Simulation and analysis of GaN-based light-emitting diodes with diamond shaped

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ABSTRACT

Improving light extraction efficiency (LEE) is important to enhance efficiency of light-emitting diodes (LEDs) and the issue has been studied comprehensively. A GaN-based LED chip with diamond shaped is presented in this letter and LEE was analyzed. The LEEs of the conventional chip and flip chip with different angle of slant from 0° to 20° were obtained through Monte-Carlo ray tracing method, which is a useful and efficient way in studying the LEE of LED. The results show that the LEE of the chip with obliquity enhanced by 20.2% compared with conventional rectangle chip with mirror bottom surface, however, there is no improve of the LEEs of flip chip and conventional chip with diffuse surface.

Keywords: Diamond shaped, light-emitting diode, Monte-Carlo simulation, light extraction efficiency

1 INTRODUCTION

GaN-based light emitting diodes (GaN-LEDs) have been studied extensively for applications as next generation promising solid-state-lighting source[1], however, the light efficiency is not high enough to satisfy people's requirement. Except for improving the internal quantum efficiency[2], which has a relationship with dislocation, piezoelectric field, doping and so on[3,4], to improve the light extract efficiency(LEE) of the GaN-LEDs is an important and efficient way to enhance the lumen efficiency . Many methods were proposed, such as pattern substrate, photonics crystal, surface roughed and other approaches[5-8].

In this paper, we proposed a GaN-LED with diamond shape, which is different from conventional rectangle chip. The LEE of the chip of conventional chip and flip chip with different obliquity degree were simulated and analyzed using Monte-Carlo ray tracing method [9.10], which can simulate transmission through any material of photon and optical effects between the interfaces. Commercial GaN-LED chips now are rectangle shaped, no matter conventional chip or flip chip. For a diamond shaped chip, it can change the route like roughed surface with more simple techniques.

2 OPTICAL MODELING FOR GAN-LED

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Firstly, a conventional GaN-LED based on a simple model was analyzed to explain why it's LEE is low and made a brief exposition of our model, as shown in fig.1 (a) and fig.1 (b). The structure of the model consists of a substrate on the bottom, a thick n-type GaN layer, a thin InGaN/GaN active layer and a thick p-type GaN layer. The refractive index of each layer is shown in table 1 [11]. The critical angle of the light escape cone is about 23° in a conventional GaN-LED calculated from Snell's law :θ_c=arcsin(n_1/n_2), where n_1 and n_2 are reflective indexes of two different media, respectively. The ratio of the photon generated from the active layer escape to the air from a certain surface is：

$$\eta_{\text{lee}} = \frac{1}{4\pi}\int_0^{\theta_c} 2\pi \sin(\theta)d\theta = \frac{1}{2}\left(1 - \frac{\sqrt{n_1^2 - n_2^2}}{n_1}\right) \qquad (1)$$

It is only 4.2% to a GaN-LED if $n_1 = n_{GaN}$ and $n_2 = n_{air}$ was taken into the formula (1). The other photons are absorbed during they transmit in LED layer. When the route photon transmit in LED is changed because of roughed surface, the chance photon escape to the air enhances and LEE improves.

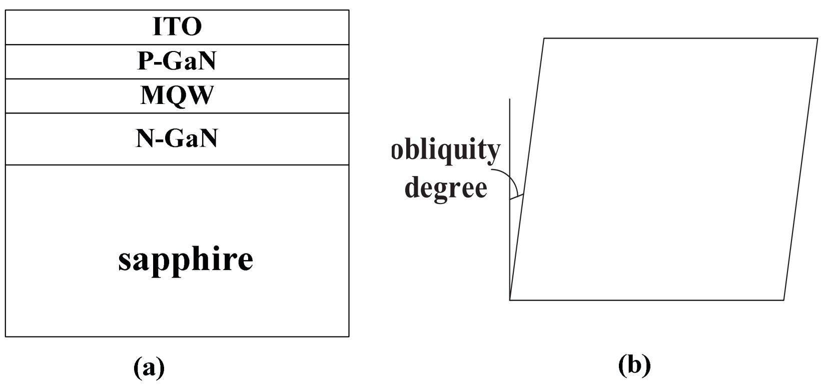

Fig.1 (a) the simple model of conventional chip structure. (b) the LED chip with a diamond shaped

The structure for the GaN-LED is based on the simple model and the parameters are shown in table 1. The chips of small size (300um*300um) and big size (1000um*1000um) were simulated. In the simulation, the effects of electric pad as well as current spreading were ignored for simplicity. Rays are generated randomly in the active layer and emit isotropically.

