Enhanced Light Extraction From Triangular GaN-Based Light-Emitting Diodes

Ja-Yeon Kim, Min-Ki Kwon, Jae-Pil Kim, and Seong-Ju Park

***Abstract*—This study investigated the characteristics of a triangular light-emitting diode (LED) and compared it to a standard quadrangular LED. The total radiant flux from the packaged triangular LED increased by 48% and 24% at input currents of 20 and 100 mA, respectively, compared to that of a quadrangular LED which was grown on patterned sapphire substrate. In light far-field beam distribution, the light extraction in the horizontal direction of the LED was much higher than that of the quadrangular LED due to the enhancement of light emission from the side walls of the triangular LED.**

***Index Terms*—Extraction efficiency, GaN, light-emitting diodes (LEDs), light output power, shaping, texturing.**

I. Introduction

GALLIUM NITRIDE (GaN) has gained special attention with the recent commercial availability of high-brightness green, blue, and white light-emitting diodes (LEDs) for solid-state lighting and displays [1]. However, though the internal quantum efficiency of GaN-based LEDs has reached more than 80%, due to the rapid development of growth techniques for high-quality epilayers, the external quantum efficiency of the nitride-based LEDs is still low, due to the large refractive index difference between the nitride epitaxial layer ($n_{\mathrm{GaN}} = 2.5$) and air ($n_{\mathrm{air}} = 1$). The improvement in light extraction efficiency is considered to be crucial [1], and several methods such as chip-shaping [2]–[4], texturing of surface [5]–[8], a flip-chip packaging [9], patterned sapphire substrate (PSS) [10], and photonic crystal [11]–[13] have been proposed to enhance the light extraction of these highly efficient LEDs. To enhance the light extraction efficiency, a textured surface was employed on the top [5], [6] and bottom [7], [8] of the LED. Huh *et al.* [5] reported that the power conversion efficiency of a bare-chip LEDs with a micro-roughened p-GaN surface was increased by 62%, compared to that for a LED chip with a smooth p-GaN surface. Fujii *et al.* [8] reported that a bare-chip LED with a n-GaN surface, which was separated from the sapphire substrate using a laser lift-off process and then textured by a photo-electrochemical etching process, showed a light extraction efficiency increase of more than 100% compared to that of a LED with a nontextured n-GaN surface. Yamada *et al.* [10] reported that the increased optical output power of LED packaged with epoxy using PSS was estimated to be 29% at 20 mA. Also, it is known that the extraction efficiency of light can be enhanced from the LEDs through the chip shaping of the sidewalls [2]–[4]. However, all these studies were performed on a quadrangular (QDA) LED. Studies on the light extraction of LEDs with other than the quadrangular shape have not been reported. In this study, the properties of a triangular (TRA) LED are compared with those of a conventional QDA LED.

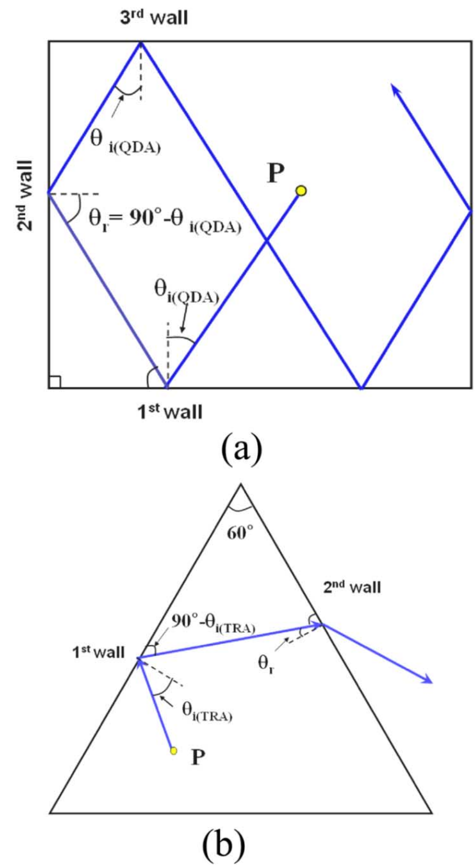

Fig. 1. Light paths inside (a) QDA LED and (b) TRA LED.

