013).

[7] P. M. Tu, C. Y. Chang, S. C. Huang, C. H. Chiu, J. R. Chang, W. T. Chang, D. S. Wu, H. W. Zan, C. C. Lin, H. C. Kuo, C. P. Hsu, “Investigation of efficiency droop for InGaN-based UV light-emitting diodes with InAlGaN barrier,” Appl. Phys. Lett. 98, 211107 (2011).

[8] X. Yang, H. Q. Sun, X. C. Fan, Z. D. Zhang, J. Sun, X. Y. Yi, Z. Y. Guo, “Optimization on the luminous efficiency in AlGaN-based ultraviolet light-emitting diodes by amendment of a superlattice hole reservoir layer,” Superlattice Microstruct. 101, 293-298 (2017).

[9] V. P. Sirkeli, O. Yilmazoglu, S. Al-Daffaie, I. Oprea, D. Sheng Ong, F. Küppers, H. L. Hartnagel, “Efficiency enhancement of InGaN/GaN light-emitting diodes with pin-doped GaN quantum barrier,” J. Phys. D 50, 035108 (2017).

[10] J. Li, Z. Y. Guo, F. Z. Li, H. Lin, C. Li, S. L. Xiang, T. F. Zhou, N. Q. Wan, Y. Liu, “Performance enhancement of blue light-emitting diodes by using special designed n and p-type doped barriers,” Superlattice Microstruct. 85, 454-460 (2015).

[11] C. Zhang, H. Q. Sun, X. N. Li, X. Yang, H. Sun, X. C. Fan, Z. D. Zhang, Z. Y. Guo, “Performance improvement of AlGaN-based deep ultraviolet light-emitting diodes with double electron blocking layers”, Chin. Phys. B 25, 028501 (2016).

[12] A. B. M. H. Islam, J. -I. Shim, and D. -S. Shin, “Optoelectronic Performance Variations in InGaN/GaN Multiple-Quantum-Well Light-Emitting Diodes: Effects of Potential Fluctuation,” Materials 11, 743 (2018).

[13] J. Piprek, Semiconductor Optoelectronic Devices, Introduction to Physics and Simulation, (Elsevier Science, USA, 2003).

[14] H. Amano, M. Kito, K. Hiramatsu, and I. Akasaki, “P-type conduction in Mg-doped GaN treated with low-energy electron beam irradiation (leebi),” Jap. J. Appl. Phys. 28, 2112-2114 (1989).

[15] G. Fasol, “Room temperature blue gallium nitride laser diode,” Science 272, 1751-1752 (1996).

[16] T. Mukai, K. Takekawa, and S. Nakamura, "InGaN-Based Blue Light-Emitting Diodes Grown on Epitaxially Laterally Overgrown GaN Substrates," Jpn. J. Appl. Phys. 37, L839 (1998).

[17] S. D. Lester, F. A. Ponce, M. G. Craford, and D. A. Steigenvald, “High dislocation densities in high efficiency GaN-based light-emitting diodes,” Appl. Phys. Lett. 66, 1249 (1995).

[18] Sh. Nakamura, and Sh. F. Chichibu, Introduction to Nitride Semiconductor Blue Lasers and Light Emitting Diodes, (CRC Press, Florida, 2000).

[19] H. Morkoc, Nitride Semiconductors and Devices, (Springer Series in Materials Science, 1999).

[20] F. Habel, and M. Seyboth, “Reduction of dislocation density and dislocation analysis of MOVPE grown GaN Layers,” 10th European Workshop on MOVPE, (Lecce, Italy, 8−11 June, 2003).

[21] A. M. Fox, Optical Properties of Solids, (Oxford University Press, 2001).

[22] H. Absalan, “Comparative Study of Diodes and their Optical Performance,” journal of Artificial Intelligence in Electrical Engineering 12, 35-45 (2023).

[23] G. -B. Lin, D. Meyaard, J. Cho, E. F. Shubert, H. Shim, and C. Sone, “Analytic model for the efficiency droop in semiconductors with asymmetric carrier-transport properties based on drift-induced reduction of injection efficiency,” Appl. Phys. Lett. 100, 161106 (2012).

[24] J. -R. Chen, Y. -C. Wu, S. -C. Ling, T. -S. Ko, T.-C. Lu, H.-C. Kuo, Y.-K. Kuo, S.-C. Wang Lu, “Investigation of wavelength-dependent efficiency droop in InGaN light-emitting diodes,” Appl. Phys. B 98, 779-789 (2010).

[25] Y. Yang, X. A. Cao, C. H. Yan, “Rapid efficiency roll-off in high-quality green light-emitting diodes on freestanding GaN substrates,” Appl. Phys. Lett. 94, 041117 (2009).

[26] H. -Y. Ryu, “Effect of Internal Polarization Fields in InGaN/GaN Multiple-Quantum Wells on the Efficiency of Blue Light-Emitting Diodes,” Jpn. J. Appl. Phys. 51, 09MK03 (2012).