Review Of the Light Extraction Efficiency of Gan Leds

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Abstract. Various new methods have emerged to enhance the light extraction efficiency (LEE) of Gallium Nitride (GaN)-based Light Emitting Diodes (LEDs),. This review examines several key techniques, including surface texturization, patterning of the GaN and substrate interface, chip geometry design, integration with photonic crystals, and epitaxial micro/nano structures. Surface texturization improves LEE by reducing light reflection and increasing scattering, although it may introduce surface defects. Interface patterning optimizes light propagation but increases manufacturing costs. Chip geometry design allows for specific light extraction paths but may pose manufacturing challenges due to complex designs. Photonic crystal technology enhances LEE though controlling light refraction but requires precise fabrication techniques. Among these approaches, epitaxial micro/nanostructures stand out for providing optimal control of the light extraction path while minimizing material waste and structural damage, despite the more demanding epitaxial conditions. Therefore, epitaxial micro/nano structures are considered the optimal strategy for significantly improving LEE in GaN-based LEDs, paving the way for more efficient and sustainable lighting technologies.

Keywords: Review, Light Extraction Efficiency, GaN LEDs.

1. Introduction

Gallium Nitride (GaN)-based Light Emitting Diodes (LEDs) have risen to prominence as key technologies, celebrated for their exceptional efficiency, longevity, and commitment to environmental sustainability. Their applications, which range from illumination to displays and communications, highlight the pivotal role GaN-based LEDs play in contemporary technology. However, despite their numerous advantageous traits, the Light Extraction Efficiency (LEE) of GaN-based LEDs remains a critical bottleneck that constrains their overall performance. This efficiency is shaped by a variety of factors, including material properties, device geometry, and optical losses. For instance, the refractive index of the material is instrumental in dictating the internal reflection and absorption of light within the LED structure. Additionally, the LED's surface and interface design significantly affect photon scattering and transmission. Optical losses due to material absorption and internal reflections also detract from the device's overall LEE. Consequently, a thorough grasp of these foundational principles is imperative for developing effective strategies to enhance LEE in LEDs.

In our review of recent literature concerning the LEE of GaN-based LEDs, a plethora of innovative approaches has been continuously introduced to augment LEE, such as surface texturization, patterning at the GaN and substrate interface, refined chip structure design, photonic crystal technology, and the cultivation of micro and nanostructured materials. We also delve into cutting-edge technologies like nano-structuring, resonant cavity design, and the application of novel materials. These methodologies are designed to bolster LEE by manipulating the structure and material properties of LED devices, thereby amplifying photon scattering, reflection, and escape. By juxtaposing the merits, drawbacks, and practical implications of these diverse methods, our review endeavors to offer a holistic understanding and insightful perspectives that will propel future research and, ultimately, foster the evolution of GaN-based LED technology.

2. Techniques for Improving Light Extraction Efficiency

2.1. Surface texturization

Recent studies have explored various techniques for surface roughening to improve Light Extraction Efficiency (LEE) in LEDs. The core idea is to transform the reflective light transmission into a scattering mechanism. Normally, photons with angles beyond the critical angle are internally reflected and absorbed at the GaN-air interface. Surface roughening, however, increases the emitting surface area and breaks total reflection, enhancing scattering and allowing more photons to escape. This approach has been validated by C. Huh *et al*. in 2003, who achieved a 62% increase in LED conversion efficiency by etching p-GaN with metal clusters [1]. In 2004, T. Fujii *et al*. further demonstrated a 2.4-fold increase in LED optical power by creating n-GaN tapered arrays through photochemical etching [2]. These findings underscore the potential of surface roughening in boosting LED performance.

