The Analysis of Light Extraction Efficiency of the GaN-based LEDs with a Novel Micro-Cavity

Jee-Gong Chang[1], Lun-De Liao[2], Chi-Chuan Hwang[3]

1)National Center for High-Performance Computing, , Taiwan, Republic of China.

2,3)Department of Engineering Science, National Cheng Kung University,

No.1, University Road, Tainan, Taiwan, Republic of China

* gs336.tw@yahoo.com.tw

Abstract

This paper demonstrates the strong enhancement of light extraction efficiency of light-emitting diodes (LEDs) by a novel three-dimensionally arranged micro-cavity. There are several optimal designed parameters, including chip dimensions, absorption coefficients, the shape of the micro-cavity and package are analyzed on the basis of a Monte-Carlo ray tracing simulation. The most important that studying includes GaN LEDs which are applied to various applications, including traffic signals, backlight system for LCD and outdoor illumination by white light LEDs. The functional of the three-dimensionally arranged micro-cavity is to make the light extraction from LED with high efficiency. The shape of micro-cavities are making like hexagon solids on the top view. The structure were evaluated and simulated by TracePro software respectively. The light extraction efficiency of LED can be greatly improved by three-dimensionally arranged micro-cavity. This study shows that the micro-cavities induced on the surface rather than that inside the LED greatly enhances the light extraction efficiency. This stipulation holds for both sapphire-based and Thin-GaN LEDs. The results indeed identify the attributes of the LED, which make it possible to achieve excellent luminance performance using a GaN-based approach from the LED of "three-dimensionally arranged micro-cavity". This structure was stringent expected to allow a high-efficiency LED, since the illumination systems needed for higher luminance energy can be added independently of the effects.

Keywords: Light extraction efficiency, Micro-cavity, GaN LEDs, Gaussian distribution

Sixth International Conference on Solid State Lighting
edited by Ian T. Ferguson, Nadarajah Narendran, Tsunemasa Taguchi, Ian E. Ashdown
Proc. of SPIE Vol. 6337, 63371I, (2006) · 0277-786X/06/$15 · doi: 10.1117/12.678662

Downloaded from SPIE Digital Library on 29 Oct 2009 to 159.226.100.225. Terms of Use: http://spiedl.org/terms

1. Introduction

Light-emitting diodes (LEDs) for solid-state lighting have been extensively studied [1]. In developing solid-state lighting based on LED, the light extraction analysis of LED chips is quite important. In this letter presented our studies on the enhancement of the light extraction efficiency of GaN-based LEDs, with the introduction of a surface variation having a specific periodic structure. One of the most important topics of study includes GaN LEDs, which can be applied to various applications, including traffic signals, back lighting in liquid-crystal display (LCD) [2] and outdoor lighting by white light LEDs. However, the property such as the energy efficiency of current GaN LEDs is not yet sufficient to satisfy consumer demands. Therefore, obtaining more energy efficient GaN LEDs is a goal attracting a great deal of attention. Generally, there are two main approaches in improving the energy efficiency. This study also presented the light extraction efficiency analysis of GaN LEDs as a function of the position of the point source in the active layer as affected by several parameters, including chip dimensions, absorption coefficients and package. These analyses are helpful in the design of high-brightness GaN LEDs. The first is to increase the internal quantum efficiency, which is determined by the material quality, epitaxial layer structure and thermal dissipation. The second is to increase the light extraction efficiency (simplified light extraction efficiency) on the chip. The third is to apply the simulation to study the light extraction efficiency of a Thin-GaN LED. Many methods to improve the light extraction efficiency have been proposed, including altering surface texture, chip shaping and other approaches [3] [4].

2. Design

The enhancement of the light extraction efficiency of GaN-based LEDs is presented in this letter and with the introduction of a surface variation having a specific periodic structure. It is well known that emitted photons may have difficulty escaping from an LED chip due to the total reflection on the boundary of the chip, especially at the interface boundary between two media with a large difference in the refractive index. This leads to lower external quantum efficiency. Typically, two approaches are used to increase the light extraction efficiency. The first approach is to shape the chip, while the second involves bulk scattering of the chip. In the bulk scattering surface approach, the scattering

Downloaded from SPIE Digital Library on 29 Oct 2009 to 159.226.100.225. Terms of Use: http://spiedl.org/terms

distribution function (SDF) is defined the scattering in biological tissue and uses the Henyey-Greenstein model [5] as

$$SDF = p(\theta) = \frac{1 - g^2}{4\pi(1 + g^2 - 2g\cos\theta)^{\frac{3}{2}}}$$

where g is called the anisotropy factor, and g can take on values between -1 and 1. When g is positive, ray are scattered more in forward direction, and when g is negative, they are scattered more in the backward direction. When g is zero, the scattering is isotropic, i.e. the same in all directions. When a ray enters a scattering medium, it propagates a random distance x governed by probability distribution

$$P(x) = e^{-\mu_s x} dx$$

when μ_s is called the scattering coefficient. The inverse of the scattering coefficient is the mean free path of the ray in the material. When a ray enters a piece of material that is thin compared to the beam free path, it is likely to pass through the material without being scattered.

