Enhancing Lighting Efficiency in GaN Materials: Injection Efficiency, Doping Method and Structural Optimization

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***Abstract*—This report focuses on enhancing the lighting efficiency of Gallium Nitride (GaN) based light-emitting diodes (LEDs). Key methods explored include the implementation of P-type doping and structural optimizations such as the use of electron-blocking layers and V-pit formation. The research demonstrates that these techniques significantly improve the internal quantum efficiency and light extraction efficiency of GaN LEDs. Increased magnesium (Mg) doping in the p-AlGaN electron-blocking layer is found to be particularly effective in enhancing hole-injection efficiency. The study also highlights the potential of GaN/InGaN materials in advancing LED technology, offering insights into the future of efficient and sustainable lighting solutions.**

***Keywords*—Gallium Nitride (GaN), Light-Emitting Diodes (LEDs), Lighting Efficiency, P-type Doping, Mg Doping, Hole-Injection Efficiency, carrier matching, p-AlGaN, structural optimization, Electron-Blocking Layer (EBL), V-pit Formation, Internal Quantum Efficiency, Light Extraction Efficiency**

I. INTRODUCTION

The quest for efficient and sustainable lighting solutions has led to significant advancements in semiconductor technology, particularly in the development of light-emitting diodes (LEDs). This report focuses on enhancing the lighting efficiency of Gallium Nitride (GaN) based LEDs, a technology that has shown great promise due to its high efficiency and durability. The study primarily investigates methods to optimize the performance of GaN LEDs through advanced doping techniques and structural optimizations.

In the realm of solid-state lighting, LEDs have emerged as a superior alternative to traditional lighting sources like incandescent and fluorescent lamps, owing to their higher efficiency, longer lifespan, and lower environmental impact. However, achieving optimal performance in GaN LEDs involves overcoming challenges related to carrier injection and recombination, which are critical for maximizing light output and efficiency.

This report presents a comprehensive analysis of various strategies employed to improve the efficiency of GaN LEDs. Key areas of focus include P-type doping, with a special emphasis on magnesium (Mg) doping in the p-AlGaN electron-blocking layer, and structural modifications such as the incorporation of V-pit formations. These techniques are explored in the context of their impact on internal quantum efficiency and light extraction efficiency.

The discussion also covers the evolution of lighting technology, highlighting the transition from traditional lighting systems to advanced semiconductor-based LEDs. The study delves into the early development of LEDs, examining the limitations of the initial AlGaAs/GaAs systems and the subsequent shift to GaN/InGaN materials. This transition relies on significant breakthroughs in buffer layer and p-type doping technologies, which have been important in enhancing the performance of GaN LEDs.

By addressing the key challenges in GaN LED technology and exploring innovative solutions, this report aims to contribute to the ongoing evolution of LED lighting. The findings and methodologies discussed here not only enhance our understanding of GaN-based LED performance but also pave the way for future advancements in the field of energy-efficient lighting.

II. GAN/INGAN MATERIALS FOR SOLID-STATE LIGHTING

In exploring sustainable and efficient lighting, solid-state lighting, especially LED technologies using GaN/InGaN materials, has become essential. This section starts with a historical overview of lighting, highlighting the deficiencies of traditional incandescent and fluorescent lights. Advancements in material science and manufacturing have brought solid-state, semiconductor-based lighting, particularly LEDs, to prominence. We discuss LED operating principles, their energy efficiency, environmental friendliness, and the ability to tune light color by altering the bandgap. The paper then traces LED development, initially using the AlGaAs material system and its limitations. The focus shifts to why GaN/InGaN materials are now central in LED research, with a brief review of significant advancements in GaN/InGaN technology.

A. *Evolution of Lighting Technology and Advantages of LED Lighting*

Traditional lighting technologies, such as incandescent and halogen lamps [1], were primarily based on thermal radiation sources, with conversion efficiencies capped at approximately 15%. This inefficiency, predominantly manifesting as heat, marked a substantial energy wastage. To address these inefficiencies, fluorescent lighting emerged as a gas-discharge source, offering improved efficiency rates of around 50%. However, the environmental and health hazards posed by mercury in these lamps necessitated the exploration of safer, more efficient alternatives.

With advancements in material science and fabrication techniques, LED (Light Emitting Diode) lighting has gained prominence for its energy efficiency, carbon neutrality, and longevity, and offers significant advantages both in principle and application. These devices emit light when a positive voltage causes carriers in the active region to recombine, releasing energy as photons. The color of the emitted light, determined by the semiconductor's bandgap width, can be varied by adjusting this width. This feature, along with their low power consumption and minimal carbon footprint, makes LEDs ideal for a range of uses, including home and landscape lighting, as well as display screens.

