

Research on Light Extraction of GaN-based LED with Surface/Interface Coarsening

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Abstract. Light-emitting diodes (LEDs) are a highly versatile light source that have been widely employed in various fields. In order to maximize its quantum efficiency, it is essential to boost the efficiency of light extraction. Internal photon reflection can have a distinct negative impact on the luminous output power of GaN-based LEDs, which can be addressed by surface and interface texturing of different LED layers. This article discusses the mechanisms of light extraction losses in GaN-based LEDs and summarizes various surface and interface coarsening techniques proposed for improving the light extraction rate, including a range of physical and chemical etching methods.

Keywords: gallium nitride, light-emitting diode, surface coarsening, light extraction.

1. Introduction

LED is a semiconductor light source based on p-n junction (Fig. 1). Today, various colors of LEDs, including blue, green, purple and white, are commercially available. They are widely used in some fields, such as general lighting, indicators, displays, medical equipment and so on. LEDs have many advantages. For example, environmental protection, rich colors, high efficiency, low power consumption, long lifespan, small size and high conversion frequency[1]. However, nowadays, their photoelectric conversion rate is still constrained by many critical problems, among which is low light extraction efficiency.



Figure 1. LED bulbs of different colors.[2]

The main factors that limit the efficiency of light extraction in LEDs include total internal reflection loss[3], absorption loss of electrode and semiconductor materials, Fresnel loss, and current droop loss[4]. Among these, total internal reflection loss plays a dominant role. The epitaxial structure of GaN-based LEDs works as a planar waveguide structure. A high refraction rate of epitaxial GaN material leads to a small total reflection critical angle, resulting in photons restricted in the materials. Then the photons propagate in a guided mode of interface total reflection and end up absorbed by the materials. Modulating the surface and interface roughness of semiconductor materials has been shown to decrease total internal reflection loss and increase light extraction efficiency in LED research conducted by many institutions.

2. Surface/Interface coarsening techniques

2.1. Surface coarsening

Photons, with emergence angles greater than the critical angle, are reflected by the flat surface of

LEDs. Surface coarsening introduces light scattering at the surface. By increasing the surface area available for light emission and reducing total internal reflection, light is more likely to be scattered rather than reflected at the interface between the chips and air, allowing more photons to escape from the LED. On the other hand, reflected photons will propagate randomly, thus more likely to enter the optical escape cone after multiple reflections.

Surface coarsening structures can be divided into random and periodic array structures. Random structures can be obtained directly by chemical or physical methods, while periodic array structures entail the preparation of masks.

H. Kim et al. used a random dry-etching process with an H_3PO_4 solution at predetermined temperatures to create hexagonal pits on the n-type GaN surface (Fig. 2). Different etching temperatures were employed to fabricate etch pits of various sizes and investigate the texturing effects respectively. The LED light extraction efficiency was augmented by 54% at most.[5]

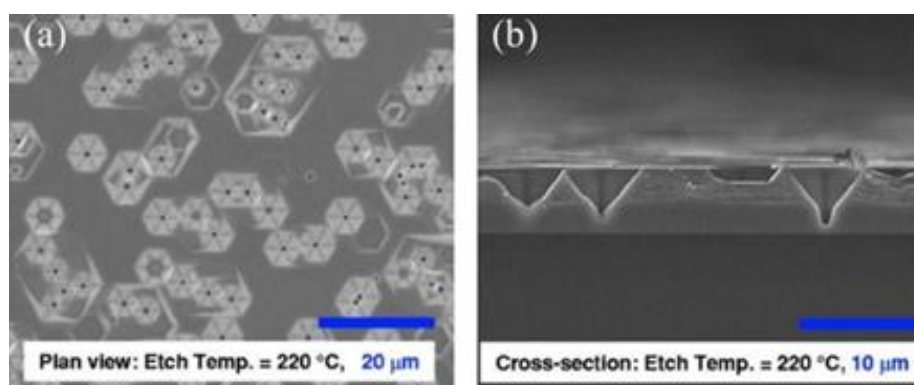


Figure 2. SEM illustrations of hexagonally arranged corrosion pits on n-type GaN: (a) Plan-view image at 20 μm and (b) cross-sectional images at 10 μm.[5]