Table 1 Parameters of each layer in the simulated LED

material	Sapphire	n-GaN	MQW	p-GaN	ITO
Thickness(um)	90	3	0.1	0.3	0.4
Refraction index	1.78	2.5	2.5	2.5	2

3 RESULTS AND DISCUSSION

The LEEs of conventional wire bonding chip and flip chip with different oblique angle are shown in fig.2 and fig.3, respectively. From fig.2 we can see that the conventional chip with diamond shaped can improve the LEE, especially for small chip with mirror reflection bottom surface, whose LEE enhanced by 20.2%. The simulation results show that the slanting surfaces can change the pathway of photon transmitting in GaN-LED chip. The LEEs improve quickly when the obliquity angle of the chip increase from 0°to 5°and then LEEs improve slowly and became stable for conventional chip with mirror reflection. However, if the bottom surfaces are diffuse reflection, the LEEs increase slightly. This is due to the roughed surface can change the route of most photons. In comparison with the diffuse reflecting surface, the slanting side surface is so small that only a few photons reflect at the surfaces, so there is no much improvement for the chip whose bottom surface is diffuse reflection. For the same reason, the LEEs are nearly a constant at different inclination angle for flip chip, which is shown in fig.3. The height of flip chip that have already removed substrate is only several micrometer, far lower than conventional chip that is why the LEE of flip chip is smaller than that of conventional chip under the condition of mirror surface.

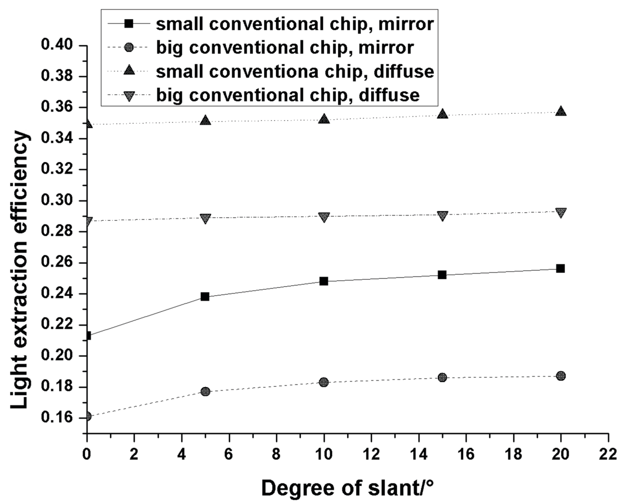

Fig.2 LEEs of conventional chip with different degree of slant.

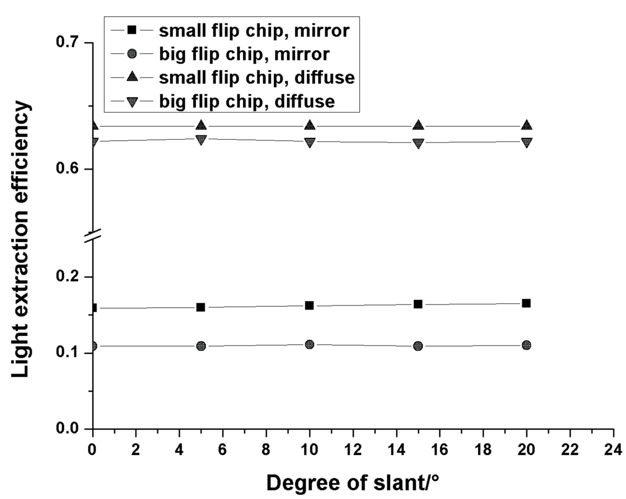

Fig.3 LEEs of flip chip with different degree of slant.

Under the condition of conventional chip with mirror bottom surface and obliquity angle 5°, the LEEs were simulated under different thickness of the substrate, as shown in fig.4. The results revealed that LEEs increased with the increasing thickness of substrate and changed to be steady near 120um. Photons generated at the active layer (MQW) randomly and uniformly, only a small part of photons those are close to edge of chip change direction and escaped to the air, it can be proved from fig.5, which showed that the LEEs decrease with size increasing, however, the LEEs of rectangle shaped chip was higher nearly 3 percentage point than those of diamond shaped chip.