B. *Early Development in LED Lighting and Limitations of AlGaAs/GaAs Material Systems*

In 1907, H. J. Round in the United States first observed electroluminescence in SiC crystal materials. It wasn't until the 1950s that Heinrich Welker brought III-V group compound semiconductors into focus, leading to research on GaAs materials. Initially, GaAs was only suitable for producing infrared LEDs with wavelengths of 870-980nm. In 1962, Nick Holonyak, Jr. and others used GaAsP material on a GaAs substrate to develop the world's first visible red LED. In 1966, H. Rupprecht and his team developed a novel GaAs LED with a solution-regrown, silicon-doped p-n junction, resulting in a wide light-emitting region and energy below GaAs band gap at 300°K. Their LEDs, with anti-reflective coatings, achieved an external quantum efficiency of up to 6%, significantly outperforming standard Zn-doped LEDs [2]. Subsequently, visible spectrum LEDs, especially those using GaAsP and AlGaAs materials, garnered significant attention from researchers.

The initial phases of LED development centered around the AlGaAs material system. Despite its pioneering role, this system faced critical challenges, including low luminous efficiency and lattice mismatch issues.

In this study, S. Kishino and colleagues investigated lattice mismatch at the interface of epitaxial layers in GaP/GaP and GaAlAs/GaAs systems, using X-ray diffraction techniques. They observed a planar defect at the interface due to lattice mismatch, causing expansion or contraction of the epitaxial layer's lattice normal to the substrate, without altering parallel spacing. An optical photograph of a section of the GaAlAs wafer is shown in Fig 1. The straight line appearing in this photograph is the interface, and the upper and the lower parts correspond to the GaAlAs epitaxial layer and the GaAs substrate, respectively [3].

Moreover, when the Al content in the AlGaInP and AlGaAs/GaAs systems exceeded 53%, the transition from a direct to an indirect bandgap occurred, significantly hampering radiative recombination efficiency. This limitation was particularly pronounced in the development of short-wavelength, high-brightness LEDs.

Therefore, due to inherent limitations in the GaAlAs/GaAs LED system, there is a need for new material systems to advance semiconductor lighting technology

C. *Emergence of GaN Material Systems and Key Breakthroughs in GaN Technology*

The search for more efficient and versatile LED materials led to the adoption of GaN/InGaN systems. These materials provided significant improvements over their predecessors, particularly in terms of higher luminous efficiency and better adaptation to short-wavelength applications. The GaN/InGaN system's ability to maintain direct bandgap across a wide composition range addressed the fundamental limitations of the earlier AlGaAs/GaAs systems, marking a substantial leap in LED technology.

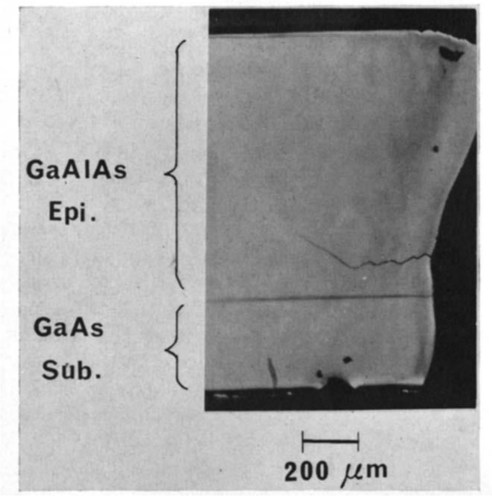

Fig. 1. An optical photograph of a section of the GaAlAs wafer

Hence, the latest advancements in GaN/InGaN technology are crucial for the evolution of LED lighting. Breakthroughs in this field have not only enhanced luminous efficiency but also expanded the achievable color spectrum and operational stability. The successful application of GaN/InGaN materials owes much to two key technological breakthroughs: buffer layer technology and p-type doping technology.

- Buffer layer technology: This technology involves introducing a buffer layer between GaN and the substrate material, effectively reducing lattice mismatch and improving the quality of GaN films.

- P-type doping technology: The breakthrough in p-type doping allows for the effective introduction of holes in GaN materials, which is essential for manufacturing high-efficiency LEDs.

III. Enhancing GaN LED Lighting Efficiency through Carrier Matching

The key to enhancing the lighting efficiency of LEDs lies in enhancing the Internal Quantum Efficiency (IQE). A critical factor in boosting LED efficiency is the degree of carrier matching. Carrier matching refers to the consistency in concentration and distribution of electrons and holes in the quantum well's active region of the LED. A low level of carrier matching, which means an imbalance in electron and hole concentrations, can lead to two major issues: a reduction in the overlap of electron and hole wave functions, thereby decreasing the recombination efficiency, and an increased likelihood of electron overflow to the P-layer under high currents, exacerbating efficiency droop problems.

Several factors influence the matching of carrier concentrations in LEDs. Notably, difficulties in p-type doping and the low Injection Efficiency (IE) of holes are significant contributors to this challenge.