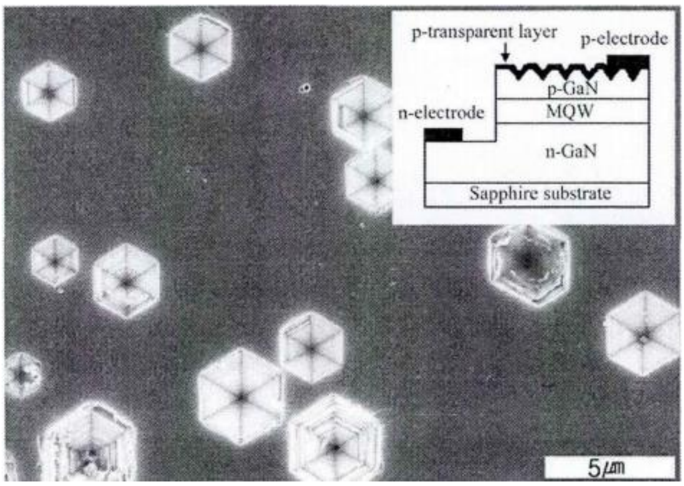

Figure 1. SEM images of top p-GaN surfaces of LEDs etched using KE solution. Inset shows schematic cross section of InGaN-GaN MQW LED with textured p-GaN surface [3].

As shown in Figure 1, S.-I.Na *et al*. (2006) increased LED optical power by 29.4% using glycol-based KOH etching [3]. Song *et al*. (2011) further enhanced this by 72% with a micro-nanocomposite structure [4]. The Figure 2 reveals that Zhuo *et al*. (2014) improved light efficiency by 30.4% through direct nano-rough p-GaN growth [5]. Lai et al. (2023) achieved a 305% LEE increase with dry-etched pyramidal structures [6], demonstrating the potential of both surface and sidewall roughening techniques.

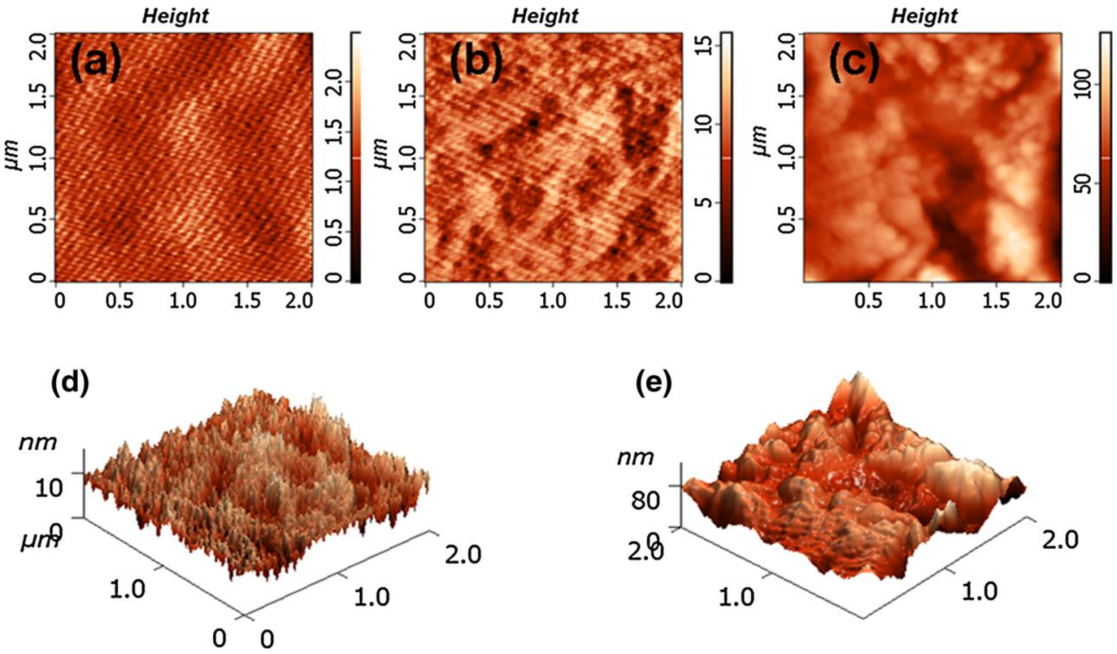

Figure 2. AFM images (2 x 2 um^2) of surface morphology for sample A (a), sample C (b), and sample D (c), 3D images for sample C (d) and sample D (e) [5].

