Double-sided Hemispherical Pattern Design on Patterned Sapphire Substrate of GaN-based LEDs

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***Abstract*— In this paper, we established a optical model and optimized a double-sided hemispherical patterned sapphire substrate (PSS) for highly efficient flip-chip GaN-based light emitting diodes (LEDs). A simulation is conducted to study how light extraction efficiency changes with the change in the parameters of the unit hemisphere for LEDs fabricated on hemispherical PSS. Results show that the light extraction efficiency of flip-chip LEDs can be enhanced by the optimized hemispherical PSS by over 50% and is approximately 115% higher than that of flip-chip LEDs with non-PSS.**

Keywords—flip-chip LED, double-sided pattern design, hemispherical patterns, light extraction efficiency

I. INTRODUCTION

Patterned sapphire substrate (PSS) technique have been intriguing due to its benefit to the epitaxial growth of GaN and light extraction efficiency (LEE), leading to enhancement of external quantum efficiency (EQE) for GaN-based LEDs[1-3]. Recently, the hemisphere pattern is reported as an efficient pattern to be fabricated on the sapphire substrate of GaN-based LEDs [4, 5]. Studies have shown that a hemispherical PSS pattern is better than other patterns in terms of improving the light extraction efficiency of LEDs [4, 6]. However, it is not reported before that the hemisphere patterns can be fabricated on double sides of sapphire substrate and how is it to influence the LEE of flip chip. In this study, we simulate and analyze the light extraction efficiency of flip-chip GaN-based LEDs with different types of hemispherical patterns.

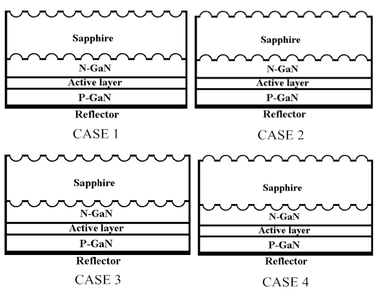

Fig. 1. Four types of hemispherical pattern on the two surfaces of the sapphire substrate.

II. OPTICAL MODEL OF PSS-LED FLIP CHIP

In this section, the optical models of a PSS-LED flip chip are established. As shown in Fig.1, this chip has a patterned sapphire substrate which four types hemisphere patterns were fabricated on the top and bottom surfaces.

According to the refraction law, the photons from active layer (light source) have greater chance to escape from the chip due to curved surface structure of hemisphere. And the light extraction efficiency of chip enhanced while the total internal reflection reduced [7].

The optical model of flip chip is composed of sapphire substrate, n-GaN layer, active layer and p-GaN layer. And their optical parameters and thickness are listed in Table 1.

Table 1. Optical parameters and thickness of the model

materials	Thickness/μm	Refractive index	Absorption coefficient/mm^{-1}
Sapphire	100	1.67	0.001
N-GaN	4	2.45	10
Active layer	0.1	2.45	10
P-GaN	0.3	2.45	10

The light extraction efficiency of PSS-LED flip chip with different hemispherical patterns is simulated. The simulation is based on the Monte Carlo ray tracing method [8, 9].

III. RESULTS AND DISCUSSIONS

In the below, the hemispherical patterns are considered as efficient structures for the enhancement of light extraction efficiency. These patterns were fabricated on top and bottom surfaces of the sapphire substrate. The parameters that we focus on are the edge distance and radius of hemispherical patterns, which influence the LEE of LEDs and the results are shown in Fig.2 and Fig.3.

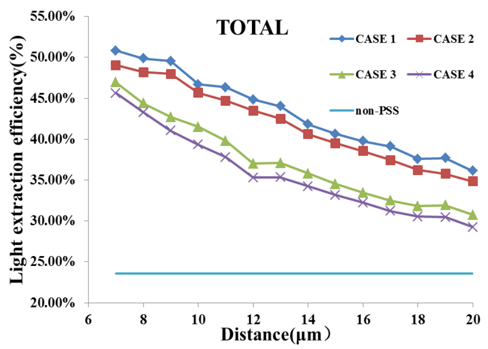

Fig. 2. LEE of the LED flip chip with hemispherical patterns on the two surfaces of the sapphire substrate.

Fig.2 shows that the influence to the LEE caused by variation in the distance is opposite. When the distance increase, the LEE increase. It can be attributed to the decrease in the number of patterns when increasing distance. The more the patterns are dense, the better the LEE is. When the distance is 7µm and the radius is 3µm, the maximum LEE 50.8%, which is 115.3% higher than the LED chip on a normal planar sapphire substrate (non-PSS), respectively.

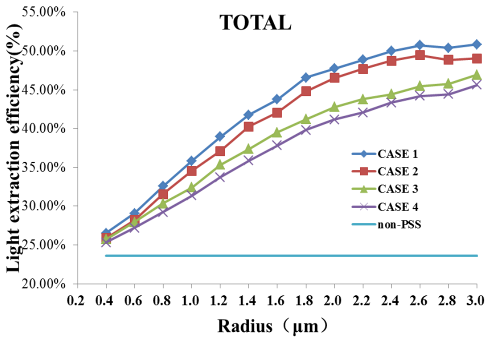

Fig. 3. Total LEE of flip chips grown on hemispherical PSS with optimized distance as a function of the radius

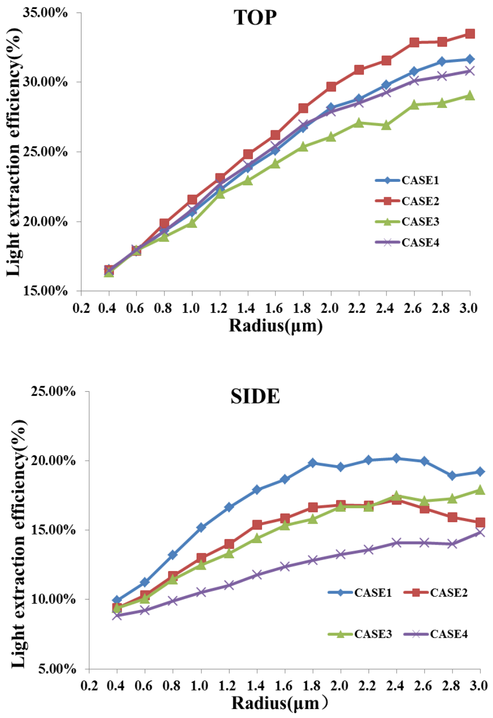

Fig. 4. LEE from top and four side facets of PSS-LED chip as a function of radius, when the distance is 7µm

More detailed analysis is given in Fig.3 and Fig.4, which represents the LEE from total, top, and sum of four side facets of the chip model as a function of the radius, respectively. It reaches its maximum when the radius is 3µm. Fig.3 demonstrates that generally, a larger unit hemisphere helps to achieve larger total LEE. In Fig.4, we spot that the increasing radius is helpful to top LEE, which is similar to the total LEE. With the increase in the radius, the side light extraction efficiency of CASE 1 and CASE 2 presents a fluctuating downward trend after the radius of 1.8 µm, whereas the light extraction efficiency of CASE 3 and CASE 4 increases slowly. It is informative to guide us to choose the optima parameter for some specially designed LEDs, such as side-illuminating LEDs.

The above results indicate that the small distance and large radius of hemisphere for hemispherical PSS would be effective to enhance LED efficacy. It also reveals that when concave hemispherical patterns were fabricated on the top and bottom surfaces of the sapphire substrate of the PSS LED flip chip, the light extraction efficiency of the hemispherical PSS improved; its total luminous flux exhibited the highest light extraction efficiency at a distance of 7 µm and radius of 3 µm.

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