Fig. 1(a) and (b) shows the light paths in the QDA and TRA bare-chip LEDs, respectively. In the QDA LED, if the incident angle (θ_{i}) of the photon emitted from the point-like light source (P) is smaller than a light escape cone critical angle [$\theta_{\mathrm{c}} = \sin^{-1}(\mathrm{n_{air}}/\mathrm{n_{GaN}})$] of 23.5°, photons will escape from the LED. However, if the incident angle ($\theta_{\mathrm{i(QDA)}}$) of the photon is larger than that of the critical angle (θ_{c}), the photon will be reflected back at the first sidewall of the QDA LED and the incident angle θ_{r} will be $90° - \theta_{\mathrm{i(QDA)}}$ at the second sidewall of the QDA LED as shown in the Fig. 1(a). If θ_{r} is larger than 23.5°

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at the second sidewall, the photon will be circulated inside the QDA LED. Thus, the range of incident angle for the total internal reflection (TIR) for photons kept inside the QDA LED is given by

$$23.5^\circ < \theta_{\rm i(QDA)} < 66.5^\circ. \quad (1)$$

For an equilateral TRA LED, if the incident angle $(\theta_{\rm i(TRA)})$ of the photon emitted from the point-like light source (P) is smaller than the escaped-light cone angle $(\theta_{\rm c})$ of 23.5°, the photon can escape from the TRA LED as shown in Fig. 1(b). However, if the $\theta_{\rm i(TRA)}$ of the photon is larger than a $\theta_{\rm c}$ of 23.5°, the photon will be reflected back at the first sidewall of the TRA LED and the incident angle becomes $\theta_{\rm r}$ at the second sidewall of the TRA LED. If $\theta_{\rm i(TRA)}$ is larger than a $\theta_{\rm c}$ of 23.5° and the $\theta_{\rm r}$ of $60^\circ - \theta_{\rm i(TRA)}$ is larger than 23.5°, then the photon is reflected back again inside the TRA LED. In this example, the range of incident angles for TIR inside the TRA LED can be estimated by

$$23.5^\circ < \theta_{\rm i(TRA)} < 36.5^\circ. \quad (2)$$

This simple calculation shows that the range of incident angle for TIR of the TRA LED is much smaller than that of the QDA LED. Therefore, the light extraction efficiency of the TRA LED can be greatly enhanced with an increase in the probability of the emitting photon from the LED chip compared to the QDA LED. For TIR of the QDA and TRA LEDs packaged with epoxy, the range of incident angle for TIR of the QDA LED can be estimated by considering the critical angle $[\theta_{\rm c} = \sin^{-1}(\rm n_{epoxy}/n_{GaN}), n_{epoxy} = 1.5, n_{GaN} = 2.5]$ of 36.8° and the result is given by

$$36.8^\circ < \theta_{\rm i(QDA)} < 53.2^\circ. \quad (3)$$

In the TRA LED, the photon with an incident angle larger than the critical angle of 36.8° will be reflected back at the first sidewall of the TRA LED but will be emitted to the epoxy at the second sidewall of the TRA LED. These results indicate that the light extraction from the packaged TRA LED is more enhanced compared to the packaged QDA LED.

II. Experiments

To investigate the effect of LED chip geometry, GaN LEDs with a 455-nm emission were grown by metal–organic chemical vapor deposition (MOCVD) on a c-plane PSS with a hexagonal pattern. The GaN LED consisted of the following layers: a 2-μm-thick Si-doped GaN layer; a multiquantum-well active layer consisting of undoped InGaN wells and undoped GaN barriers; and a Mg-doped p-GaN with a thickness of 0.15 μm. A whole concentration of 3×10^{17} cm^{-3} was obtained after thermal annealing of p-GaN at 800 °C for 5 min. For the electrode formation, mesa patterns were formed by an inductively coupled plasma (ICP) etching process using $Cl_2/CH_4/H_2/Ar$ gases. An Ag/ITO (3/200 nm) layer was used as a transparent contact layer and a Cr/Au layer (20/100 nm) was deposited by electron-beam evaporation onto both the exposed transparent and the n-GaN layers to serve as the p- and n-bonding pads. The sapphire substrate of LED wafer was lapped and polished and the thickness of sapphire substrate was reduced from 330 to 80 μm. Then the LED wafers of TRA and QDA LED with a 80-μm-thick sapphire substrate were easily diced without producing any broken LED chips.