2.2. GaN and substrate interface graphics

Usually, the interface between GaN and sapphire substrate is planar, and this structure forms specular reflection, which leads to the formation of planar waveguide inside the LED, which is unfavorable for light extraction. If the GaN and substrate interface is made graphically rough or if an air cavity with a low refractive index is introduced, it can disrupt total internal reflection, alter the direction of light reflection, and dismantle the planar waveguide structure inherent to GaN-based LEDs. This manipulation increases the likelihood of photons entering the escape cone, thereby enhancing the efficiency of light extraction from the LED.

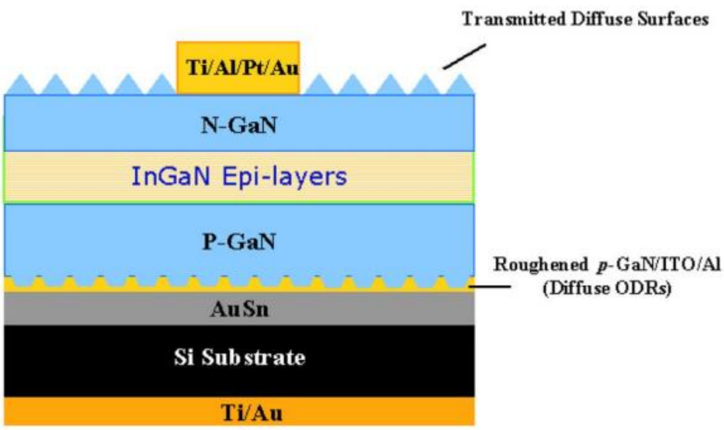

Figure 3. Schematic cross section of a LED with double diffuse surfaces [7].

In 2006, Lee *et al*. created a GaN LED with a dual diffuse surface,clearly show in Figure 3, achieving high light extraction, with an external quantum efficiency of around 40%. The device featured roughening at the GaN-substrate interface, which significantly increased luminous efficacy. Compared to LEDs with only upper surface texturing, it improved by 56%. When compared to LEDs without any surface texturing, the efficacy was enhanced by a remarkable 236% [7].

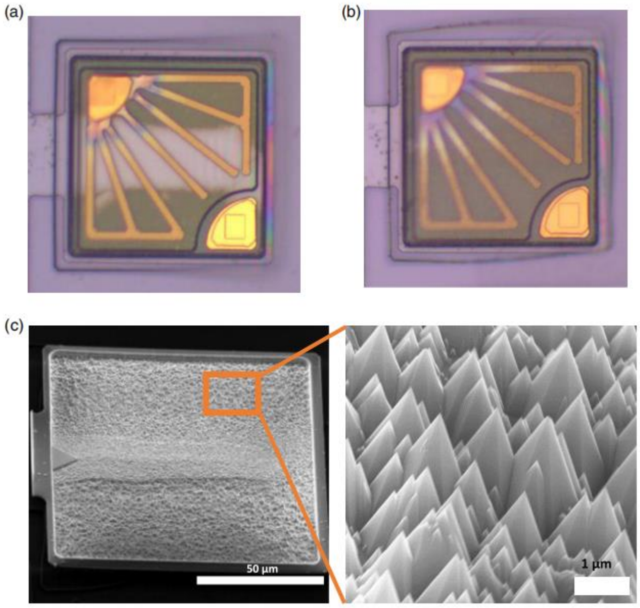

Figure 4. (a) Optical image of released LEDs of size 110×110 μm^2 with a partially roughened backside, (b) with a completely roughened backside, and (c) SEM images of released LEDs with a roughened backside [8].

As shown in Figure 4, in 2022, Zeinab *et al*. succeeded in improving the LEE by a factor of 1.8 by roughening the interface between GaN and Si substrate during micro-transfer printing [8].

2.3. Optimized chip structure design

Typically, an LED chip is a six-sided rectangle with one light emitting side, four sides and a back side. The front and back, left and right, up and down faces are parallel to each other, this structure makes the light restricted to propagate back and forth in the chip until it is absorbed and consumed. The above phenomenon can be effectively avoided by changing the design of the chip geometry, which significantly improves the LEE of LEDs.

In 2001, Schad *et al*. investigated the effect of the shapes of SiC and sapphire substrates on the LEE of InGaN-based LEDs through theoretical calculations. The lateral inclination of the substrate is the main factor affecting the LEE of small-size LED chips, and the optimal lateral inclination values of both SiC and sapphire substrates are around 64°. The optimally shaped sapphire substrate enhances the LED LEE by 60%, and the optimally shaped SiC substrate improves the LED luminous efficiency by 282% [9].