2.1 Analysis of light extraction efficiency by the Monte-Carlo ray tracing method

The light extraction efficiency of the LED is defined by the ratio of rays escaping from the LED chip to the total number of rays generated by the active layer, and is limited by critical angle loss, Fresnel loss, current spreading conditions and absorption of the materials. A Monte Carlo algorithm is used to obtain the light distribution from the chip. In a conventional GaN LED, the critical angle of the light escape cone is about 23°, if the refractive index is 2.5 as for GaN. Generally, the light extraction efficiency is less than 20% so how to increase the light extraction efficiency is important. To figure out the light extraction efficiency under various conditions and parameters, a Monte-Carlo ray tracing simulation is used to obtain the light distribution across the whole volume of the chip [6]. The following simulation results assume that the current spreading is uniform and the photon recycling effect is negligible.

Downloaded from SPIE Digital Library on 29 Oct 2009 to 159.226.100.225. Terms of Use: http://spiedl.org/terms

2.2 The light extraction efficiency of GaN-based LEDs with a Novel Micro-Cavity

The chip area is $300 \times 300\ \mu m^2$ and the central wavelength of the emitting light is assumed to be 425 nm and the all structures of the simulated GaN LEDs are described in Table 1. First at all, the light extraction efficiency is analyzed for different single point source positions on the active layer. The micro-cavity I shown in Fig. 1 and Fig.2 is called the "Tip-Cutting Cone". And the micro-cavity II also shown in Fig. 3 is introduced between the sapphire substrate and the n-GaN because the refractive index difference between these two media is relatively large. In Fig. 2, the opening width is D, the bottom width is d, and the depth is H. When D=0.005 mm and d=0.004 mm and H=0.01, it is a well structure with high light extraction efficiency. In the simulation of the light extraction efficiency as a function of H, the results show that a well structure has the highest light extraction efficiency with micro-cavity I and micro-cavity II ,when H=0.004 to 0.013 mm, as shown in Fig. 3. The possible reason is that a "Tip-Cutting Cone" structure provides appropriate slant surfaces on the interface, which are helpful to the light extraction. Accordingly, the study also made further simulations of the light extraction efficiency for various "Tip-Cutting Cone" structures. In the condition of D= mm, d=50, and H=0.01 mm and with the regular radius change of micro-cavity II on the sapphire, the light extraction efficiency is as high as 88% when absorption is not considered in the simulation. About the regular radius change of micro-cavity II, as show in Fig.4, is very difference with the unit-micro-cavity distribution and which has the advantage for controlling the rays out of the chip more effectively. The regular radius change of micro-cavity II is slightly reduced along circle outside toward inside direction, as show in Fig.4. The Fig. 5 shows the results of the light extraction efficiency of the chip dimensions issue for the single point source at different position on the active layer with the micro-cavity II on the sapphire substrate.

The results shows that the light extraction efficiency of the light emitted from the central portion of the active layer is very close the light escaping from the larger chip by using the point source of micro-cavity I and the regular radius change of micro-cavity II. By the way, the light extraction efficiency from the four side-faces would be not quickly decreases when the chip dimensions increases and the absorption coefficient increases, as shown in Fig.6. The possible reason is that a regular radius change of micro-cavity II provides appropriate angle when the rays out of chip, which are helpful to the light extraction. The results show that the light extraction efficiency is larger when the point source of the "Tip-Cutting Cone" structure is longer and with regular radius change of micro-cavity II on the sapphire.

Downloaded from SPIE Digital Library on 29 Oct 2009 to 159.226.100.225. Terms of Use: http://spiedl.org/terms

2.3 The light extraction efficiency of Thin-GaN-based LEDs with a Novel Micro-Cavity

This paper also applied the simulation to study the light extraction efficiency of a Thin-GaN LED [7]. The Thin-GaN LED was obtained using a removal process from the sapphire substrate and with chip bonding [8]. In the case one, for comparison with a typical sapphire-based LED, the Thin-GaN LED has a more uniform current distribution with out any micro-cavities, as shown in Fig.7-a. In addition, the luminance of the Thin-GaN LED can be assumed to have a Gaussian-like distribution of the following form:

$$L(\theta, x, y) = L_i \, e^{-\frac{1}{2}\left(\frac{\theta}{\rho_i}\right)^2}, i = 1 \sim n, \ \phi = 0 \sim 2\pi \quad for \ (x, y) \in a_i$$