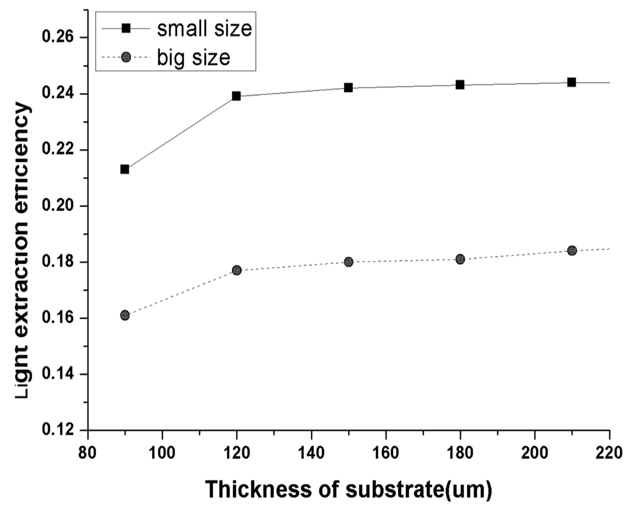

Fig.4 The LEEs of the conventional chip with different thickness of substrate

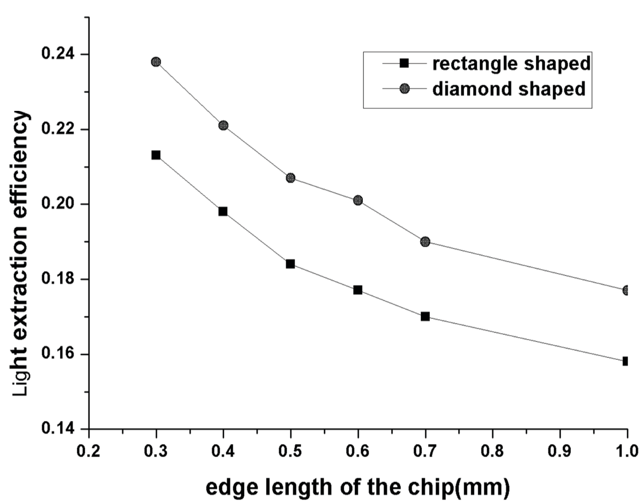

Fig.5 The LEEs of rectangle and diamond shaped conventional chip with different size

4 CONCLUSION

In this paper, the LEEs of a GaN-LED chip with diamond shaped under different condition were simulated and analyzed based on Monte-Carlo ray trace method. In the simulation results, we conclude that the LEE of a small size chip with diamond shaped improved greatly. When size became bigger or any surface is diffuse reflection, the diamond shaped structures have no impact on the LEE. Anyway, diamond shaped chips have the simplest technique. The realistically properties of this kind of GaN-LED will be studied in our next work.

REFEREBCE

1. Steigerwald. D. A., Bhat. J. C., Collins. D., Fletcher. R. M., Holcomb. M. O., Ludowise. M. J., Martin. P. S., and Rudaz S. L, "Illumination with solid state lighting technology, " IEEE J. Select. Topics Quantum Electron. 8, 310, (2002).
2. Wang. T., Bai. J., and Sakai. S., "Investigation of the emission mechanism in InGaN/GaN-based light-emitting diodes, " Appl. Phys. Lett. 78, 2617 (2001).
3. Wu. Z. H., Fischer. A. M., and Ponce. F. A., Lee. W., Ryou. J. H., Limb. J., Yoo. D., and Dupuis. R. D. Effect of internal electrostatic fields in InGaN quantum wells on the properties of green light emitting diodes. Appl Phys Lett, 91(4), 041915(2007)
4. Wu. G. M., Chung. T. J., Nee. T. E., Kuo. D. C., Chen. W. J., Ke. C. C., Hung. C. W., Jen-Cheng Wang, and Nei-Chuan Chen. Improvements of quantum efficiency and thermal stability by using Si delta doping in blue InGaN/GaN multiple quantum well light-emitting diodes. Phys. Stat. sol.(c)4, No.7, 2797-2801 (2007).
5. Kim. T. S., Kim. S. M., Jang. Y. H., and Gun. Y. J., "Increase of light extraction from GaN based light emitting diodes incorporating patterned structure by colloidal lithography". Appl Phys Lett.91,171114(2007)
6. Hsieh. M. L., Lo. K. C., Lan. Y. S., Yang. S. Y., Lin. C. H., Liu. H. M., and Kuo. H. C., "One-Shot Exposure for Patterning Two-Dimensional Photonic Crystals to Enhance Light Extraction of InGaN-Based Green LEDs". IEEE PHOTONICS TECHNOLOGY LETTERS, 20, 2,(2008)
7. Peng. W. C. and Wua Y. C., "Enhanced performance of an InGaN–GaN light-emitting diode by roughening the undoped-GaN surface and applying a mirror coating to the sapphire substrate. " Appl Phys Lett, 88,181117(2006)
8. Krames. M. R., Holcomb. M. O., Hofler. G. E., Coman. C. C., Chen. E. I., Tan. I.-H., Grillot. P., Gardner. N. F., Chui. H. C., Huang. J. W., Stockman. S. A., Kish. F. A., and Craford. M. G.. "High-power truncated-inverted-pyramid $(Al_xGa_{1-x})_{0.5}In_{0.5}P/GaP$ light-emitting diodes exhibiting >50% external quantum efficiency. " Appl Phys Lett, 76(16),2365 (1999):
9. Lee. S. J., "Analysis of light-emitting diodes by Monte Carlo photon simulation, " applied optics, 40(9),1427-1437,(2001)
10. Lee. T. X., Gao. K. F., Chien. W. T. and Sun. C. C., "Light extraction analysis of GaN-based light-emitting diodes with surface texture and/or patterned substrate, " optics express, 15(11), 6670-6676, (2007)
11. Aleksandra B. Djuriié, Y. Chan, and B. Herbert Li, "Calculations of the Refractive Index of A1GaN/GaN Quantum Well, " Proc SPIE,V4238, 630-637,(2001)