In 2010, Wang *et al.* fabricated square-triangular to square-heptagonal GaN-based LEDs with equal effective light output area by laser scribing and compared the external quantum efficiencies [10]. With the conclusions of the simulation and experiment, in which the square LEDs have the lowest optical power among all the samples, and the square-heptagonal LEDs have the highest optical power. Figure 5 illustrates the luminescence diagram of the device with different shapes.

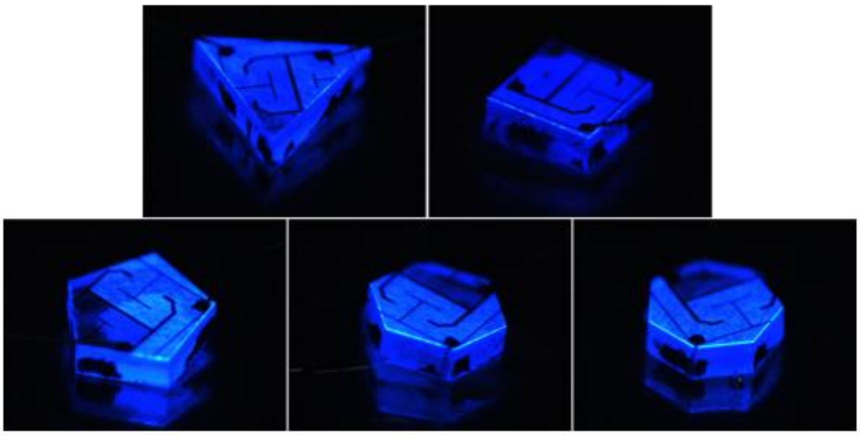

Figure 5. Optical microscopy images of polygonal LED chips operated at a bias voltage of 2.5 V; the center wavelength of emission is 470nm [10].

2.4. Photonic crystal technology

In 1987, E. Yablonovitch [11] first introduced the concept of photonic crystals, which are materials whose dielectric constant (refractive index) varies periodically in space. There are two explanations for the mechanism of photonic crystal structure to enhance light extraction, one is to use the photon forbidden band to limit the transmission of transverse waveguide modes and enhance the longitudinal emission mode of photons, the other is to extract the waveguide light by using the photonic pintle as a diffraction grating.

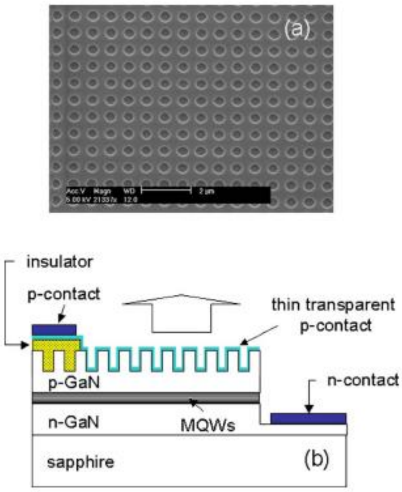

Figure 6. (a) Scanning electron microscope image for a PC-LED device surface. The square-lattice air-hole array pattern was generated by the holographic double-exposure method. The lattice period of this specific example is 700 nm. (b) Schematic view of the PC-LED, illustrating the vertical layer structure of the device [12].

In 2005, Kim *et al.* used methods shown in Figure 6 to enhanced LEE of GaN-based LED with holographically generated two-dimensional photonic crystal patterns by 2.1 times [12]. In 2011, Chang *et al*. propose a simple, low cost, and mass producible imprint lithography method to texture indium tin oxide (ITO) contact layer of nitride-based LEDs and enhanced LEE by 12% [13].