The validation of this function is presented in [9], which is defined as the luminance cone angle, i.e. the angle at which half of the maximum luminance, L_i, is observed. Note that L_i is the luminance in area a_i when $\theta = 0$, where θ is the zenith angle from the pole and ranges from 0 to $\pi/2$. Note also, that in Eq. (1), ϕ is the azimuth angle around the pole. The pole axis direction is defined as the normal direction to the panel surface. The parameter ρ_i is used to control the waist of the Gaussian distribution. In case two, the polar candela distribution plot of the rays out of chip shows for the sapphire-based LEDs only with the micro-cavity I and with the light extraction efficiency about 64%, as shown in Fig. 7-b. In the case three, the polar candela distribution plot shows for sapphire-based LEDs with the micro-cavity I and the micro-cavity II, as shown in Fig. 7-c. The results by the Monte-Carlo ray tracing method of the case three show the light extraction efficiency about 88%. The candela distribution of the case three agrees which can control the rays out of the chip with more efficiency by using the micro-cavity II. In the case four, the polar candela distribution plot shows for the Thin-GaN LEDs with the micro-cavity I and the micro-cavity II, as shown in Fig. 7-d. The results by the Monte-Carlo ray tracing method of the case four show the light extraction efficiency about 79%. The four cases are shown in Fig. 8. illustrates a comparison of the light extraction efficiency without considering the absorption among the LEDs. The results show that the light extraction efficiency of the Thin-GaN LEDs is a little smaller than that of sapphire-based LEDs. Most important, the

Downloaded from SPIE Digital Library on 29 Oct 2009 to 159.226.100.225. Terms of Use: http://spiedl.org/terms

polar candela distribution plot of the rays out of chip for the sapphire-based LEDs with the micro-cavity I and II is much close to the Thin-GaN LEDs, as shown in Fig. 7-a and 7-c. The texture of the surface is more useful for this than that inside the LEDs.

4. Summary

In summary, this paper has presented our study of simulating the high light extraction efficiency from a GaN LED having micro-cavities based on a Monte Carlo simulation. In the first, based on a Monte Carlo simulation, the results show the highest light extraction efficiency with the micro-cavity I and micro-cavity II, when H=0.004 to 0.013 mm, as shown in Fig. 5. We found the highest efficiency of the GaN LED is to be approximately 88% both with the micro-cavity I and micro-cavity II. The possible reason is that a "Tip-Cutting Cone" structure provides appropriate slant surfaces on the interface, which are helpful to the light extraction. The novel structures are helpful in the design of the high brightness LED and to obtain high light extraction efficiency. In the Second, about the chip dimensions issue, the results based on a Monte Carlo simulation conclude that the light extraction efficiency of the corner point source is very close to the center point source. And the light extraction efficiency has slowly decreases as the absorption coefficient of the active layer and chip size increases. The results show the micro-cavity II is helpful in controlling the rays out of the chip with more effectively. Thus, both of the micro-cavity I and II are most useful in increasing the light extraction efficiency of an LED. In the third, Thin-GaN LED, the simulation results show that most of the light is escaped from the top surface so it may look brighter. However, the light extraction efficiency is not larger than the sapphire-based one and is more sensitive to the absorption coefficient of the active layer [10]. The light extraction efficiency can be greatly improved by the surface texture. Most importantly, the candela distribution based on a Monte Carlo simulation for the sapphire-based LEDs with the micro-cavity I and II is much close to the candela distribution of the Thin-GaN LED. This study shows that the micro-cavity I and II induced on the surface rather than that inside the LED greatly enhances the light extraction efficiency. This stipulation holds for both sapphire-based and Thin-GaN LEDs.

Reference

1. A. Zukauskas, M. S. Shur, and R. Caska, "Introduction to Solid-state Lighting", ISBN: 0-471-21574-0, John Wiley & Sons, New York (2002).
2. F. Yamada, Y. Sakaguichi, "LED backlighting for LCDs", ISSN 0098-0966X/98/2901,

Downloaded from SPIE Digital Library on 29 Oct 2009 to 159.226.100.225. Terms of Use: http://spiedl.org/terms

SID, (1998).
3. C. C. Sun, C. Y. Lin, T. X. Lee, and T. H. Yang, “Enhancement of light extraction of GaN-based LED with introducing micro-structure array”, Opt. Eng. 43, 1700 (2004).
4. Jung-Tsung Hsu, Wen-Yung Yeh, Ghang-Cheng Chuo, “Beveled sidewall formation and its effect on the light output of a GaInN multiquantum well light –emitting diode with sapphire substrate”, Opt. Eng. 44, 111304(2005).
5. S. L. Jacques and L. H. Wang, “Monte Carlo modeling of light transport in tissues”, in Optical Thermal Response of Laser Irradiated Tissue, edited by A. J. Welch and M. J. C. van Gemert Plenum Press, New York, (1995),pp. 79-100.
6. S. J. Lee, “Analysis of light-emitting diode by Monte Carlo Photo simulation”, Appl. Opt. 40, 1427(2001).
7. Hon Schang Jing, Lai Mu Jen, “Gallium nitride vertical light emitting diode structure and method of separating a substrate and a thin film in the structure”, U.S. patent 7001824 (2006).
8. OSRAM Co. 2002, Opto Semiconductors, http://www.osram-os.com/
9. M. Oren and S. Nayar., “Generalization of the lambertian model and implication for machine vision.”, IJCV, 14(3) :227-251, April (1995).
10. Tsung-Xian Lee, Chao-Ying Lin, Shih-Hsin Ma and Ching-Cherng Sun, “Analysis of position-dependent light extraction of GaN-based LEDs”, Opt. Express, Vol. 13, No. 11 (2005).

