Light extraction efficiency analysis of GaN-based LED with nanopatterned sapphire substrates

Finite-Difference Time-Domain

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Abstract—In this paper, the nano-patterned sapphire substrates (NPSS) light emitting diode (LED) is proposed to simulate with the Finite-Difference Time-Domain (FDTD) algorithm. The NPSS with pattern of the triangle arrays is simulated. A trend of the Light Extraction Efficiency (LEE) enhancement is found when we change some parameters for the pattern on the NPSS. The LEE enhancement is observed not only on top monitor but on bottom monitor. The top monitor receives the optical wave which can be extracted to air and the bottom monitor receives the optical which propagates to the sapphire under NPSS. And the escape cone of the angular space is proposed discussing the trend of NPSS LED.

Index Terms—light emitting diode (LED), light extraction efficiency (LEE), patterned sapphire substrates (PSS), Finite-Difference Time-Domain (FDTD)

I. INTRODUCTION

Since the light emitting diode (LED) is invented in 1960s, it emits the light in a variety of colors depend on the energy gap of the active semiconductors. Besides, the LED present many advantages including the long lifetime, small volume, lower energy consumption and high resist compression compare with the conventional light sources. All the advantages of the LED fit the request of the energy crisis and it’s an undisputed fact that the LED will be the new indicator of the illumination in the future [1].

For improving the external quantum efficiency (EQE) of the LED, there are two main ways: increasing internal quantum efficiency (IQE) and increasing light extraction efficiency (LEE). However, the LEE is one major part to increase the EQE of the LED. Because the refractive index of the semiconductor relative to air is high, the massive total internal reflection and Fresnel loss are occurred in the conventional LED. A lot of methods have been applied for improving the LEE of the LED, such as the nano-patterned sapphire substrates (NPSS) [2-3], surface texturing [4-5], rough-surface [6], flip chip [7], and thin film LEDs [8].

In recent years, the NPSS LED is proposed to use because the NPSS LED not only can increase the IQE but also can increase the LEE of the LED. In this work, the LEE enhancement of the NPSS LED with the triangle pattern is calculated by the Finite-Difference Time-Domain (FDTD) algorithm. And a trend of the LEE enhancement is found when we change some parameters for the pattern on the NPSS. And the trend is analyses by the escape cone of the angular space.

II. PARAMETER OF THE NPSS MODEL FOR FDTD SIMULATION

The NPSS LED simulation contains a P-GaN layer, MQW, an N-GaN layer, and a sapphire substrate with the nanopattern as shown in the Fig. 1(a). The thickness and refractive index of each layer for the FDTD simulations are shown in the Fig. 1(b). In the Fig 1(a), the perfectly matched layers (PML) boundary conditions are added to the edge of the simulation region. The PML boundary absorb incident light with zero reflection [9]. The top monitor receives the optical wave which can be extracted to air and the bottom monitor receives the optical wave which propagates to the sapphire under NPSS. The LED chip area of 16×16 (μm)2 is considered in the FDTD simulation. In order to observe the LEE enhancement of the NPSS LED, the triangle is used as pattern on the NPSS. Furthermore, some variables for pattern on the NPSS such as period (P), high (H) and diameter (D) are taken into account when we optimize the NPSS LED to get the larger LEE enhancement shown in the Fig. 1(a).

There are two definition of the variables, filled factor (D/P) and aspect ratio (H/D) for the fabrication process issue. The filled factor and aspect ratio are used conveniently to avoid the difficulties of the manufacture for pattern on the NPSS.
III. THE LEE ENHANCEMENT OF THE TRIANGLE NPSS

The NPSS with pattern of the triangle arrays is simulated. The filled factor is fixed with 0.6 [10] and the two other variables, period and aspect ratio, are swept. The top LEE enhancement and the bottom LEE enhancement are shown in the Fig. 2.

The Fig. 2(a) specifies that top LEE enhancement almost doesn’t enhance obviously when the period is below 400 nm. The reason may be that the period of the triangle NPSS is too small to vary the optical wave from the MQW layer. And in the Fig. 2(a) and Fig. 2(b), a trend show that the larger top LEE enhancement and bottom LEE enhancement appear simultaneously at the aspect ratio with 1 for an increasing period. It means that the optical wave can be extracted efficiently from the NPSS LED to air with this geometry parameter. The top LEE enhancement can be used to illuminate directly and the bottom LEE enhancement can be reflected to the top monitor if the reflector is added at the sapphire bottom surface. Therefore, the larger top LEE enhancement and bottom LEE enhancement are the good performance to application of the illumination. The distributions of the electric fields in the N-GaN layer are illustrated in the Fig. 2(a). The electric field density in the N-GaN layer shows that the triangle NPSS can efficiently reflect the optical wave from the MQW rather than the no pattern due to the slant angle of the triangle NPSS.

According to [5], the escape cone of the angular space can be controlled by changing the slant angle of pattern. The slant angle of pattern with triangle NPSS is labeled as \( \alpha \) in Fig. 1(a). In this work, we vary the aspect ratio of triangle NPSS, so that the slant angle can be modified. The simple escape cone of the angular space is shown in Fig. 3, the red circle with a radius of \( R_1 \) is the escape triangle for the GaN/Air interface. The blue circle with a radius of \( R_2 \) is the escape triangle for the GaN/Sapphire interface. According to Snell’s law, \( R_1 \) and \( R_2 \) can be calculated to be 240 and 460 respectively. With the slant angle of triangle NPSS, the center of the blue circle is at a distance of slant angle from the origin of angular space. There are two of main path in NPSS LED shown in Fig. 1 (a) when the LEE enhancement from side of NPSS LED is not taken into account. The path 1 is the optical wave from MQW layer and resulted total internal reflects from the triangle NPSS into air. The path 2 is the optical wave from MQW layer and transmitted into sapphire. The path 1 and path 2 are received with top and bottom monitor respectively in our model without reflection at the bottom surface of sapphire substrate. The LEE enhancement from monitor of path 1 and path 2 can be
explained by the region of angular space. In Fig. 3, the region A is the overlapping area between the outside area of the blue circle and the inside area of the red circle. The region B is the inside area of the blue circle. The path 1 and path 2 increase as the probability of region A and region B increase, respectively. Therefore, the LEE enhancement from monitor of path 1 and path 2 can be analyses with the region of the angular space by changing the slant angle of triangle NPSS. For path 1, the region A increases when the slant angle of triangle NPSS increase. However, the region B is enlarged for an increasing slant angle, so that the probability of total internal reflection from NPSS is decreased for an increasing slant angle. Owing to the two factors constrain each other, the top LEE enhancement reach larger result at aspect ratio with 1. For path 2, the region B increases when the slant angle of triangle NPSS increase. However, the region B will reach the max area and then decrease by increases in slant angle due to the limited size of angular space. Owing to the two factors constrain each other, the bottom LEE enhancement reach larger result at aspect ratio with 1. This trend is good performance to application of the illumination when the reflection of is added. Moreover, it is easy to fabricate the NPSS with the aspect ratio with 1 rather than with a single value for the larger LEE enhancement in the manufacturing processes.

IV. CONCLUSIONS

In this study, the trend is found by FDTD simulation and analysis of the escape cone of the angular space. When the triangle NPSS is used, the period below 400 nm results the lower top LEE enhancement. When the aspect ratio with 1 is used, it is shown that the larger top and bottom LEE enhancement are appeared.

Figure 3. The simple escape triangle with triangle NPSS that has a slant angle of the slant angle degrees in the angular space.

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