Enhanced Light Extraction Efficiency (LEE) of GaN-based LED Die through Substrate Side Surface Grooving

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Abstract. High refractive index difference between GaN-based light-emitting diode (LED) die material and surrounding medium causes low light extraction efficiency. Introduction of surface grooves to sapphire substrate side surfaces improves the light extraction efficiency of GaN-based LED die by altering the normal for the impinging light rays inside the substrate layer. Comparison of light output power given out by GaN-based LED die with grooved sapphire substrate and un-grooved sapphire substrate were studied using ray-tracing simulation. Three types of surface grooves at different aspect ratios were simulated which includes elliptical groove, triangular groove and rectangular groove. Based on the results obtained, GaN-based LED die with elliptically grooved sapphire substrate gives the best enhancement in light output power by 121.2426% compared to an un-grooved GaN-based LED die at an aspect ratio of 0.05. Surface grooves with curvature or angled plane gives a better enhancement in light extraction efficiency compared to a flat surface.

1. Introduction
Light-emitting diodes (LEDs) has dominated the current commercial lighting market due to its superior durability and efficiency over traditional light sources [1]. There are various types of LEDs available in the market. Among those LEDs, GaN-based LED grabs the most attention due to the fact that the GaN-based LED can be converted into white LED with the addition of phosphor [2]. Generally, the substrate layer of a GaN-based LED die would be sapphire. Lattice mismatch and difference in thermal expansion coefficients between GaN and sapphire causes high density of threading dislocations [3]. Currently, studies are being carried on growing GaN layer on GaN substrate to overcome the treading dislocation.

Light rays are generated as a result of recombination of electrons and holes in the active region. When the LED is forward biased, electrons from the n-GaN and holes from the p-GaN are injected into the multi-quantum well. Recombination of electrons and holes yields blue light which corresponds to the energy bandgap of the semiconductor material [2]. The efficiency of a GaN-based LED is limited by its inability to extract most of the light rays generated in the active layer [4]. This is due to the high refractive index difference between the die material and the surrounding medium [5]. Most of the light bounces back into the die rather than exiting due to total internal reflection [4]. This light is then trapped inside the die and eventually absorbed by the die material itself [5].

Different approach were used in previous studies on enhancing light extraction efficiency of LEDs. These approach include surface texturing [6], die shaping [7], photonic crystals [8], buried micro-reflectors [9] and reflective submount [9]. Different level of enhancement in light extraction
efficiency were achieved using these methods. Among those method, surface texturing has shown notable level of enhancement in light extraction efficiency \cite{10}\cite{11}.

In this paper, surface texturing was simulated by creating different groove structures on the sapphire substrate side surfaces since part of the light rays generated in active region will be also trapped inside the substrate layer. Introduction of groove structures would alter the normal for the light rays confined in the substrate layer. This increases the possibilities of light rays escaping into the surrounding medium. Effect of surface grooving on sapphire substrate on enhancement in light output power has been examined using ray-tracing simulation. Shape and dimension of the groove structures were varied to study the best shape and dimension that gives the best enhancement in light output power.

2. Theory

2.1. Effect of Total Internal Reflection

Light generated during recombination process in the LED die’s active layer will propagate across the die layers and into the air based on reflection and refraction phenomena. The reflection that occurs inside the LED die is called total internal reflection where the light rays will continuously hit the die surface causing the light ray to bounce inside the die \cite{12}. In order for a light ray to undergo total internal reflection, two condition need to be satisfied. The first condition is the propagation of light ray should occur from a higher refractive index medium to a lower refractive index medium and the second condition is that the angle of incidence of the light ray should be greater than the critical angle for the two media \cite{13}. When a light ray undergoes total internal reflection, the light ray will not be able to escape into the surrounding and eventually will be absorbed by the die material itself. Considering a GaN-based LED die with one GaN layer and a substrate, the critical angle for each material can be calculated using Snell’s law \cite{13}. The refractive index of GaN and sapphire are taken as 2.4 and 1.78 respectively \cite{10}. Based on Snell’s law, critical angle of GaN layer to air, GaN layer to sapphire substrate and sapphire substrate to air is shown in Table 1.

| Material Interface          | Critical Angle |
|-----------------------------|----------------|
| GaN-air                     | 24.6243°       |
| GaN-sapphire substrate      | 47.8736°       |
| Sapphire substrate-air      | 34.1802°       |

The light rays generated inside the GaN layer will have three ways of light propagation to the air. First, light rays from GaN layer can emitted into the air if the light rays have angle of incidence less than 24.6243°. If the light rays has incidence angle greater than the critical angle, the light rays might undergo continuous total internal reflection inside the GaN layer or can pass through into sapphire substrate if the light rays hits the GaN-sapphire substrate interface at an angle less than 47.8736°. The light rays that are able to pass into the sapphire substrate can be released into the air if the light rays hits the sapphire substrate-air interface at an angle less than 34.1802° or else will undergo total internal reflection inside the substrate. Total internal reflection causes limited emission of light rays into the air.

2.2. Effect of Surface Texturing on Light Extraction Efficiency

Surface texturing is a method of enhancing the light extraction efficiency of LED die by implementing surface textures on LED die surface. Introduction of surface textures would enable the light rays confined in LED die to escape into surrounding medium by randomizing the propagation of light rays and increasing single path escape probability \cite{14}. When a light ray strikes a medium interface more than the critical angle, it will be reflected back into the same medium. When the surface of the medium is textured, the normal to the surface would be altered thus changing the angle of incident of
the light ray. The light ray may escape from the medium on the first attempt or the next attempt. Figure 1 shows the illustration of a GaN-based LED die with one side elliptically grooved sapphire substrate with an aspect ratio of 0.0625.