Table and figure captions

Table I Parameters of the simulated GaN LEDs of each layer.

Layer	Sapphire	GaN	N-type	MQW	P-type
Refractive Index	1.78	240	2.39	2.61	2.41
Thickness(μm)	250	1.5	1.5	0.08	0.05

Downloaded from SPIE Digital Library on 29 Oct 2009 to 159.226.100.225. Terms of Use: http://spiedl.org/terms

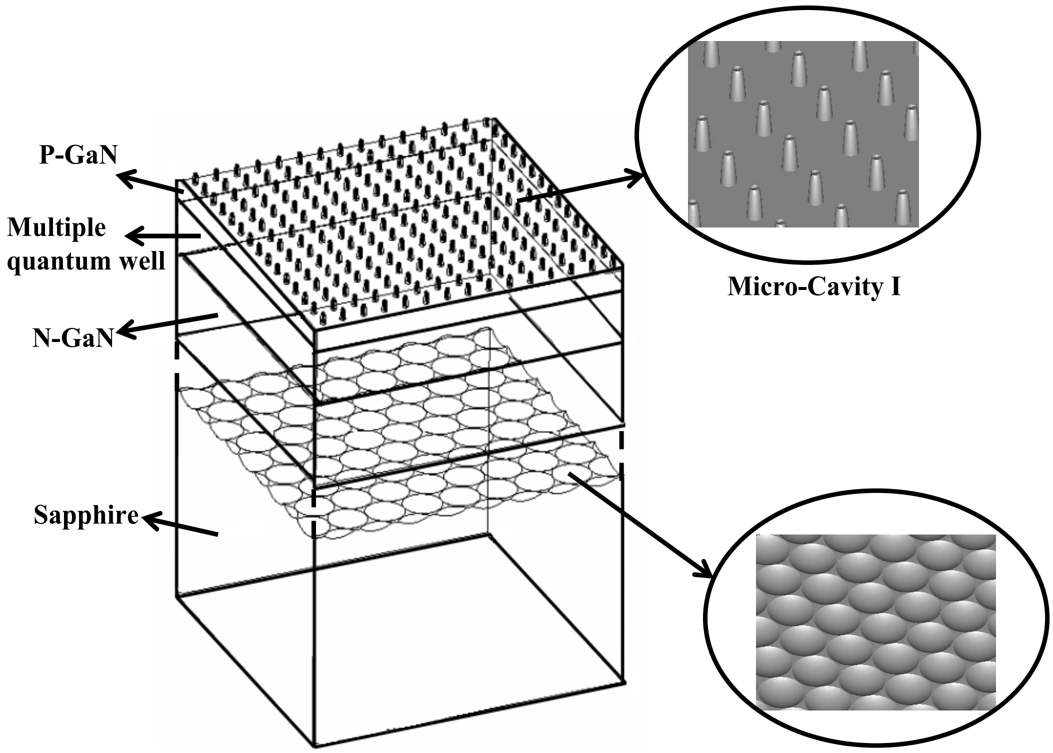

Fig. 1 The micro-cavity I of “Tip-Cutting Cone” on the top layer and the micro-cavity II is between the sapphire substrate and the n-GaN

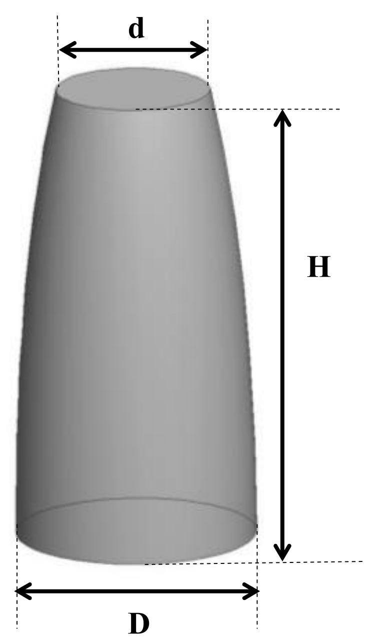

Fig. 2 The shape of the micro-cavity I at the top surface

Downloaded from SPIE Digital Library on 29 Oct 2009 to 159.226.100.225. Terms of Use: http://spiedl.org/terms