A. *P-Type Doping and Its Effect on Lighting Efficiency in GaN LEDs*

Continuing from the discussion of key breakthroughs in GaN technology, this section explores the pivotal role of p-type doping in enhancing the lighting efficiency of GaN LEDs. Despite significant advances, achieving high hole concentration in p-doped GaN remains a challenge, especially when compared to electron concentrations in n-type doped materials. This disparity, which means a low level of carrier matching, significantly impacts the internal quantum efficiency (IQE) and injection efficiency (IE) of carriers in the active region of LEDs.

1) Elucidating Lighting Efficiency in GaN LEDs and Injection Efficiency

It is important to first elucidate the concept of lighting efficiency, which supports our focus on Internal Quantum Efficiency (IQE) and Injection Efficiency (IE). Lighting efficiency, or power-conversion efficiency (PCE), is defined as the ratio of the optical output power emitted by the LED to the electrical input power. It can be expressed as:

$$PCE = VfE \times IQE \times LEE \tag{1}$$

Here, the forward-voltage efficiency (VfE) represents the electrical efficiency of an LED, essentially the portion of input electrical power that is available for light generation. Light-extraction efficiency (LEE) is the fraction of photons emitted from the active region that can be emitted into free space.

The focus of our study, Internal Quantum Efficiency (IQE), is calculated by:

$$\text{IQE} = \frac{number\ of\ photons\ emitted\ from\ active\ region\ per\ second}{number\ of\ electrons\ injected\ into\ LED\ per\ second} \tag{2}$$

Therefore, IQE can be verified as the product of Radiative Efficiency (RE) and Injection Efficiency (IE), simplified as $IQE = RE \times IE$. To enhance lighting efficiency, it's essential to improve both radiative efficiency and injection efficiency.

Considering RE as the number of photons emitted from the active region per second divided by the number of electrons injected into that region per second, and IE as the ratio of electrons injected into the active region per second to the total number of electrons injected into the LED per second, it becomes clear that to improve the lighting efficiency, particularly the internal quantum efficiency, our emphasis should be on studying injection efficiency.

In the context of P-type doping, if we assume that each carrier injected into the active region undergoes radiative recombination (RE = 100%), the focus on enhancing the internal quantum efficiency within lighting efficiency shifts to researching injection efficiency. It's important to note that not all carriers are injected into the active region of an LED. Some may leak out or traverse the region without being captured. While both electrons and holes can leak, in practice, it is predominantly electrons that do so, attributed to their generally lighter mass and higher mobility.

2) Challenges in P-type doping for carrier matching, disparity in carrier concentrations, and Their Impact on Injection Efficiency

Following the elucidation of lighting efficiency in GaN LEDs, it becomes imperative to examine the challenges encountered in p-type doping. At room temperature, GaN materials exhibit high background carrier (electron) concentrations, displaying n-type conductivity. This inherent characteristic of GaN complicates the achievement of effective p-GaN, as the hole concentration in p-type doped materials is substantially lower compared to the electron concentration in n-type doped counterparts. This disparity in carrier concentrations leads to uneven injection efficiencies, subsequently reducing the lighting efficiency of the LEDs.

For efficient light emission, both electrons and holes must be effectively injected into the active region, typically quantum wells, where they recombine to produce light. However, a major challenge arises when electrons, unable to find holes for recombination, overflow or bypass the quantum wells. This phenomenon significantly lowers lighting efficiency. Conversely, enhancing the injection efficiency of holes to match their concentration with that of electrons in the quantum wells can lead to improved recombination rates. Therefore, achieving a balanced concentration of electrons and holes is essential for optimizing lighting efficiency.

To overcome these challenges and achieve a more uniform carrier concentration, the focus shifts to structural optimization in GaN LEDs. By refining the structural aspects and improving p-type doping techniques, it is possible to narrow the gap between the concentrations of electrons and holes. This approach not only enhances the injection efficiency but also leads to a significant improvement in the overall lighting efficiency of the LEDs.

IV. Structural Optimization and Electron Blocking Layer

In the pursuit of enhancing the lighting efficiency of GaN LEDs, the concept of structural optimization plays a crucial role. Apart from the inherent issue of low hole concentration in the P-layer, another reason for the imbalance in electron and hole concentrations (the disparity in carrier concentration which results in a low level of carrier matching) within the quantum wells is the low injection efficiency of holes. With electrons having a higher concentration and longer diffusion length, there is a tendency for them to overflow from the quantum wells to the P-layer. To counteract this electron leakage, an electron-blocking layer (EBL), typically made of p-AlGaN, is often inserted between the quantum wells and the p-GaN layer. However, the EBL itself presents challenges. The strong polarization electric field between the GaN barrier and the p-AlGaN EBL leads to band bending, creating a potential barrier that hinders hole injection into the quantum wells.

