Paper

Dependence of Light Extraction From Near-Ultraviolet Light-Emitting Diodes on Refraction Index, Transmittance and Shape

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ABSTRACT

We have studied the relation between light extraction from light-emitting diodes (LEDs) and the characteristics and shape of resin by using ray tracing simulations. Light extraction efficiency (η_{ext}) was calculated for various resins of with different refraction indexes, transmittances and radii of curvature of the air-resin interface of a fixed LED package. The models of the LED packages included the packaging substrate, reflector, resin, and LED chip, which consisted of an InGaN chip on a patterned sapphire substrate (PSS). It was found that light extraction from LED packages is enhanced by optimization of the extraction paths of the rays by changing the resin characteristics or curvatures.

KEYWORDS: light extraction efficiency, light distribution, extraction path

1. Introduction

LEDs White light-emitting diodes (LEDs) have been used primarily as a source of backlighting in liquid crystal displays. As the luminous flux of white LEDs increased, the manufacturers began to incorporate them into products such as flashlights and illumination light sources. As a next step, even higher efficiency white LEDs are necessary for solid-state lighting technology to be used as a replacement for conventional incandescent and fluorescent lamps.

According to recent studies, the luminous efficacy of white LEDs has exceeded 150 lm/W. The external quantum efficiency (η_{EQE}) of InGaN-based LEDs has reached 50%^{1,2)}. Improvements in η_{EQE} lead to higher luminous efficacy. The η_{EQE} is obtained by multiplying the internal quantum efficiency (η_{IQE}) by the light extraction efficiency (η_{ext}).

Generally speaking, one of the fundamental limitations regarding the η_{ext} of LEDs is the occurrence of trapped light within semiconductors with high reflective index.

Based on Snell's law, the angle of the escape cone at the semiconductor-air interface is rather small due to the boundary between the areas with low and high refractive index. Encapsulating resins, such as epoxy or silicone, reduce the refraction index, resulting in a larger light-escape cone according to equation (1), as shown in Figure 1³⁾.

In this study, we used ray-tracing simulations to calculate η_{ext} for near-ultraviolet (n-UV) LEDs (405 nm) with resins of various refraction indexes, transmittances, and shapes of packages encapsulation.

2. Simulation model

LightTools 6.1.0 (Optical Research Associates), which is based on Monte Carlo ray tracing, was used in this analysis.

The size of the LED chips, consisting of GaN, sapphire, and an electrode, were modeled with an area of 0.35 mm² and a height of 90 nm in the simulation. The interface structures of sapphire were modeled in a striped pattern

$$\begin{aligned} n_{\text{resin}}/\sin \theta_{\text{c air}} &= \sin \theta_{\text{c resin}}/\sin \theta_{\text{c resin}} \\ \theta_{\text{critical}} &= \arcsin [(n_{\text{air}}/n_{\text{resin}}) \sin \theta_{\text{c resin}}] \end{aligned} \quad (1)$$

Figure 1 Escape cone of LED chip in resin or air

Figure 2 Schematics of (a) cross section of LED chip. (b) PSS

Figure 3 Direction distribution of extracted rays concave on the bare model.

Figure 4 (a) top view of the LED package model.
(b) cross-sectional view.

(Patterned sapphire substrate: PSS), as shown in Figure 2(b)⁴⁾. Figure 3 shows the calculated light distribution of the bare chip on the flat plate in the air by ray tracing simulations. We modeled the entire LED package, in which LED chips are placed with GaN face down (flip-chip) with a reflector. The chip is encapsulated in resin as shown in Figure 4. In the ray tracing simulation, we varied the resin refractive index between 1.30 and 1.70 to evaluate the dependence of light extraction on the refractive index under various resin transmittances at 2 mm from 90 to 100%. The dependence (i.e., dependence on the radius of the curvature) on both concave and convex shapes was also evaluated at a fixed resin refractive index of 1.50 and a fixed resin transmittance at 2 mm of 90%. The reflectance of the reflector cup was assumed to be 85% in all simulations.

3. Propriety of simulation analysis

In this chapter, the simulation analysis and the result of experiment were compared. LED package of which the shape is shown in Figure 4 and which were encapsulated by resins with various characteristics were modeled for the simulation analysis and were fabricated by the real experiments. Characteristics of resin were shown in Table 1. Figure 5 shows the comparison of the calculated value with the experiment value and the error bars, respectively. Because the η_{ext} cannot be directly measured by experiments for the lack of η_{IQE} values, the evaluated values were the encapsulation efficiency (%), which means

Table 1 Characteristics of resin

	resin 1	resin 2	resin 3	resin 4	resin 5	resin 6
Refraction index	1.4	1.41	1.49	1.5	1.51	1.53
Transmittance	0.88	0.89	0.86	0.88	0.83	0.88

Figure 5 Comparison of simulation analysis with Experiment result.

the ratio of radiant flux generated out from the encapsulated package to that from bare package. Figure 5 shows that the calculations were equivalent to the result of experiments in the error bars. Thus, at least the tendency of the simulation results is reliable.

As the η_{IQE} of 64% at 406nm for InGaN-based LEDs on PSS⁵⁾ was multiplied by the η_{ext} (50%) of simulation analysis, the η_{EQE} of simulation analysis were approximately equal to that of real experiments (32%). Therefore, the η_{ext} of simulation analysis is also strikingly reliable.

4. Results and Discussion

4.1 Analysis of light extraction efficiency

The results showing the refractive index dependence are shown in Figure 6, and the shape dependence as a function of the value of the curvature radius of the air-resin interface at a fixed refractive index of 1.50 and a transmittance of 90% at 2 mm are shown in Figure 7.

