Light Extraction Enhancement Analysis of GaN-Based LED with Surface Spherical Crown Array

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***Abstract*-For promoting the light extraction efficiency (LEE) of GaN-LED with nano-spherical hexagonal arrays, finite-difference time-domain (FDTD) method was used for optimizing the structure parameters such as spherical radius and height. The LEE of GaN spherical crown hexagonal array with 473nm radius and 250nm height over the LED surface exhibited 5.7 times enhancement than that of the planar LED, better than the LEE of whole-sphere array and pure-hemisphere array both.**

I. Introduction

With the development of recent III-V semiconductor industry, great energy-saving impulse is now pushing GaN-based light-emitting diode (LED) research ahead. With the well known attributes of long life, high reliability and energy saving, the GaN-based LED plays an important role in daily life such as medical application, traffic light, back light, advertise outdoor and so on.

However, in a real LED, the vertical light extraction efficiency (LEE) of the LED, due to total internal reflection (TIR) at the interface of the semiconductor and the outer medium (air in common), not all the power emitted from the active region is emitted into free space. Due to Fresnel reflection at the boundary, even with 100% internal quantum efficiency, LEE is limited to about 4%.

During the past 20 years, many approaches have been applied for improving the extraction efficiency of LEDs, such as surface roughening[1], patterned surface[2], patterned sapphire[3], photonic crystal[4], nano-rode[5], surface plasmon[6], and so on. The patterned sapphire and photonic crystals process use either e-beam lithography or holography lithography. These methods need high cost and can hardly be invested for the large-scale production. There are reports about the fabrication method of self-assembled 2-D SiO_2/polytstyrene (PS) microlens arrays with various PS thickness on top-emitting InGaN quantum well LEDs, the hemisphere of GaN and SiO_2 array also brought the LEE well increase [7, 8]. The approaches based on inexpensive methods are highly desirable for commercialization.

Although there has been some experiments on the LED with surface nano-sphere structures, research for systematic theoretical optimization is rarely reported in the literatures. Meanwhile, the Monte Carlo ray tracing methods are usually applied for surface microlens structure, but compared with the wavelength of light, the size of microlens is sometimes too small to be simulated. For the sake of optimizing the parameters of LED with surface microlens structure and providing a theoretical reference, the comprehensive research is desired. In this report, the FDTD method has been applied for the SiO_2 and GaN spherical crown array with different radius, followed by the comparison of LEE of LED with height varied spherical crown above LED surface. With the geometrical parameters optimized, more than 5 times LEE enhancement has been achieved than that of the ordinary LED.

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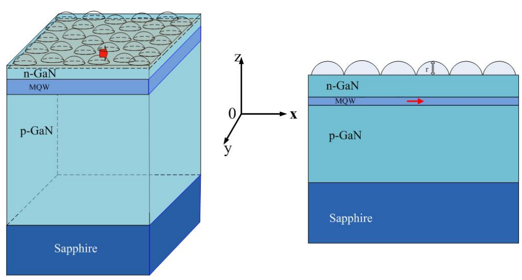
II. Numerical Methods In Simulation

In this study, as in Fig.1, a three dimension model and vertical cross-section of the simulated structure are schematically depicted. The LED layers are grown on a sapphire substrate. The refractive index of GaN in the visible spectrum is 2.5,while the refractive index of sapphire substrate and SiO_2 are 1.7 and 1.46.

A 4μm×4μm×3μm three-dimension field distribution was calculated using the FDTD method, also a space and time discretion of Maxwell curl equation. A single dipole source was chosen in the simulation. The source in this study is short Gaussian pause. A perfectly matched layer(PML) enclosing the computing domain was used to absorb outgoing waves and avoid non-physical reflections.



(a) (b)

Fig.1. Schematically diagrammed model of LED simulation. Structure used to calculate the extraction efficiency and far field radiation pattern of LED with (a)3D and (b)2D cross section of the spherical crown array.