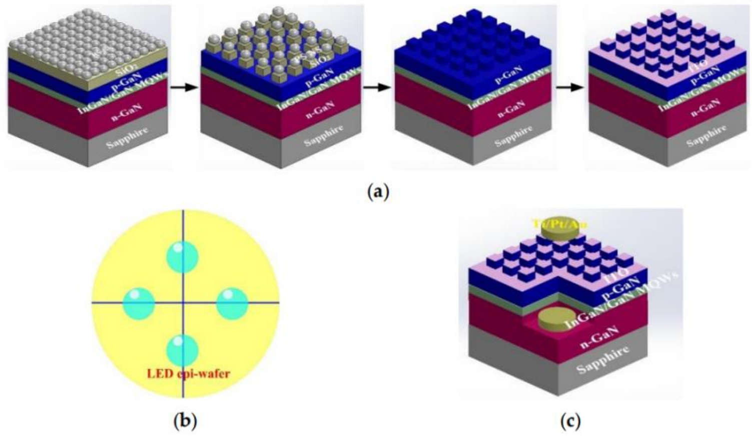

Figure 7. Schematic illustrations of (a) process of the PC-structured p-GaN nanorods, (b) positions on the substrate for thesecond-time spin-coating process, and (c) the finished device [14].

In 2021, Lei *et al*. improved emission intensity by 41% by directly preparing GaN layers for photonic crystal structures [14]. Figure 7 illustrates the schematic of the device preparation process and the finished product.

2.5. Epitaxial micro/nano structures

All the methods mentioned above can enhance the light-emitting efficiency of LEDs, but they involve some form of processing on the LED chip itself, which can cause damage. Growing micro/nanostructures on the surface of LEDs has garnered significant attention as a means to enhance Light Extraction Efficiency (LEE). This approach involves creating structures externally on the LED chip without altering the chip's internal structure, thus preventing any damage to the chip itself. The method of growing micro/nanostructures is simple, low cost, good light extraction effect, no damage to the chip, and it has become the most advantageous means.

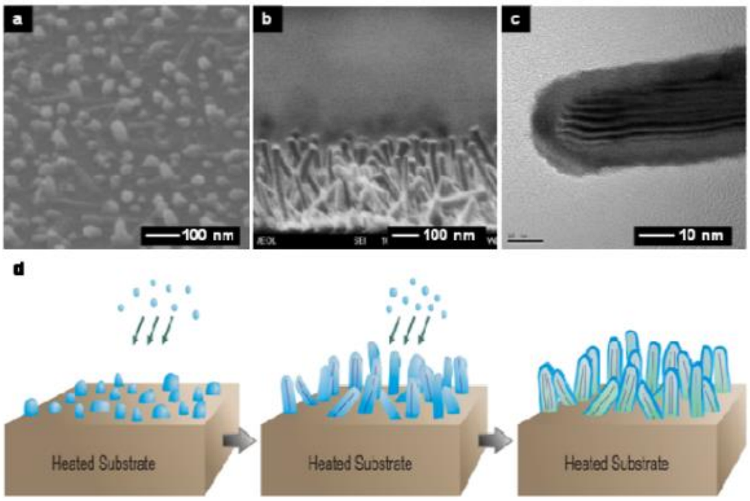

Figure 8. (a) Scanning electron micrograph of the nucleation cores at the beginning of evaporation, (b) the cross-sectional view of deposited nanorods, (c) the tunneling electron micrograph (TEM) of a nanorod, and (d) schematics for the ITO nanorod growth mechanism [15].

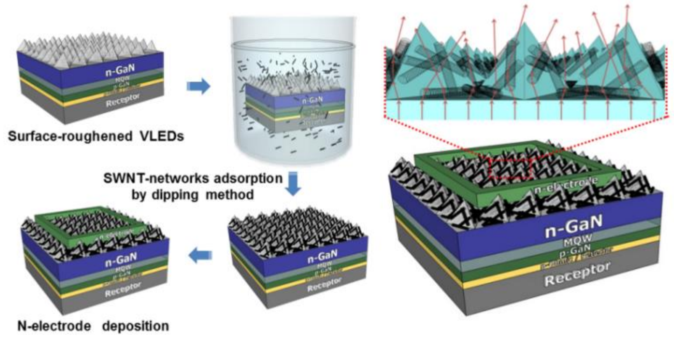

Figure. 9 The schematic illustration of GaN-based vertical LEDs with surface roughened by wet etching and coated with ultra-thin SWNT networks [16].