T. Fujii et al. prepared hexagonal conical arrays on the n-side of n-GaN LED chips by photochemical (PEC) etching (Fig. 3). They employed a KOH solution as the electrolyte and a Xenon lamp as the illumination source to perform PEC etching on Ga-face GaN surfaces, leading to the formation of conelike patterns with carrying sized depending on the etching time. Moreover, the shape feature of PEC-etched Ga-face GaN surfaces was proved to be different, resulting from surface polarity. The optical power of LEDs showed an increase of 240%.[6]

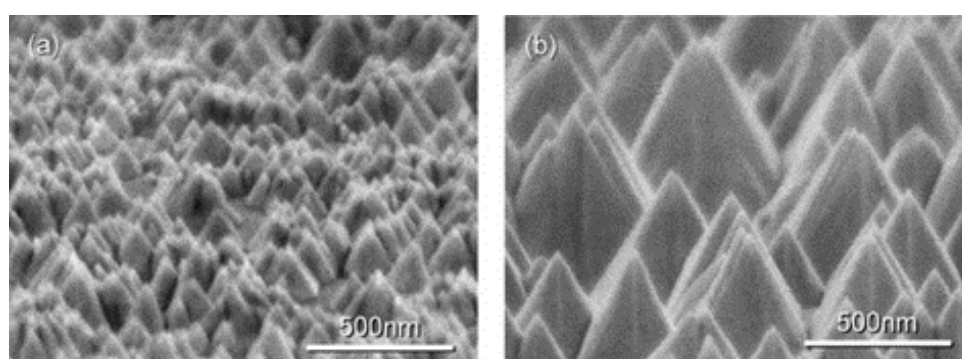


Figure 3. SEM images of n-side surface of GaN LED chips after etching of different time with a KOH-based PEC method at 500 nm: (a) 2 min and (b) 10 min.[6]

C. Huh et al. used a metal cluster as a mask to etch the p-GaN layer and fabricated micro-scale rough out-light surfaces (Fig. 4). A Pt film of 5 nm was deposited with an electronbeam evaporator and thermally annealed to get a Pt cluster. Afterward, an H_3PO_4 solution was adopted in a wet chemical etching process to roughen the surface, using Pt clusters as a mask. There was a 62% increase in the optical output of the LEDs.[7]

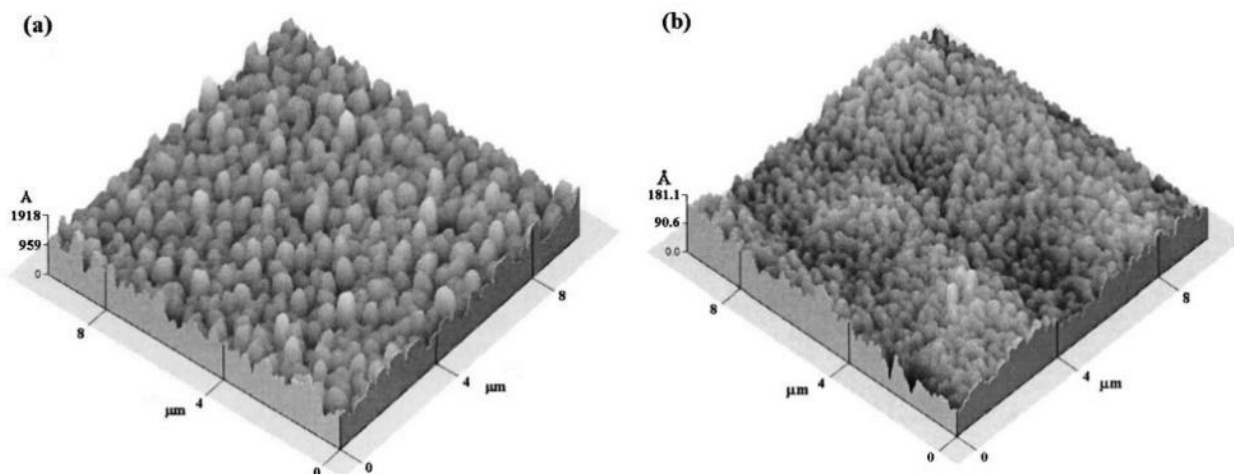


Figure 4. AFM images of top surface appearance of (a) Pt clusters on the p-GaN and (b) microroughened GaN.[7]