Researchers have explored various strategies to enhance hole injection while ensuring the electron-blocking capabilities of the p-AlGaN layer.

A. *Enhancing the Hole-Injection Efficiency of a Light-Emitting Diode by Increasing Mg Doping in the p-AlGaN Electron-Blocking Layer*

The first strategy is to increase the Magnesium (Mg) doping level in the p-AlGaN electron-blocking layer (EBL), particularly around the interface between the EBL and the top quantum barrier (QB) of the LED, which is implemented by C.-Y. Su et al. from the Institute of Photonics and Optoelectronics at National Taiwan University. Their research, published in the IEEE Transactions on Electron Devices in 2017, focused on the impact of increased magnesium doping in the p-AlGaN electron-blocking layer of LEDs. [4].

TABLE I. LED SAMPLE ASSIGNMENTS, MG PREFLOW GROWTH CONDITIONS, AND LED CHARACTERIZATION RESULTS

sample	R	A	B	C
Pre-flow duration before p-AlGaN growth (sec)	0	300	600	0
Pre-flow duration before p-GaN growth (sec)	0	0	300	600
High-temperature duration (sec)	481	871	1561	1171
IQE (%)	36.7	41.7	35.2	37.5
Normalized EL intensity at 100 mA	1	9.4	8.4	----
Applied voltage at 20 mA (V)	4.3	3.9	3.7	5.3
Differential resistance (Ω)	18.5	22.0	22.6	21.1

The core idea of this approach is to utilize the Mg pre-flow growth technique, where the Mg source is introduced into the vapor deposition chamber before the growth of p-AlGaN or p-GaN layers. This increase in Mg-doping leads to a higher hole concentration in the EBL, thereby screening the polarization field within this layer. As a result, the potential barrier that hinders hole tunneling is effectively reduced, enhancing hole injection efficiency. This improved hole injection efficiency, in turn, contributes to an overall increase in the LED's lighting efficiency

Researchers recorded the different Mg pre-flow conditions for each sample in Table 1. They analyzed four LED samples, each with different Magnesium (Mg) doping conditions, to observe how these variations impact the LED's emission efficiency. The key difference between these samples was the Mg pre-flow process during their fabrication. This process involves preloading the chamber with Mg before the growth of specific layers, which directly affects the Mg doping levels.

- Sample R: Served as the reference with standard Mg doping levels.
- Sample A: Included a 300-second Mg preflow before the growth of the p-AlGaN layer.
- Sample B: Had a 600-second Mg preflow before p-AlGaN and a 300-second preflow before p-GaN.
- Sample C: Only had a 600-second Mg preflow before the p-GaN layer.

This table also includes information about the total duration of high-temperature growth for each sample, which can influence the quantum well structure and thus the IQE of the LEDs. Additionally, we noted that the surface roughness and dislocation densities of all samples remained consistent, indicating that increased Mg doping did not lower the crystal quality. Finally, we fabricated LEDs based on these structures and measured their performances. The increased Mg doping, particularly in the p-AlGaN electron-blocking layer, is expected to enhance the LED’s emission efficiency by improving hole injection into the quantum wells.

1) Mg Composition Distributions

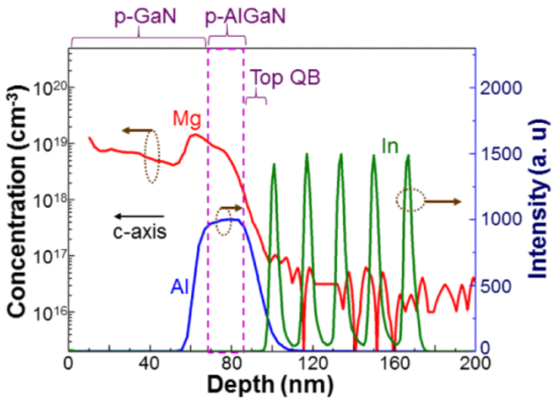

Fig. 2. SIMS results of sample R, showing the depth-dependent concentrations of Mg (with the left ordinate), Al, and In (with the right ordinate).

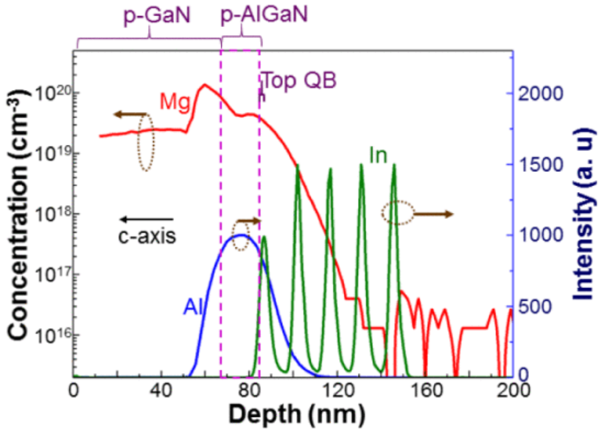

Fig. 3. SIMS results of sample B, showing the depth-dependent concentrations of Mg (with the left ordinate), Al, and In (with the right ordinate).