The extraction efficiency was calculated from the power flux extracted from the structure with respect to the overall emitted power from the source:

$$\eta_{extr} = \frac{p^{+}_{z,out}}{p^{+}_{x,in} + p^{-}_{x,in} + p^{+}_{y,in} + p^{-}_{y,in} + p^{+}_{z,in} + p^{-}_{z,in}} \quad (1)$$

the $p^{+}_{z,out}$ means the power flow integrated over a plane just above the LED structure and $p^{+}_{x,in}$, $p^{-}_{x,in}$ are the integrated power flux through the plane normal to x, as shown in Fig.1. The + and - indicate power flow parallel or anti-parallel to the axis. The vertical LEE enhancement factor F is designed as follow:

$$F = \frac{\eta_{extr}}{\eta_0} \quad (2)$$

The η_{extr} is the vertical LEE of nano-sphere LED while η_0 is the vertical LEE of the ordinary LED.

III. SIMULATION RESULT

In simulation, the position of dipole was fixed at 200nm below the top GaN surface. As is depicted in Fig.2, with the variation of the angle θ, both of the radiuses of sphere (R) and bottom circuit (r) change accordingly. The calculated LEE enhancement of LED models with GaN/SiO_2 spherical crown hexagonal array on the top surface is shown in Fig.2. From the results in Fig.2, It is showed that the LEE of LED with GaN and SiO_2 spherical crown hexagonal array both rise with θ increasing. The key point is the line for LED surface structure made of GaN rises more obviously than that of SiO_2. The LEE reached climax when θ=65°, with the corresponding spherical radius of 473nm.

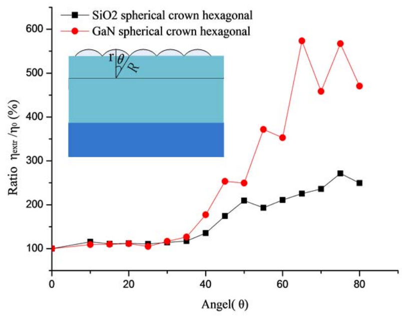


Fig.2. The LEE enhancement factor changed as the function of the incident angel θ. Fixed the dipole at the spherical center, the black curve is corresponding to the SiO_2 spherical crown, while the red one is corresponding to the GaN. The inset indicates the schematic diagram of simulation structure of spherical crown arrays.

For the sake of further optimization, the radius of sphere was set to 473nm and change the vertical position of the sphere so that the heights of spherical crowns vary as was shown in Fig.3.

The LEE enhancement factors of LED model with spherical crown of various heights were also shown in Fig.3. From the calculated results, it could be noted that the line for LEE of the LED with SiO_2 hemisphere structure does not change very extensively with respect to the height. However, the LEE of the LED with GaN spherical structure changed remarkably. The LEE enhancement factor reached 570% when the height is about 250nm, which is a very promising value of LEE enhancement.

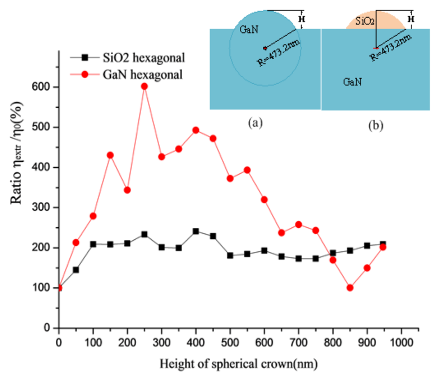


Fig.3. The LEE changed as function of the height of spherical crown above the LED surface. Fixed with 473nm radius, the black one is corresponding to the SiO_2, while the red one is corresponding to the GaN spherical crown. The insets above indicate the single unit among the simulate structure (left one is GaN spherical crown, right one is SiO_2).

IV. CONCLUSION

Comprehensive research to optimize the LEE of GaN-based LED with SiO_2 and GaN spherical crown arrays in different parameters has been carried out. The results showed that GaN is more suitable than SiO_2 to compose the surface hemisphere microlens structures. When the radius of sphere is 473nm, the height above the top surface of LED is 250nm, the LEE could obtain 5.7 times enhancement than LED model without surface microlens structures. The optimized results provide important reference for further experiments and commercial application.

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