Y. M. Song et al. created micro-nano hierarchical structures on LEDs resembling insect compound eyes (Fig. 5). Firstly, they prepared a micron-scale photoresist column on the GaP window layer by photolithography. The photoresist column was used as a template, and GaP microstructures (MSs) were etched through an inductively couple plasma (ICP) process. Then, Ag was sputtered above and transformed into Ag nanoparticles by annealing. Finally, they used the nanoparticles as a template to etch subwavelength microstructures (SWSs). The composite structure increased the optical power of LEDs by 72%. Its enhancement effect is more significant than that of solely MSs or SWSs.[8]

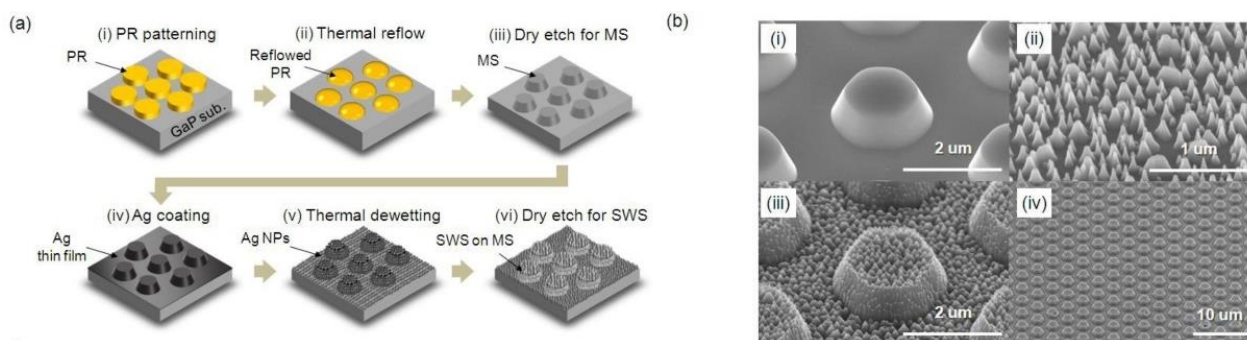


Figure 5. (a) Schematic diagram illustrating the fabrication procedures for the SWS/MS hybrid structure; (b) SEM images: (i) MSs at 2 μm , (ii) SWSs at 1 μm , (iii) a single SWS/MS architecture at 2 μm and (iv) SWS/MS structures at 10 μm on the GaP.[8]

L. Kuna et al. used a femtosecond pulsed laser to produce holes of different sizes and depths on the flipside sapphire surface of GaN LEDs (Fig. 6). The pattern was designed in the form of a bitmap file, which controlled the following structuring process. By modifying the laser's parameters, they obtained up to a 22% increase in light extraction efficiency.[9]

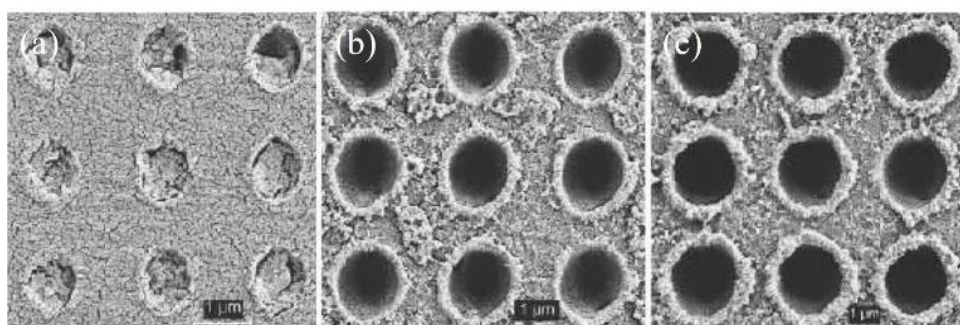


Figure 6. SEM images of pit arrays produced with different laser output powers at 1 μm : (a) 80 μW , (b) 100 μW , and (c) 120 μW . [9]