In this study, Figures 2, 3, and 4 illustrate the distribution of materials within different layers of LED samples. Figures 2 and 3 provide Secondary Ion Mass Spectrometry (SIMS) profiles for samples R and B, respectively, showing the concentrations of Magnesium (Mg), Aluminum (Al), and Indium (In) at various depths.

Figure 2 shows the concentrations of Mg, Al, and In in sample R, revealing the structure of the p-AlGaN EBL and the quantum wells. Figure 3 does the same for sample B, highlighting a thinner top quantum barrier due to the Mg preflow process which facilitates hydrogen back-etching.

Figure 4 compares Mg concentrations across four samples, demonstrating how Mg preflow increases Mg levels, particularly near the interface between the p-AlGaN EBL and the top QB. This increase is crucial as it suggests a more effective hole injection, which is key to enhancing the LED's emission efficiency.

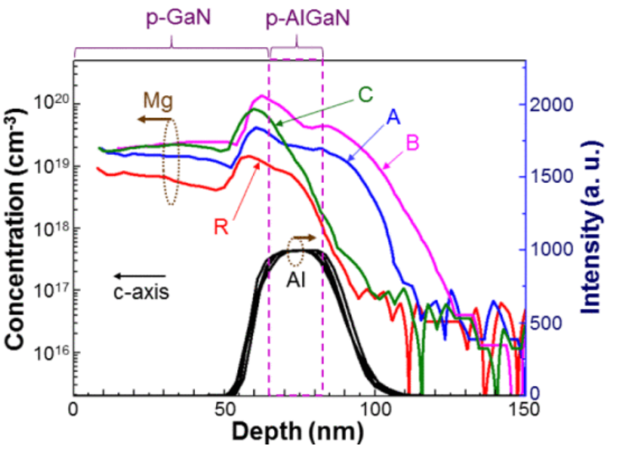

Fig. 4. Comparison of Mg concentration profiles of the four LED samples. The Al content profiles are also plotted to identify the depth ranges of the p-AlGaN EBLs in those samples.

2) Simulation Results

In this research, the simulated band structures and carrier densities presented in Figures 5 to 8, along with the summarized results in Table II, illustrate the effects of Mg doping on the performance of LEDs.

Figure 5 shows the energy bands and quasi-Fermi levels for electrons and holes in the LED structure. The simulations indicate that increasing Mg doping reduces the energy barriers for holes, facilitating their movement into the quantum wells (QWs).

Figure 6 reveals the carrier densities within the structure, highlighting that higher Mg doping (seen in samples A and B) leads to an increase in hole densities within the QWs, which is advantageous for the LED's performance.

Figure 7 displays the potential barrier heights within the valence band, showing that the barriers are significantly lowered in samples A and B due to Mg preflow, which implies a better hole injection efficiency.

Figure 8 complements this by showing the potential barrier heights within the conduction band, where samples A and B again show increased barrier heights, indicative of effective electron blocking.

Table II consolidates these findings, demonstrating that sample B, with the highest Mg doping, presents the lowest barrier for hole injection and the highest hole density in the QWs, leading to an enhanced hole-injection efficiency.

These simulation results are crucial as they support the conclusion that increasing Mg doping at the p-AlGaN EBL and the interface with the top QW significantly boosts the LED's emission intensity – a finding that is backed by experimental data showing a 9.4 times increase in emission intensity. This enhanced efficiency is due to the increased hole density in the quantum wells, achieved by optimizing the Mg doping concentration to reduce the potential barriers for holes.

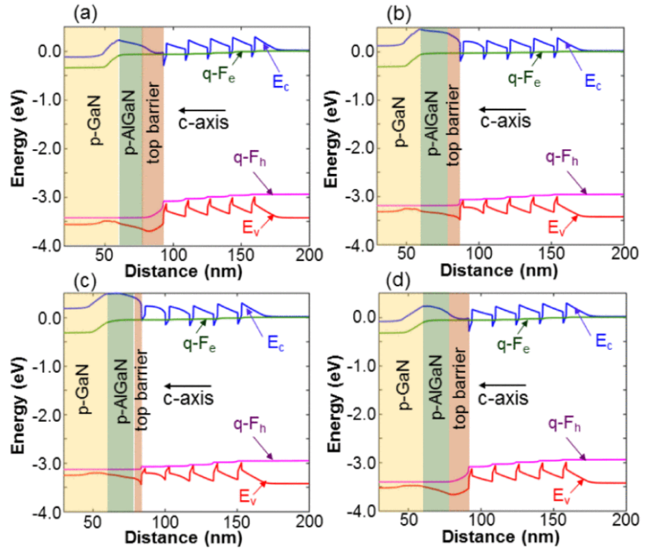

Fig. 5. (a)–(d) Simulated band structures (Ec and Ev for the conduction and valence bands, respectively) and quasi-Fermi levels (q-fe and q-Fh for the electron and hole, respectively) of samples R and A–C, respectively, when the injected current density is 100 A/cm^2.

