Air-structured embedded mirror for enhancement of light extraction efficiency in vertical light-emitting diodes

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We have investigated the effect of the embedded air prism (EAP) on enhancement of light output power of InGaN LED by the various distance ratios. The well-aligned EAP structure was uniformly formed by one step wet etching process on 2 in. sapphire substrate using specific SiO_2 mask pattern. The LEDs with EAP structure significantly improved the optical power of LED by the light redirection toward front side and backside of LED. As a result, the optical powers of optimized EAP LED have been observed to be 2.16 times higher than that of the conventional LED at injection current of 20 mA.

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1. Introduction

There has been rapid developments in GaN-based blue light emitting diodes (LEDs) for their application to solid-state lighting, and high performance back lighting units in liquid crystal displays [1,2]. However, LED devices still require further improvement in their extraction of photons from the multiple quantum wells (MQWs) layers. Researchers from many research laboratories are actively investigating various approaches to improve output efficiency. The limitations in the extraction of the photons are mostly captured by the GaN and sapphire and GaN and air in the form of guided modes. This is largely due to the refractive index differences at the GaN-air (the optical critical angle [$\theta_\varepsilon = \sin^{-1}(n_{air}/n_{GaN})$] is approximately 23°) and GaN-sapphire interfaces, resulting in total internal reflection (TIR), which traps light in the high-index GaN (2.5) and in the sapphire substrate (1.78) (critical angle is 45°) [3]. There have been great efforts in solving this problem. Recently, technologies of embedded structures in GaN have attempted to improve the light extraction efficiency by using a pattern dielectric layer for the photonic crystal, metal particles for the surface plasmon, inverted pyramid shape, and patterned substrates [4–13] and demonstrated significant light extraction enhancement. Therefore, it has been found that the embedded structures in the GaN are an effective way of enhancing the light output power of the device.

However, more detailed studies are necessary to improve the LEDs, by effective shaping and high refractive index difference between the embedded air elements and the GaN.

This work will present a simulation analyzes and comparison with experimental data. Simulation was realized by commercial package *LightTools*™. It is a set of optical modeling tools that allows you to set up, view, modify, and analyze optical systems graphically, in a manner similar to sophisticated CAD programs. Package has the extended numerical precision and specialized 3D ray tracing tools that are required for optical design and engineering [14].

2. Structure description

To analyze the LED structure, geometrical data for simple planal LED is presented. First, the sapphire substrate with size 650×220×100 μm is used. 4-μm-thick layer of Si-doped *n*-type GaN, five-period MQWs of InGaN/GaN pairs for a 460 nm emission and 110 nm *p*-GaN are subsequently placed, and finally, 300 nm indium titanium oxide (ITO) with refractive index of (1.9) is positioned. The surface source with Lambertian intensity distribution is used as an emitter without the need of any additional features. The size of the source matches the lens size of the LED. After simulation it was found the extraction efficiency of conventional planar LED is 15.9 %.

3. LED with patterned sapphire substrate (PSS)

First of all the model was tested on more popular structure of LED with patterned sapphire substrate (PSS) [15]. Light-emitting diodes (LEDs) performance can be enhanced by PSS technique due to the reduction of dislocation density by the lateral growth mechanism. Additionally, it was found that inclined facets of PSS are another important factor for the enhancement of performance due to the increase of light extraction by such facets [16]. Furthermore, smaller spacing between each pattern is also found to help enhance the LEDs performance [17, 18]. To prove it, structure with different placement (hexagonal of rectangular), sizes of hemisphere and distance between them was calculated. Results presented on Fig. 1 show the week dependence from size of hemisphere and placement but larger variation of results with change of DD parameter (relation of distance between hemispheres and its diameter). Also hexagonal packing of structures is more effective due to larger fill-factor and more effective redirecting of rays in LED. The blue dot shows the data received from [18] (Hemisphere PSS structure with DD factor of 1.1 gives 44% improvement comparing to conventional LED).

Further increasing can be made by including air structures in GaN due to decreasing effective index of refraction [19].

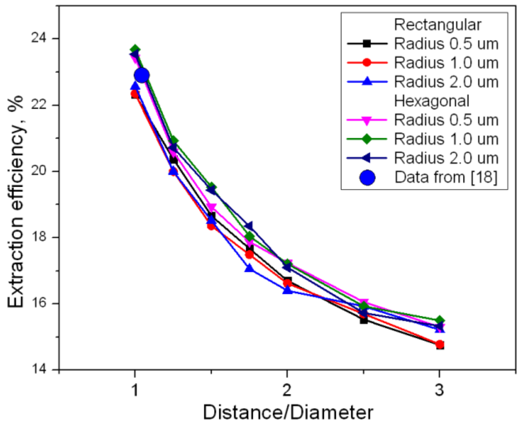

Fig. 1. Extraction efficiency vs. DD parameter for different sizes of hemisphere and packaging.

4. Air prism arrays as an embedded reflector

In this section extraction efficiency of LED with embedded air – prisms in GaN will be analyzed. Schematically structure presented in Fig. 2.

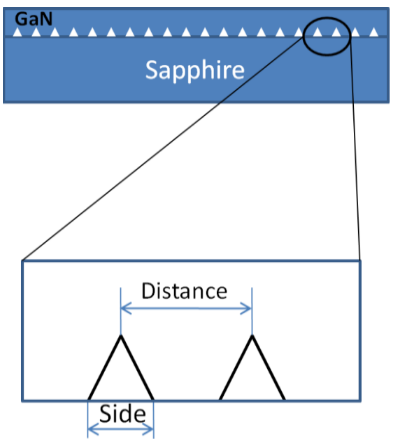

Fig. 2. Air prism embedded reflector.