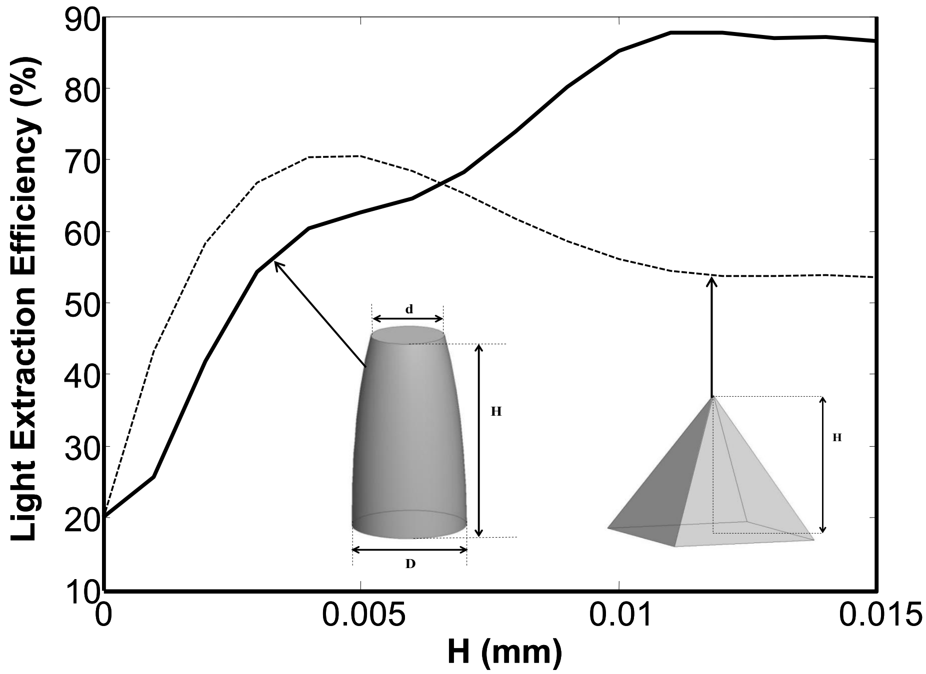

Fig. 3 The light extraction efficiency of the altitude change of the micro-cavity and the typical cavity

Downloaded from SPIE Digital Library on 29 Oct 2009 to 159.226.100.225. Terms of Use: http://spiedl.org/terms

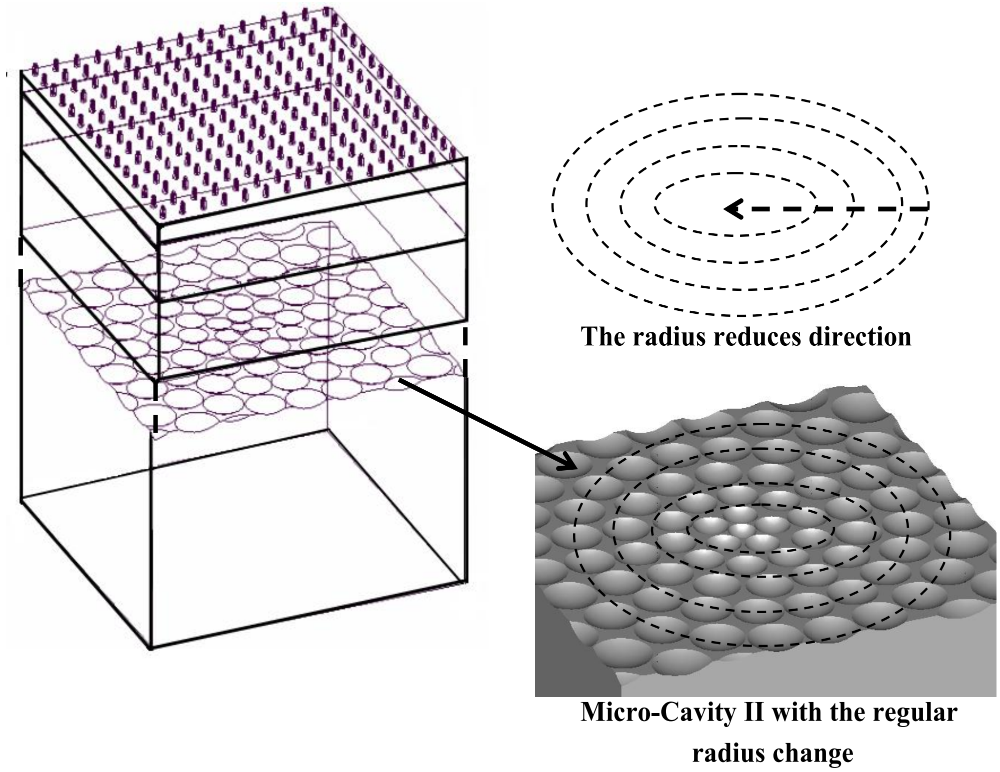

Fig. 4 The regular radius change of micro-cavity II is slightly reduced along circle outside toward inside direction