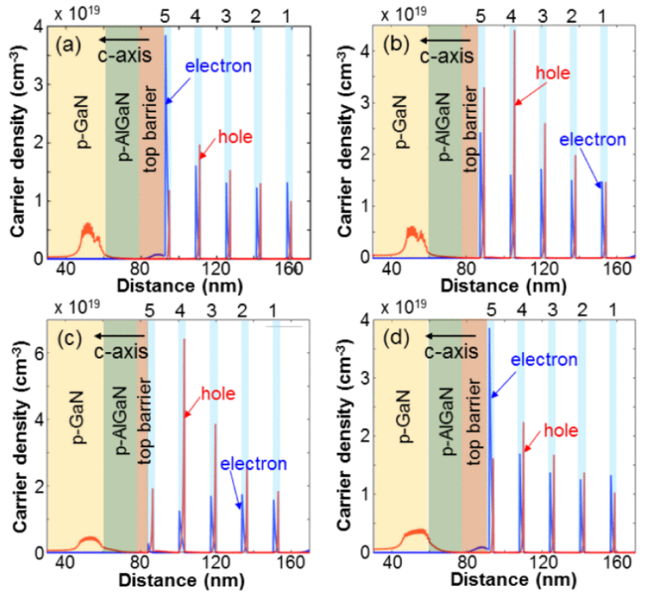

Fig. 6. (a)–(d) Simulated distributions of electron and hole densities in the QW structure, p-AlGaN, and p-GaN layers of samples R and A–C, respectively, when the injected current density is 100 A/cm2 . The five QWs are labeled with 1–5 at the top of each part of the figure.

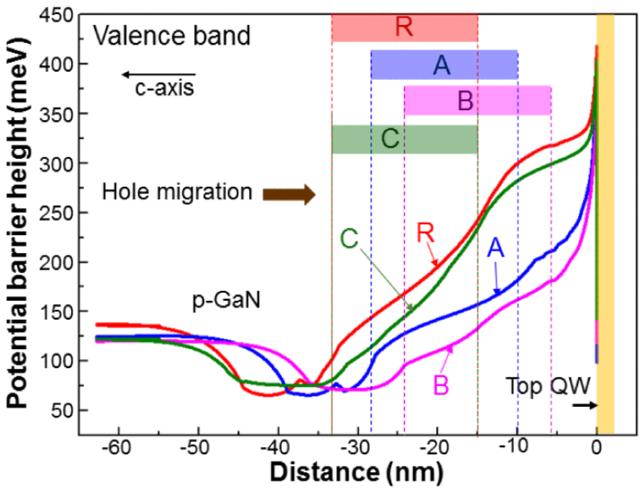

Fig. 7. Simulated distributions of the potential barrier height in the valence bands of samples R and A–C. The zero point in the horizontal axis corresponds to the upper boundary of the top QW (QW 5). The distance in the horizontal axis decreases toward the p-GaN side. The shaded blocks with different colors and the vertical dashed lines show roughly the distance ranges of the p-AlGaN EBLs in various samples.

TABLE II. SIMULATION RESULTS OF VARIOUS SAMPLES WHEN THE INJECTED CURRENT DENSITY IS 100 A/cm^2 IN EACH SAMPLE

Sample	R	A	B	C
Maximum barrier height of hole (meV)	417.8	391.9	364.4	403.5
Total hole density in the QWs (cm^{-3})	1.52×10^{20}	3.40×10^{20}	4.76×10^{20}	1.74×10^{20}
Maximum barrier height of electron (meV)	342.7	553.1	610.4	345.2
Total electron density in the QWs (cm^{-3})	3.99×10^{20}	4.01×10^{20}	3.19×10^{20}	4.14×10^{20}

3) Analysis

In the discussion of their research findings, C.-Y. Su et al. elaborates on the impact of the Mg preflow process on the hole-injection efficiency of LEDs. By increasing the Mg concentration in the p-AlGaN electron-blocking layer (EBL), particularly at the interface with the top quantum barrier (QB), they observed a reduction in potential barriers for hole tunneling. This is evident from the simulated band structures shown in Figures 5(b) and (c), compared to Figure 5 (a), which illustrates a closer band edge to the quasi-Fermi level of holes, indicative of a reduced hole potential barrier.