The formation of the air prism arrays is attributed to the etching rate on the GaN planes characteristic during wet etching [19]. It has been observed that the stripe SiO_2 mask vanishes, and that TFAPs are uniformly formed. After this process, regular air-prism arrays are formed in the place of the vanishing stripe SiO_2 pattern by an injection of aqueous KOH solution through the exposed SiO_2 hexagonal patterned region. Here, the aqueous KOH solution etches specifically on the *N*-face GaN {000-1}. The etching starts from the *N*-face, and stops at the {10-1-1} facets of the stable chemical bond, adjacent to the sapphire substrate. This family of planes has an angle $\theta = 62°$ with respect to the {0001} plane. The height of the air prism has been already determined by the crystallographic plane of GaN. The height is about tan $\theta \times$ stripe mask width/2.

Such structure were analyzed for different prism heights and prism positions (‖ - parallel and ═ - perpendicular to long side of LED). Fig. 3 shows that EE for perpendicular structure is slightly higher because more stripes can be placed. The blue dots shows the data extracted from [19] (LED II is the efficiency for conventional LED, LED-I is an air prism structure with DS (distance to side) parameter of 2 gives 33% and LED-III is two-floor air prism arrays gives 113% of efficiency improvement, respectively). Here we assume that LED-III structure can be replaced as one-layer array with DS factor of 1).

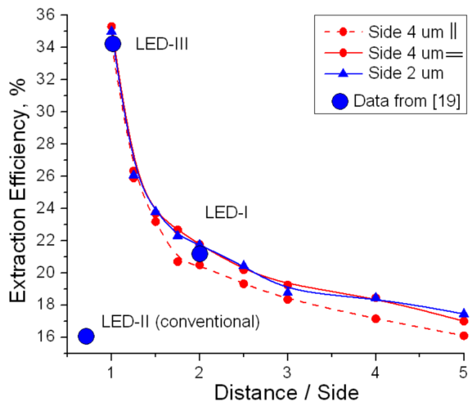

Fig. 3. Extraction efficiency vs. DD parameter for different prism heights.

As in the PSS LED, EE change strongly with change of Distance/Side parameter nor the size. It allows using larger mask pattern to deposit SiO_2 on substrate.

Fig. 4 shows change of EE for air trapezoid array with different base angles from 62° (prism case) up 90° (line stripe case). Maximum EE is for structure with angle 82° due to closer to optimal round shape.

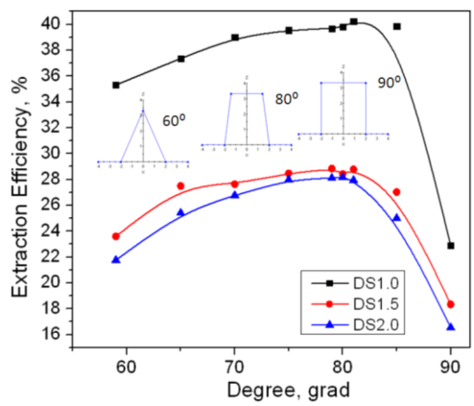

Fig. 4. Extraction efficiency vs. base angle for different Distance/Side values.

5. LED with 3D air textures

In previous chapter, we discuss 2D structures but 3D structures are more efficient due to more effective light redirection (Fig. 5). Results show that devices with 3D hemispherical air textures have the maximal efficiency. Slightly lower efficiency is for devises with cone texture and the lowest for pyramidal structures. The red dot shows the data extracted from [20] (3D air-conical structure with DD parameter of 2.25 gives 54% efficiency enhancement comparing to planar LED).

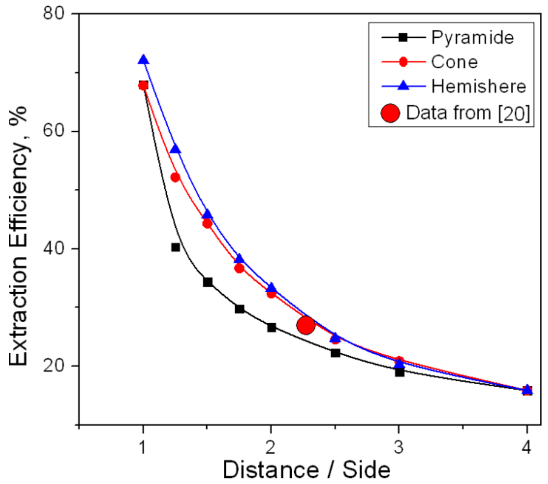

Fig. 5. Extraction efficiency vs. DD parameter for different 3D textures.

5. Conclusions

Extraction efficiency for blue GaN-based LED is analyzed using commercial 3D ray-tracing program LightTools^{TM}.

Analysis of PSS device shows strongly dependence between the size of sphere and packing density but weakly depend on hemisphere size. Also hexagonal packing of structures is more effective due to larger fill-factor and more effective redirecting of rays in LED.

Structure with air-prism structure also shows independence on size of prism but strong relation on distance/size parameter. It allows using larger mask pattern to deposit SiO_2 on substrate.

LED with air trapezoidal structure shows maximal efficiency at side angle of 80^0 because such structure is closer to hemispherical one.

LED with 3D air textures the maximal efficiency shows devices with hemispherical texture. Slightly lower efficiency for cone and the lowest for pyramid structures.

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