Besides corrosion or etching of the material, attaching patterned materials on the surface can also boost light extraction. C. L. Lin et al. applied micro polystyrene (PS) sphere masks and affixed a layer of honeycomb-like nanostructure on the surface of n-GaN (Fig. 7). A layer of latex composed of PS balls and a solution that contained Al ions was applied onto the surface of n-GaN, through which a mask of PS arrays was formed. Then, through an annealing process, the PS particles decomposed and the Al ions were oxidized, resulting in the generation of a nanotextured surface of n-GaN. This led to a 35% increase in LED optical efficiency.[10]

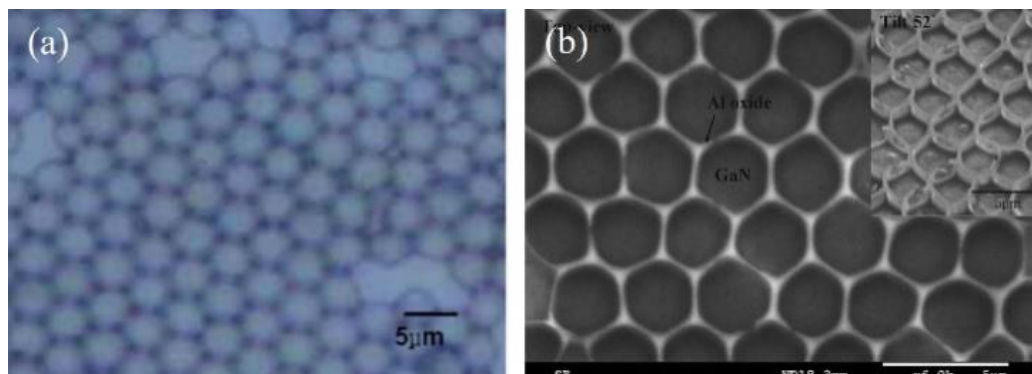


Figure 7. SEM illustrations of (a) PS spheres and (b) honeycomb nanostructures attached to the top of n-GaN layer at 5 μm. [10]

2.2. Interface coarsening

Like the surface of the chip, the flat interface between the epitaxial layer and substrate leads to specular reflection, forming a planar waveguide in LEDs, which hinders light extraction. The specular reflection can be altered by creating microstructures, like cones, hexagons, spheres and nanoholes. Chemical and physical methods are used to achieve randomly or periodically roughened interfaces, which is called patterned sapphire substrate (PSS).

H. Gao et al. used a chemical etching method to produce pyramid patterns of micro- and nanoscale (Fig. 8). First, a SiO₂ layer was deposited and etched after a photolithography process. Then, the photoresist was stripped with a solution containing H₂SO₄ and H₂O₂. Finally, patterned SiO₂ served as a mask, a solution containing a mixture of H₂SO₄ and H₃PO₄ was used for wet etching of the sapphire substrate. SiO₂ was lifted off with an HF solution, leaving the microstructures on the substrate. Similarly, nanostructure was produced with Ni nanoland masks. LED light output was improved by 29% and 48% respectively.[11]