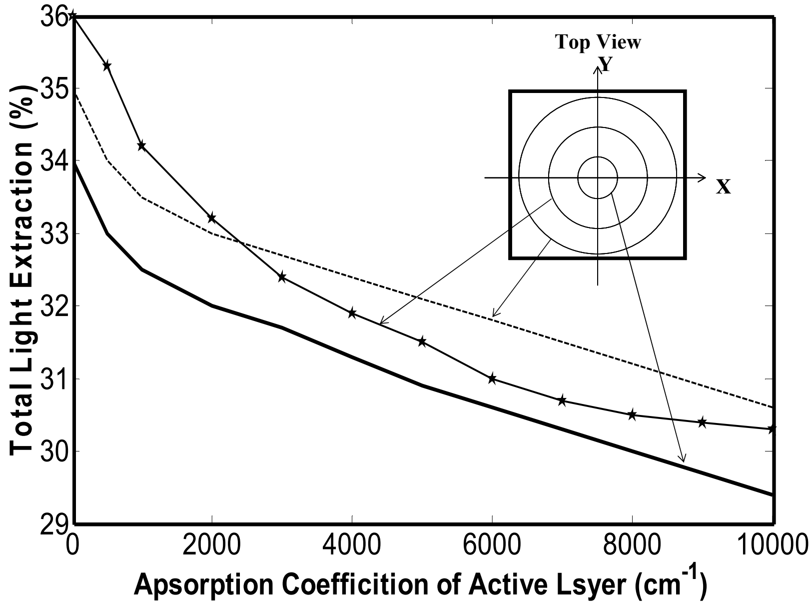

Fig. 5 The issue of the absorption coefficient of the active layer for the point sources of micro-cavity I in three different positions and with the micro-cavity II in the sapphire layer.

Downloaded from SPIE Digital Library on 29 Oct 2009 to 159.226.100.225. Terms of Use: http://spiedl.org/terms

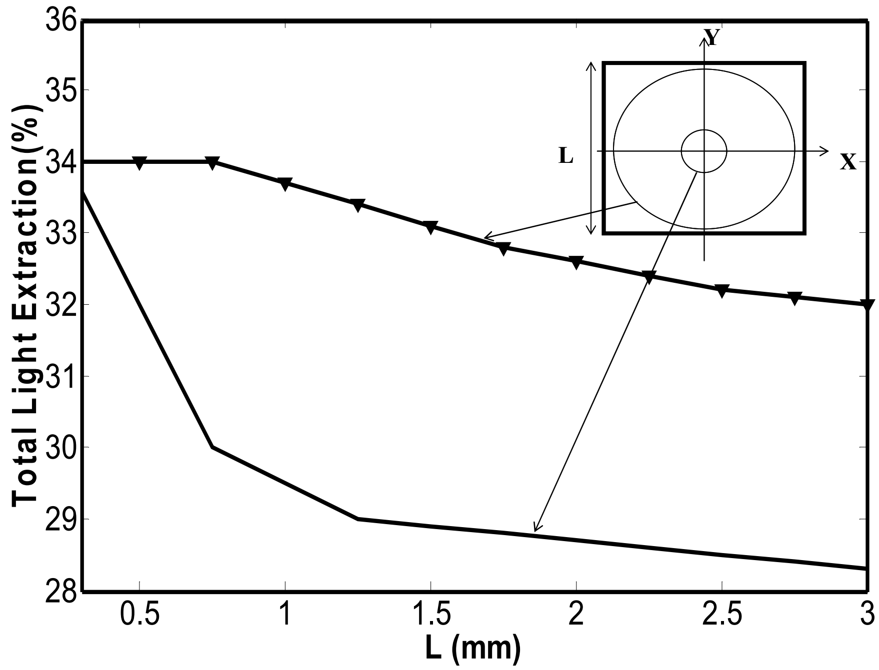

Fig. 6 The issue of the chip dimensions for center and corner point sources

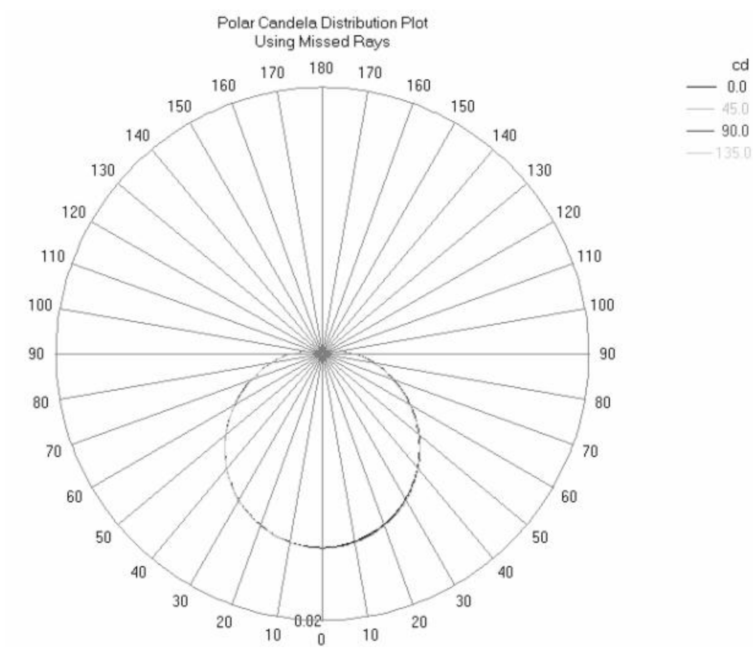

Fig. 7-a The polar candela distribution plot for the Thin-GaN LED without any micro-cavities

Downloaded from SPIE Digital Library on 29 Oct 2009 to 159.226.100.225. Terms of Use: http://spiedl.org/terms