However, this process also leads to increased hole scattering and potential defect creation when Mg is heavily doped in the p-GaN layer, as seen in samples like C. This can adversely affect hole mobility and current spreading within the layer, as supported by the slight increase in simulated hole density yet lower overall emission efficiency observed in sample C.

Moreover, the research suggests that an optimized distribution of Mg doping — high in the p-AlGaN EBL and controlled in the p-GaN layer — could potentially yield even higher LED emission efficiencies. The Mg preflow technique is highlighted as a valuable method for achieving this targeted doping concentration.

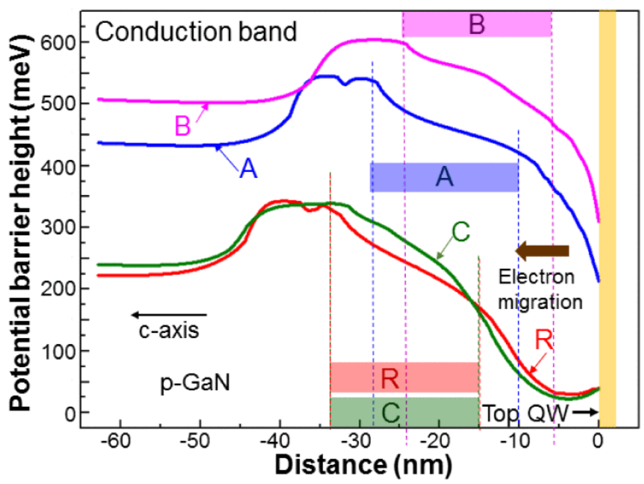

Fig. 8. Simulated distributions of the potential barrier height in the conduction bands of samples R and A–C correspond to the results shown in Fig. 7.

Interestingly, the thinner top QBs in samples A and B, a result of hydrogen back-etching, modify the quantum confinement and ultimately affect the hole densities within the QWs. The researchers propose that this back-etching issue could be resolved by initially growing a thicker top QB to account for any etching during the Mg preflow process.

The discussion also touches on the higher differential resistance levels seen in samples A–C, suggesting poorer current spreading in the p-GaN layers. This can be improved with additional transparent conductive layers or high-conductivity structures.

Lastly, the research acknowledges that while the simulations illustrate the fundamental enhancements in hole injection, they do not capture all the complexities of LED performance, such as carrier localization and the behavior of different hole types. Despite this, the key takeaway remains clear: optimizing the Mg doping profile through the Mg preflow technique is a proven method to substantially boost LED emission intensity, aligning with the overall conclusion that increased Mg doping near the EBL and top QB interface is instrumental in achieving higher LED emission efficiencies.

Therefore, by implementing this strategy, it was observed that increasing the Mg-doping level by approximately 20 times near the interface between the EBL and the top QB resulted in a remarkable enhancement of the LED's emission intensity by approximately 9.4 times. Simulation studies further supported these findings, demonstrating a reduction in the energy difference between the valence band edge and the quasi-Fermi level of the hole in the EBL, leading to an increased total hole density in the quantum wells and thereby enhancing the LED emission efficiency.

B. Superlattices in LED

There are other methods to enhance hole injection while also ensuring the electron-blocking capabilities of the p-AlGaN layer. One such measure is the application of InGaN/AlGaN superlattices in nanowire LEDs [5], which is shown in Figure 9.

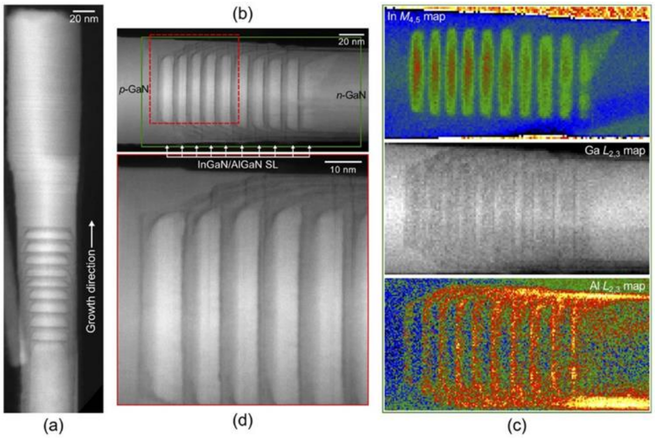

Fig. 9. InGaN/AlGaN Superlattices in Nanowire LEDs.

In this unique superlattice structure, layers of InGaN and AlGaN are alternately stacked in a specific periodic pattern, creating distributed AlGaN electron-blocking layers (EBLs). These distributed EBLs function as multiple barriers that facilitate electron tunneling, significantly reducing the effects of thermal carriers and achieving a more uniform distribution of carriers across the active region of the device.