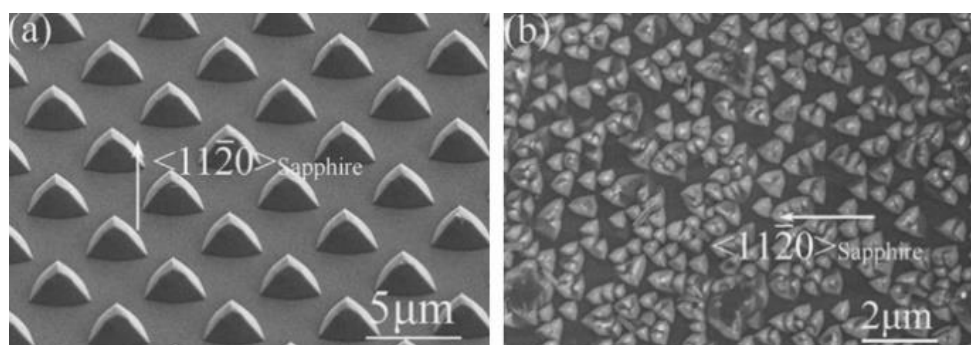


Figure 8. SEM images of pyramidal (a) microstructures at 5 μm and (b) nanostructures on the sapphire substrate at 2 μm.[11]

J. H. Lee et al. produced a rectangular-shaped photoresist pattern through photolithography and altered it into a cone shape through a hard-baking process. Then PSS was attained through an ICP process subsequently (Fig. 9). LED light output was improved by 35%.[12]

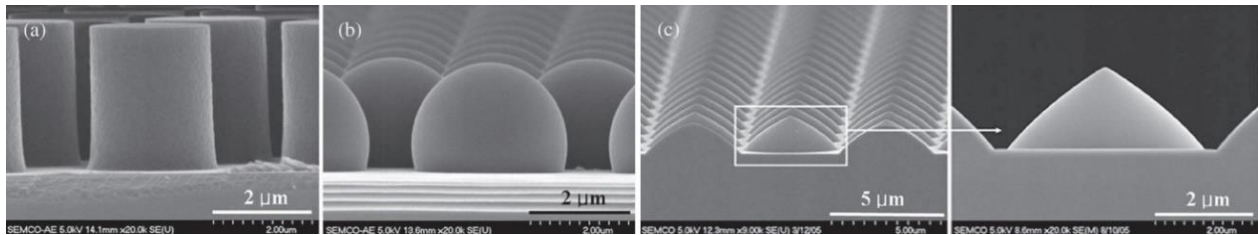


Figure 9. SEM images of (a) rectangular-shaped photoresist at 2 μm, (b) cone-shaped photoresist at 2 μm and (c) PSS at 5 μm and 2 μm. [12]

H. W. Huang et al. generated a nano-hole patterned sapphire substrate (NHPSS) through a nano-imprint lithography process (Fig. 10). They coated a film of polymer on the surface of the sapphire substrate, then placed a mold to create a nano-hole pattern. After removing the mold, they applied an ICP process to reproduce the pattern onto the underlying material. This increased the LED optical power by 33%. [13]

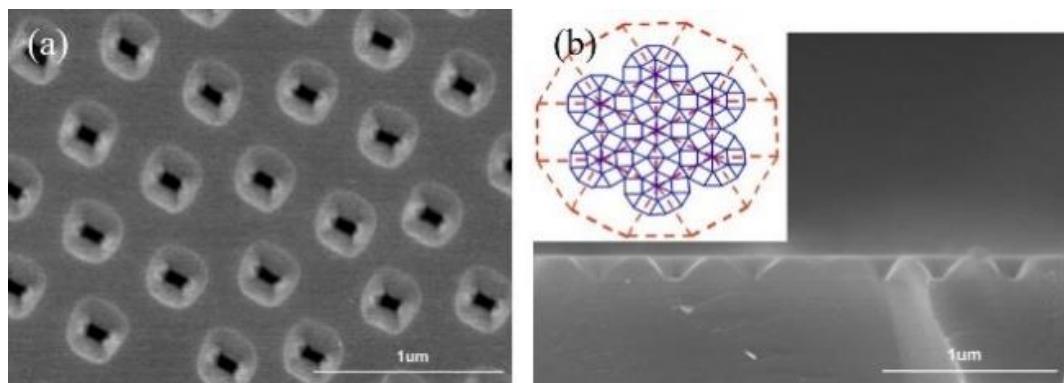


Figure 10. SEM images of NHPSS: (a) Top view image at 1 μm and (b) cross-sectional image at 1 μm with a quasi-crystal model to depict the structure of the holes. [13]