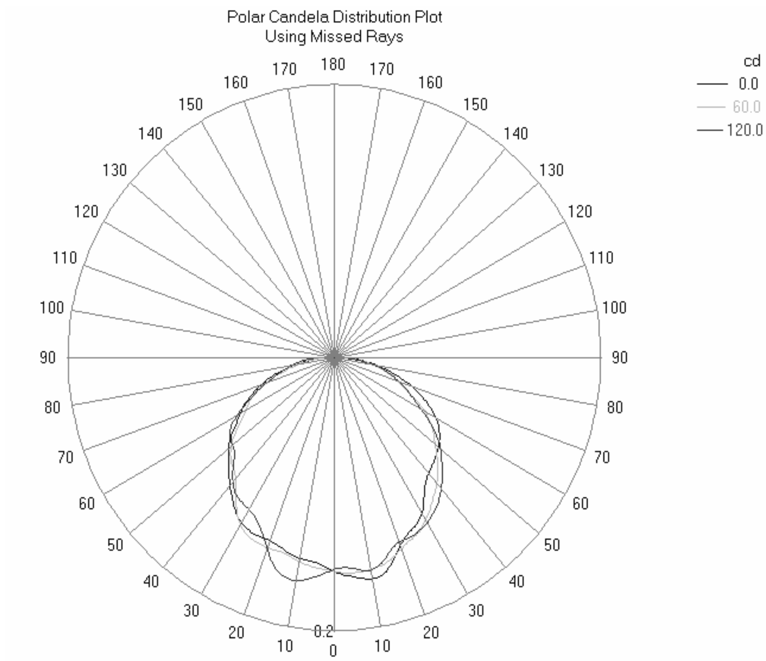

Fig. 7-b The polar candela distribution plot for the sapphire-based LEDs only with the micro-cavity I

Downloaded from SPIE Digital Library on 29 Oct 2009 to 159.226.100.225. Terms of Use: http://spiedl.org/terms

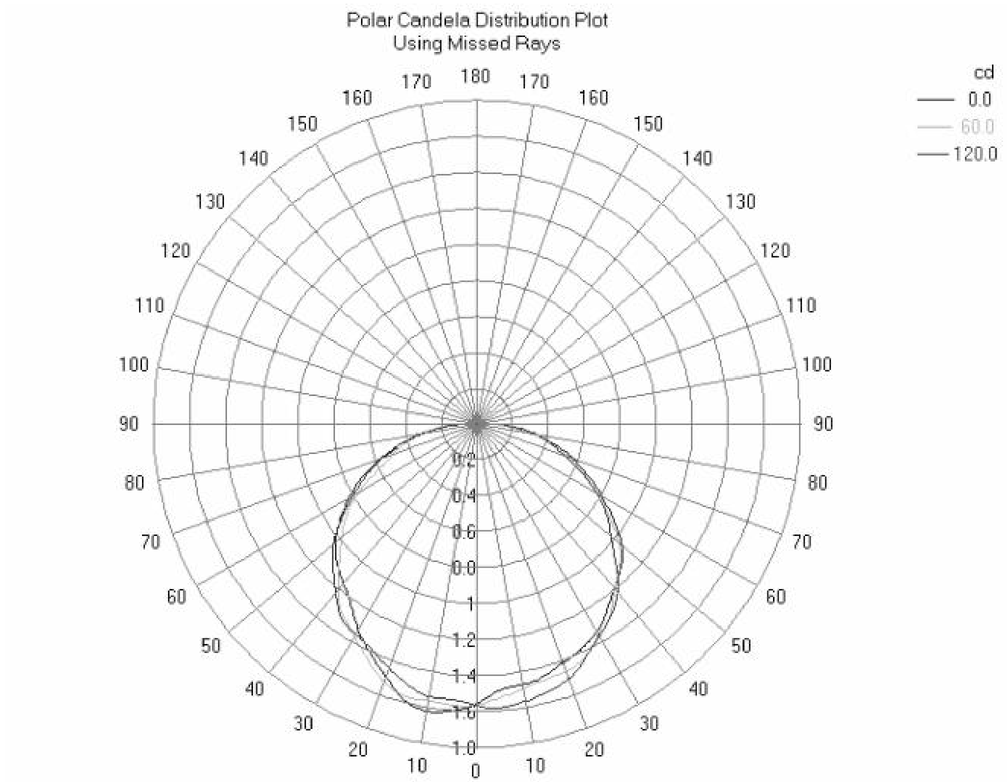

Fig. 7-c The polar candela distribution plot for sapphire-based LEDs with the micro-cavity I and the micro-cavity II

Downloaded from SPIE Digital Library on 29 Oct 2009 to 159.226.100.225. Terms of Use: http://spiedl.org/terms