Compared to traditional InGaN/GaN LED heterostructures, the alternating pattern of InGaN and AlGaN forming distributed EBLs can more effectively prevent electron overflow. The evenly distributed AlGaN layers throughout the structure serve as an array of barriers, promoting electron tunneling injection, which notably diminishes the thermal carrier effect and results in a more uniform carrier distribution in the active area.

Hence, this structure is not only highly effective in suppressing electron overflow and enhancing hole transport but also ensures a more uniform carrier distribution throughout the active region compared to conventional InGaN/GaN LEDs. This leads to a significant improvement in the lighting efficiency and stability of the LED.

C. Optimizing Quantum Well Structures: V-Pit

The third method to enhance lighting efficiency is the improvement of light extraction efficiency and reduction of leakage current in GaN-based LED Via V-Pit Formation [6].

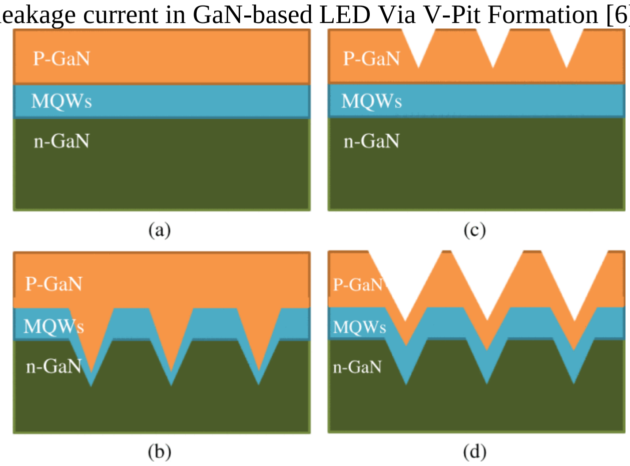

Fig. 10. Schematic of LEDs with different V-pit embedded structures (a) LED1 (conventional LED), (b) LED2, (c) LED3, and (d) LED4, respectively.

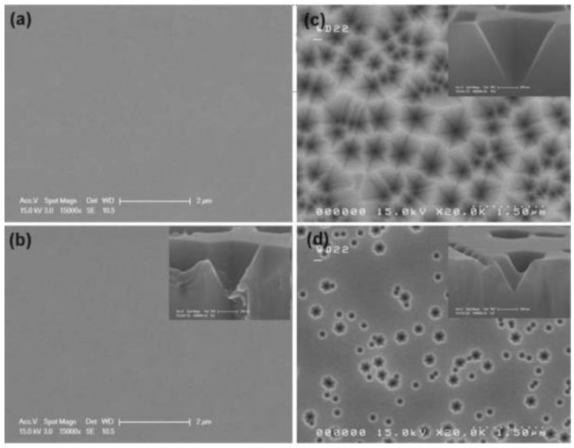

Fig. 11. Top-view SEM images of the p-GaN surface with different V-pit embedded structures for (a) LED1, (b) LED2, (c) LED3, and (d) LED4, respectively. Inset shows the SEM cross-sectional images obtained (b) before p-GaN and (c) and (d) after p-GaN layer growth.

These V-shaped features are added to the LEDs by adjusting the conditions during the manufacturing process. They contribute to lighting efficiency in two key ways:

- Enhancing Light Output: V-pits create a rougher surface on the LED, which interrupts the internal paths that light usually takes within the device. This roughness helps more light escape by scattering it in different directions, which is preferable to having it bounce around inside the LED until it's absorbed. LEDs with V-pits on the surface (LED3 and LED4) have shown a noticeable increase in the light they emit compared to traditional LEDs without V-pits.
- Reducing Leakage Current: V-pits can also improve the LED's electrical efficiency by reducing leakage current. This is the unwanted flow of electrical current that can occur in areas where it's not supposed to, like through defects in the LED. V-pits help to block these pathways, leading to less leakage. When V-pits are embedded within the LED structure, as seen in LED4, there's a marked decrease in leakage current, improving the overall performance of the device.

In conclusion, V-pit-embedded structures in GaN-based LEDs serve to both scatter light more effectively and block dislocations, which leads to higher light output and more stable operation with reduced leakage current. The optimal arrangement found in LED4, with V-pits both at the surface and embedded within, indicates a superior design for enhancing LED performance

V. Conclusion

This report illustrates significant advancements in the field of GaN-based LED lighting efficiency, elucidates Lighting efficiency and injection efficiency, and discusses its challenge. By structural optimization through a combination of P-type doping, especially Mg doping in the p-AlGaN electron-blocking layer, and structural optimizations like V-pit formation, a notable increase in both internal quantum efficiency and light extraction efficiency has been achieved. These findings not only contribute to the understanding of GaN material behavior in LED applications but also pave the way for further enhancements in LED lighting technology, promising more energy-efficient and environmentally friendly lighting solutions.

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