C. -F. Lin et al. developed a roughened patterned backside structure (Fig. 11). They used a high-energy laser to decompose the n-face GaN selectively, then applied chemical corrosion to obtain pyramidally patterned interfaces. The LED spectral intensity was raised by 41%. [14]

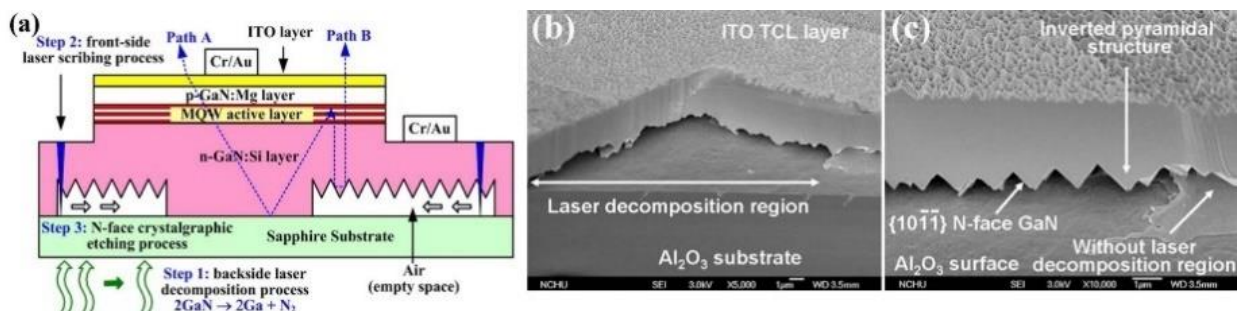


Figure 11. (a) Schematic diagram illustrating the fabrication procedures for the PSS; Tilted-view SEM images: (a) A laser-decomposed region and (b) etched patterns on the n-face GaN. [14]

H. G. Kim et al. designed an embedded air protrusion (EAP) structure (Fig. 12). First, they grew GaN-based LEDs on sapphires covered with SiO_2 patterns. Then, they removed the patterns by chemical corrosion, thus introducing air holes between the GaN and sapphire substrate. LED optical power increased by 120%. [15]

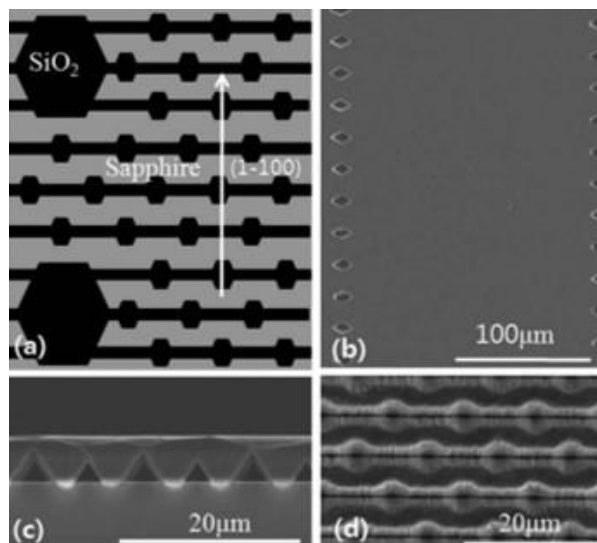


Figure 12. (a) Schematic diagrams of the pattern of the mask; SEM images of the fabricated EAP structure: (b) Top-view illustration of PSS at 100 μm , (c) cross-sectional illustration of PSS at 20 μm and (d) top-view illustration of the n-face GaN stripped from the substrate at 20 μm . [15]