![GaN-based LED die with one side elliptically grooved sapphire substrate](image1.png)

**Figure 1.** GaN-based LED die with one side elliptically grooved sapphire substrate

On the left side, a light ray given out at 33° from the source will enter the sapphire substrate with an angle of refraction of 47.2519°. This ray will then impinge the side surface of the sapphire substrate at an angle of 42.7481° and then gets reflected to the bottom surface at an angle of 47.2519°. Since the incident angle of this light ray to the sapphire substrate is greater than the critical angle of sapphire substrate to air, the light ray bounces back to GaN-sapphire substrate interface which results in continuous total internal reflection. On the right side, the light ray given out at 33° from the source will enter the sapphire substrate with an angle of refraction of 47.2519°. This ray will then impinge the side surface of the sapphire substrate. Since the side surface is now elliptically grooved, the normal for this light ray will be altered which results in an incident angle of 29.1338°. The incident angle of the ray is now less than the critical angle for sapphire substrate-air interface. The light ray will escape from the sapphire substrate into air [3].

3. Simulation

The ray tracing simulation software used for this simulation is Zemax. Three different types of groove structures were simulated which are elliptical groove, triangular groove and rectangular groove. These structures were simulated on the sapphire substrate side surfaces of a GaN-based LED die. The aspect ratio of the groove structures was manipulated in order to study the effect of dimension of groove structure to the enhancement in light output obtained. Figure 2 below shows the simulated groove structures.
The width of the grooves were manipulated from 10μm to 40μm while the depth of the grooves were manipulated from 0.5μm to 2.5μm. Aspect ratio of the grooves created is calculated using the formula below [15].

$$\text{Aspect Ratio} = \frac{\text{Depth of groove}}{\text{Width of groove}}$$  \hspace{1cm} (1)

Figure 3 shows the implementation of the surface groove on the sapphire substrate as per the design. As is seen, designs are implemented in a length wise fashion instead of spots.

Output power of these surface grooved LED die were compared with that from an un-grooved LED die. Light output power enhancement was calculated using the formula below.

$$\text{Light output power enhancement (\%)} = \frac{P_{\text{Grooved}} - P_{\text{Un-grooved}}}{P_{\text{Un-grooved}}} \times 100\%$$  \hspace{1cm} (2)
Neglecting the effect of encapsulant on the die performance, the ray-tracing includes both the active region and substrate. The active region is based on GaN and the substrate is based on sapphire. The epitaxial layers were simplified by just using GaN layer at 30µm thickness. The GaN layer thickness was fixed at 30µm to match the actual blue GaN LED die used in experimental stage. The emitters, quantum well in actuality, are simulated via spherical sources at which nine are placed equidistant from each other and with each emitting 10000 rays at 1mW. These rays undergoes refraction and reflection inside the GaN-based LED die and the rays that managed to escape from the LED die will hit the spherical detector. Figure 4 shows illustration of side and top view of simulation structure of GaN-based LED die.

4. Result and Discussion
Implementation of surface grooves on the side surfaces of the sapphire substrate reduces total internal reflection inside the substrate layer through two ways. Firstly, surface grooves reduces the incident angle of impinging light rays to the substrate layer by changing normal for the light rays. Reduction in incident angle value would increase the probability of the light rays to fall below the critical angle range making the light rays to escape to the surrounding. Secondly, these surface groove enhances angular randomization. When a light ray could not escape to the surrounding in the first attempt, it make escape in the second or third attempt since all side surfaces are grooved. The enhancement in light output power for the three groove structures at different groove depth are shown in Figure 5, Figure 6 and Figure 7. Figure 9 shows comparison of three best enhancement obtained for all three groove structures.
Figure 5. Lop enhancement against depth of elliptical surface groove

Figure 6. Lop enhancement against depth of triangular surface groove

Figure 7. Lop enhancement against depth of rectangular surface groove
Figure 8. Comparison of three highest light enhancement for all surface grooves

As shown in Fig. 8, the highest enhancement in light output power is obtained for elliptical groove which is 121.2426% at an aspect ratio of 0.05. The three best enhancement obtained for elliptical groove are from 0.5μm groove depth. Based on Fig. 6, enhancement in light output power is greater for 10μm groove width followed by 20μm, 30μm and 40μm. Smaller groove aspect ratios gives better enhancement for elliptical groove structure. Based on Fig. 7, increase in depth of triangular groove shows increase in the light output power enhancement. Since the triangular groove has angled planes, the alteration of incident angle for the light rays will be greater at greater depth. Increase in light output power at a constant depth shows a decline as the width of the groove increases. Compact groove structure gives higher possibilities for light rays to impinge the sapphire substrate-air interface at a lower incident angle. Based on Figure 7, rectangular groove structure with a groove width of 10μm gives a compact groove structure that alters the incident angle of the light rays. Rectangular grooves more than 10μm width does not give any enhancement in light output as the texture neither has curvature nor angled plane for normal alteration for the light rays. For all the three groove structures, shortest width gave the best enhancement compared to longer structure width.

5. Conclusion

Implementation of groove structures on sapphire substrate side surfaces enhances the light output of the die by extracting out the light rays that would undergo continuous total internal reflection. Among the simulated surface textures, elliptical surface texture gives best enhancement in light output by 121.2426% at an aspect ratio of 0.05 for 10μm groove width compared to un-grooved sapphire substrate. Surface grooves with curvature or angled plane gives a better enhancement in light extraction efficiency compared to a flat surface.

6. References

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