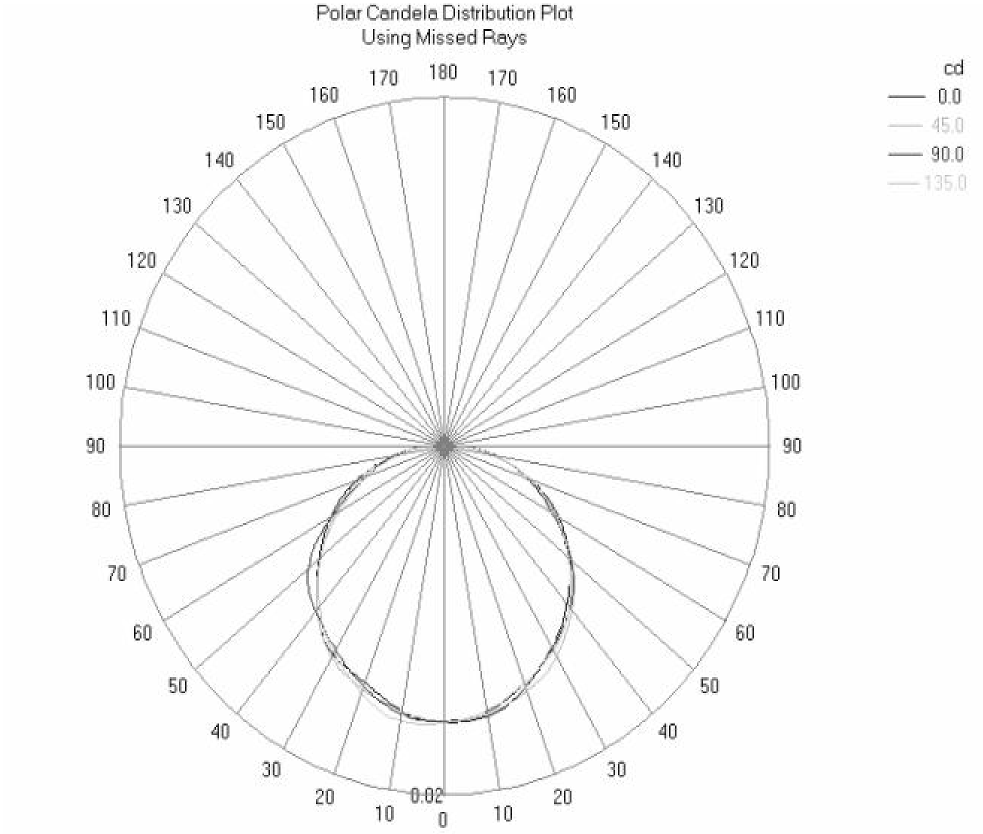

Fig. 7-d The polar candela distribution plot shows for the Thin-GaN LEDs with the micro-cavity I and the micro-cavity II

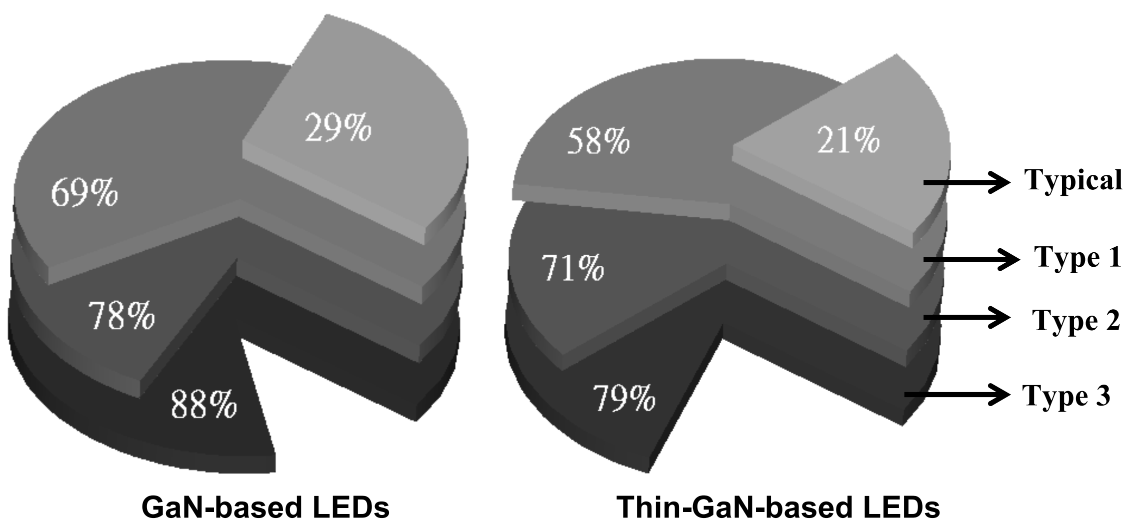

Fig. 8 Comparison of analytical calculation results of the light extraction efficiency for the four cases-(1) Typical: LEDs without any micro-cavity, (2) Type 1: Only with the micro-cavity II, (3) Type 2: Only with the micro-cavity I, (4) Type 3: Both with the micro-cavity I and micro-cavity II

Downloaded from SPIE Digital Library on 29 Oct 2009 to 159.226.100.225. Terms of Use: http://spiedl.org/terms