Figure 6 shows that the η_{ext} of the flat LED is higher than that of the bare LED (without silicone resin encapsulation) at all transmittance levels. In addition, higher transmittance results in higher η_{ext} at a constant refractive index. The maximum η_{ext} of 78% was obtained at a refractive index of 1.68 and a transmittance of 100%. This value is 1.56 times as large as the η_{ext} of the bare model (50%). The shapes of the η_{ext} curves at different transmittances are all similar to each other. These results also indicate that a higher refractive index likely results

Figure 6 Refraction index dependence of η_{ext} for a flat model. Figure 7 Relation of curvature radius and η_{ext} for convex and concave models (refraction index and transmittance are 1.50 and 90%, respectively).

in a higher η_{ext} .

Figure 7 shows that as the curvature radius decreases from 100 mm, the η_{ext} of the concave model increases slowly at first and then increases sharply as the curvature radius becomes smaller. The η_{ext} of concave model was larger than that of the flat model and the bare condition for all values of curvature radius. The peak η_{ext} is 77% at a curvature radius of 3.7 mm. This is 1.40 times as large as the η_{ext} of the flat model (55%). On the other hand, the η_{ext} of convex decreases to the lowest observed value of η_{ext} of 45% at a curvature radius of 25 mm and then increases to the maximum observed value of η_{ext} of 79% at a curvature radius of 5.0 mm as the curvature radius becomes lower. The maximum η_{ext} is 1.44 times as large as the η_{ext} of the flat model.

From highest to lowest, the peak values of η_{ext} of the resin models when the resin characteristics are constant are as follows: convex > concave > flat.

4.2 Analysis from the perspective of light direction from LED chip into the resin

There are three representative paths of ray extraction

Figure 8 Schematics of extraction path A: direct extraction, B: single-reflection extraction, C: multiple-reflection extraction.

Figure 9 Direction distribution of extracted rays concave on the flat model.

from an LED chip out to air through the resin, as shown in Figure 8. Extraction path A denotes a ray from the LED chip that is directly extracted to the air through the resin at in equation (1). Extraction path B denotes a ray that is extracted after undergoing a single reflection at the reflector in the resin. Extraction path C denotes a ray that is extracted after undergoing multiple reflections at the reflector and/or the air-resin interface of due to the limitation of θ_{critical} .

The optical intensity (radiant flux) of each extraction path depends only on the proportion of each path defined by the critical angle. Thus, a larger proportion of extraction paths A and B is preferable for the extraction of rays. This indicates that the optical intensity is decided by light distribution from the LED chip into the resin, which is dependent on the size of the light escape cone of the LED chip-resin interface, based on Snell's law. Generally, the proportion of rays extracted via extraction path B is higher than extraction path C for flat LEDs⁶⁾.

Figure 9 shows the light distribution of the flat model on

Figure 10 Direction distribution of extracted rays concave model at a curvature radius of (a) infinity, (b) 15 mm, (c) 7 mm, and (d) 3.7 mm.

Figure 11 The direction distribution of extracted ray for a convex model at a curvature radius of (a) infinity, (b) 50 mm, (c) 35 mm, (d) 25 mm, (e) 10mm, and (f) 5 mm.

the flat plate in the various resin by ray tracing simulations. These simulations indicate that most rays are irradiated at angles between 15° and 45° and between 135° and 165° . Therefore, extraction path B composes the largest portion of the total intensity. Figure 8 also indicates the high optical intensity shift at lower angles in the range of $0-90$ degree and higher angles in the range of $90-180$ degree as the refraction index becomes larger. In these cases, the proportion of extraction path B becomes larger, while that of the extraction path C becomes smaller. This causes a slow increase in η_{ext} as the refraction index changes at a resin transmittance of 100%, as the refraction index is larger, as shown in Figure 6. The decline at the refraction index between 1.3 and 1.46 at a transmittance of 90% or 95% at 2 mm, which occurs in spite of the easier light extraction resulting from the relaxation of the refractive index boundary, is considered to result from the effect of resin absorption due to long light paths.

In Figure 10, the ray extraction direction in the concave

model shows that the proportion of rays extracted with the extraction path A becomes smaller as the curvature radius becomes smaller, while that of extraction paths B and C become larger, which can be attributed to the fact that the shape of the arc becomes larger (solid line circles in Figure 10). These phenomena cause the increase of η_{ext} as shown in Figure 7 since the proportion of rays extracted via extraction path B becomes larger. In particular, this is observed at a curvature radius between 25 and 3.5 mm.

In Figure 10 (a)-(d), the curve of the convex model in Figure 7 can be attributed to the smaller change in the proportion of rays extracted via extraction path A (dotted line circles in Figure 11) and the smaller change in the proportion of rays extracted via extraction path C (dashed line circles in Figure 11) at a curvature radius between 25 mm and infinity. Figure 11 (d)-(f) show that the curve in Figure 7 also results from the much larger change of the proportion of rays extracted via extraction path A at a curvature radius between 5 and 25 mm.

5. Summary

In this study, the η_{ext} of LEDs was calculated as a function of refraction index and shape.

It was confirmed that higher refraction indexes resulted in higher values of η_{ext} for a flat model at a constant transmittance, as well as that the higher transmittance resulted in higher values of η_{ext} at a constant refraction index. When the curvature radius was varied, the maximum η_{ext} was found to be 1.45 times larger than that of the flat model.

In order to develop LEDs that have high η_{ext} , it is important to select resins with high transmittance as well as to control light distribution by controlling the resin shape and the refractive index of the resin.

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