In 2009, C.H. Chiu *et al.* grew ITO nanorod arrays on the surface of InGaN/GaN LEDs by electron-beam deposition, which improved the LEE of the LEDs by 35% at 350 mA current [15]. In 2011, Wang *et al.* prepared nanotube arrays of ITO current-extending layers and silica in n-GaN for vertically structured LEDs, and the LEE of the LEDs was increased by 103% [16]. Figures. 8 and 9 show the epitaxial layer formation process for these two efforts, respectively. In 2013, J.-T. Lian *et al.* grew InN nanocones on p-GaN, and then grew In_2O_3 nano-cones by high-temperature oxidation, which improved the LED efficacy of light output by about a factor of one [17]. In 2023, Kim *et al.* tripled the LEE by preparing arrays of TiO_2 nanospheres [18]. Figs. 10 show the epitaxial layer formation process for these two efforts.

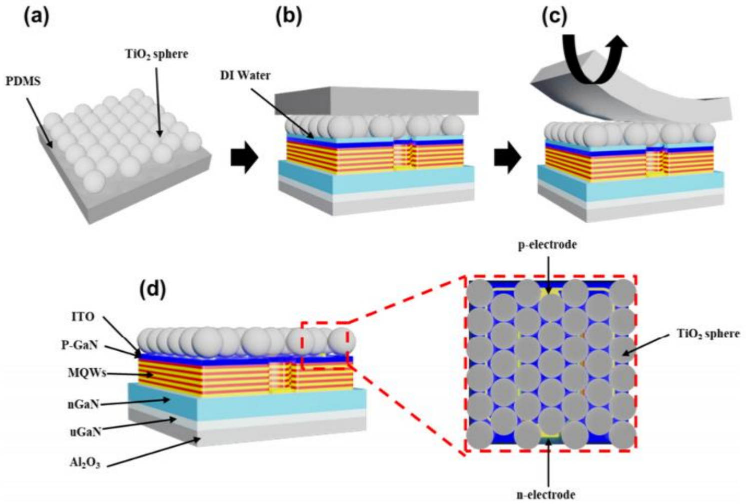

Figure 10. Process flow from formation of TiO_2, monolayer to its transfer on LED chips. (a) Formation of TiO_2, NSs ML, on a PDMS, (b) drop-casting of DI water and flip of TiO_2/PDMS pad, (c) removing of PDMS from TiO_2, NSs ML, (d) formation of arrays of TiO_2, NSs ML on LED chips [18].

3. Conclusion

In conclusion, an array of methods has been explored to augment the Light Extraction Efficiency (LEE) of Gallium Nitride (GaN)-based LEDs, each with its own merits and drawbacks. Surface texturization, which entails roughening or patterning the LED surface, is a cost-effective and accessible strategy that diminishes light reflection and augments scattering, thus enhancing LEE. Nonetheless, this technique may introduce surface imperfections, potentially affecting device reliability and uniformity in performance. Interface patterning between GaN and the substrate is another avenue for LEE enhancement, albeit one that could entail additional manufacturing steps and escalate costs. Variations in pattern quality and alignment might also impact the yield and consistency of the devices. Chip geometry design allows for the creation of specific light extraction paths, yet complex designs could present difficulties in precision manufacturing and scalability, with non-uniformities leading to performance disparities. The incorporation of photonic crystals is a promising approach for enhancing LEE through the precise manipulation of light, although it necessitates advanced fabrication techniques and could lead to higher production expenses. Among these techniques, epitaxial micro/nanostructures stand out as particularly promising. Specifically, the micro-nanostructures of Zinc Oxide (ZnO) and Titanium Dioxide (TiO_2) are notably effective for the light extraction of GaN-based LEDs. The chemical solution preparation method for fabricating micro-nanostructures of ZnO and TiO_2 offers the benefits of simplicity, cost-effectiveness, and the capability for large-area growth. While epitaxial micro/nanostructures provide superior control over light extraction pathways and minimize both material waste and structural damage. Consequently, despite the challenges, epitaxial nanostructures are considered the optimal strategy for significantly improving LEE in GaN-based LEDs. This advancement is set to usher in a new era of more efficient and sustainable lighting technologies.

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