K. Tadatomo et al. etched parallel groove-shape PSS by lithography and a reactive ion etching (RIE) process (Fig. 13). Then, they employed a lateral epitaxial process to grow n-GaN islands on the PSS surface, among which the islands on the ridges extended over the grooves and introduced air gaps into the interface of n-GaN and PSS. The efficiency of LED chips was enhanced from 18% to 24% with this structure. [16]

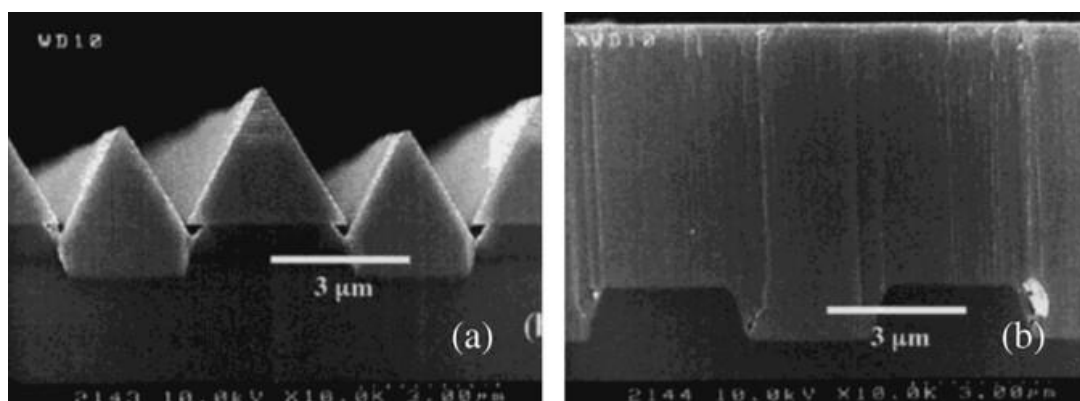


Figure 13. Cross-sectional SEM illustrations of n-GaN epitaxially grown on the PSS at 3 μm (a) at the time of 40 min and (b) when completed. [16]

N. Ham, H.-G. Kim, et al. came up with a periodical self-assembly process based on interface coarsening (Fig. 14). They made masks through photolithography and wet-etched the sapphire substrate. Then, the silica nanospheres were deposited in the holes through a spin-coating process of a colloidal solution. They improved the light extraction efficiency by 37%. [17]

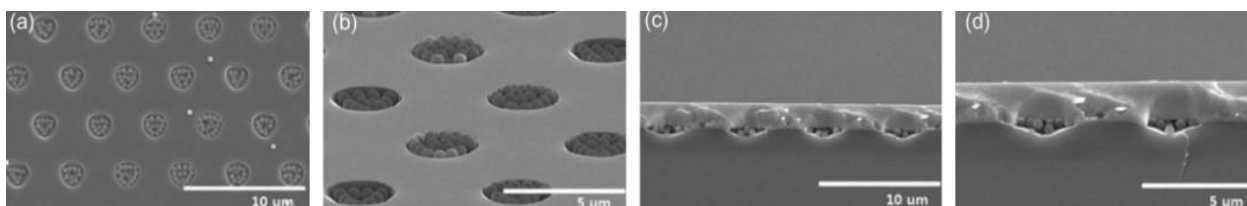


Figure 14. SEM images of PSS with nano-scale silica balls: (a) Top-view illustration and (b) tilted-view illustration; Cross-sectional SEM illustrations of the GaN-PSS interface at (c) 10 μm and (d) 5 μm . [17]

3. Conclusion

GaN-based LEDs have been extensively utilized and developed since the late 20th century. This article provides insights into loss mechanisms of light extraction in GaN-based LEDs and explores different coarsening methods that can significantly alter the conditions of total internal reflection, giving rise to a substantial increase in the light extraction efficiency. By replacing the light reflecting structure with a light scattering structure, surface micro- and nanostructures augment the probability of light emitting from the LEDs or their functional layers, which enhances light extraction. Physical etching such as ICP, RIE, laser and lithography, as well as chemical corrosion and attaching, were included in this paper. The findings of these studies manifest that coarsening can effectively improve the optical efficiency of GaN-based LEDs.

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