Improvement of Light Extraction Efficiency of GaN-based Flip-chip LEDs by a Double-sided Spherical Cap-shaped Patterned Sapphire Substrate

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***Abstract*—This study reports on the development of a cost- and time-effective means to optimize a double-sided spherical cap-shaped 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 (LEE) changed as a function of alteration in the parameters of the unit spherical cap for LEDs that are fabricated on a double-sided spherical cap-shaped PSS. Results show that the optimal double-sided spherical cap-shaped PSS can enhance LEE of flip-chip LEDs by over 5% compared with flip-chip LEDs grown on the optimal double-sided hemispherical PSS.**

***Keywords*—flip-chip LED, double-sided pattern design, spherical cap-shaped pattern, light extraction efficiency**

I. INTRODUCTION

Patterned sapphire substrate (PSS) technology is a means by which periodic patterns are etched onto the surface of the sapphire substrate, with the intention of reducing the loss of rays that is designed to improve the light extraction efficiency(LEE) of LED flip chip[1]. Studies have shown that a patterned sapphire substrate which has concave spherical cap-shaped patterns on its top surface and convex spherical cap-shaped patterns on its bottom surface is better than other patterns in terms of improving the LEE[2,3]. However, for practical matters, the machining errors of patterns are always exist, which means the hemispheres are not as prefect as we design. In this study, we simulate and analyze the LEE of GaN-based LED flip chip to find out the optimal range of each parameter of the double-sided spherical cap-shaped patterns.

II. OPTICAL MODEL OF PSS-LED FLIP CHIP

As shown in Fig.1(a), the model is composed of a patterned sapphire substrate, which has concave spherical cap-shaped patterns on the top surface and convex spherical cap-shaped patterns on the bottom surface, n-GaN layer, active layer and p-GaN layer. And their optical parameters and thickness are listed in Table 1.

Although optical simulation based on Monte Carlo ray tracing method has been widely applied in PSS technology research and has been proven to be an effective and convenient method, the theory of wave optics need to be considered when the pattern size is in the nanometer range[4,5].

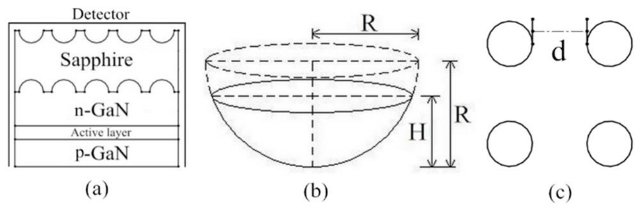

Fig. 1. (a) The optical model of the flip chip with double-sided spherical cap-shaped PSS, (b) the parameters of the spherical cap-shaped patterns, and (c) the arrangement of the spherical cap-shaped patterns.

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

III. RESULTS AND DISCUSSIONS

In the simulation, we focus on three parameters of the patterns to study their influence on the LEE of LED and explore the best spherical cap-shaped pattern design. The three parameters are the distance between two adjacent spheres, the radius and height of each sphere cap. According to the research and experiments of other groups, enhancing the LEE of the LED horizontal chip is highly effective when the radius of spherical patterns is 3 μm. However, with the progress of technology nano-scale patterns can be fabricated. Therefore, nano-scale and micron-scale patterns are both considered in this work. The parameters and arrangement of the spherical cap-shaped patterns are shown in Fig. 1(b) and Fig. 1(c).

At first, we set the patterns as hemispheres to find out the relationship between the total LEE with radius or distance, and the results are shown in Fig. 2 and Fig. 3. As shown in Fig. 2, we set radius and height are equal, and their values are 1, 2 and

3 μm, respectively. When the distance increases, the total LEE decreases steadily. The total LEE keeps at a high level before the distance of 1 μm.

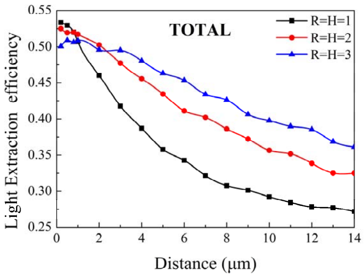

Fig. 2. The total LEE of the flip chip grown on hemispherical PSS with various radii as a function of the distance.

In Fig.3, we fix the distance to 0.2, 0.5, 0.8 and 1.2 μm and the height has the same value with the radius to simulate the model to determine the optimal range for the radius. The changing tendency shows that as the radius increases, the total LEE of the LED flip chip with hemispherical PSS increases at first, and then declines slowly. Furthermore, the total LEE of each case reaches the maximum when the ratio of radius and distance is equal to 2.

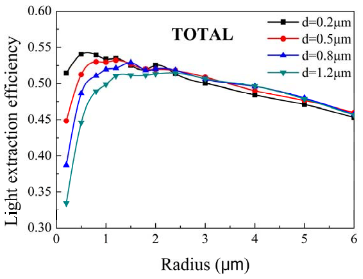

Fig. 3. The total LEE of the flip chip grown on hemispherical PSS with different distances as a function of the radius.

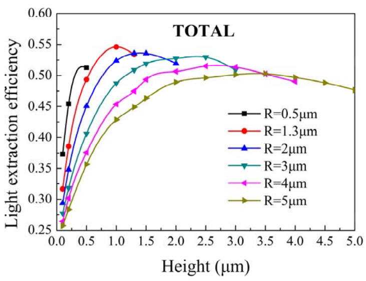

Fig. 4. The total LEE of the flip chip grown on spherical cap-shaped PSS with various radii as a function of the height.

After that, as shown in Fig. 4, we fix the distance at 0.5 μm and choose six different radii, including 0.5, 1.3, 2, 3, 4, and 5 μm, to simulate and analyze the relationship between the total LEE and the height of the spherical cap-shaped patterns. With the height increases, the total LEE increases at first, and then decreases. For each case, when the ratio of height and radius is in the range of 0.5 to 1, the total LEE keeps at a high level. Furthermore, the optimal double-sided spherical cap-shaped PSS can enhance the total LEE of the flip chip by over 5% compared with the flip chip grown on the optimal hemispherical PSS.

IV. Conclusion

The above results show that, by using flip-chip packaging, the total LEE keeps at a high level when the distance is less than 1 μm, the ratio of radius and distance is equal to 2, and the ratio of height and radius is in the range of 0.5 to 1. By applying these parameters, the process of LED flip chip is more flexible. Compared with the total LEE of the optimal hemispherical PSS-LED flip chip, the total LEE of the optimal spherical cap-shaped PSS-LED flip chip is 5% higher. Our work could serve as a reference for PSS GaN-based LED flip chip in relevant fields.

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