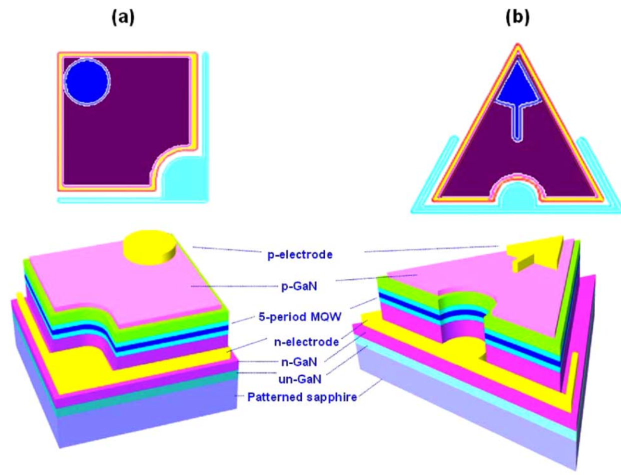

Fig. 2. Schematic diagrams of (a) the QDA and (b) TRA LED.

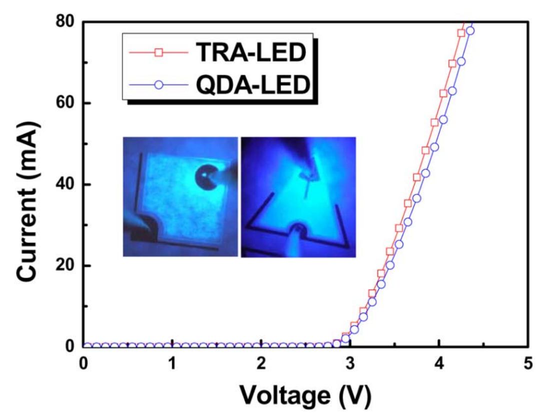

Fig. 3. Current–voltage characteristic (I–V) of the TRA and QDA LED. Inset shows photos of the TRA and QDA LED at an injection current of 1 mA.

Fig. 2(a) and (b) depict schematic diagrams of the QDA and TRA LEDs, respectively. The size of the QDA and TRA LEDs used were 312×312 μm^2 (width $\times$ length) and 440×443 μm^2 (base $\times$ height), respectively, and both had nearly the same surface area. The p- and n-electrodes of the QDA and TRA LEDs were placed face-to-face for efficient current injection. The p- and n-electrodes with the same contact area were deposited on the QDA and TRA LEDs.

III. Results and Discussion

To study the electrical properties of the QDA and the TRA LEDs, their current–voltage (I–V) characteristics were measured using a parameter analyzer (HP 4155A), as shown in Fig. 3. The forward voltage of the QDA and the TRA LEDs were 3.40 V and 3.38 V, respectively, at an input current of 20 mA, and the series resistances of the QDA and the TRA LEDs were estimated to be 11.4 Ω and 11.1 Ω, respectively. These results show that the electrical properties of the TRA LED are slightly better or the same as those of the QDA LED. The inset in Fig. 3 shows the photo images of the QDA and TRA bare-chip LEDs emitting an injection current of 1 mA. The images show that the EL emissions from the TRA LED were brighter and more uniform than those of the QDA LED.

To measure the total amount of photons emitted from LEDs in all directions, the TRA and QDA LEDs were encapsulated and packaged with epoxy. Their optical output power was measured in the integration-sphere with increases in the injection current

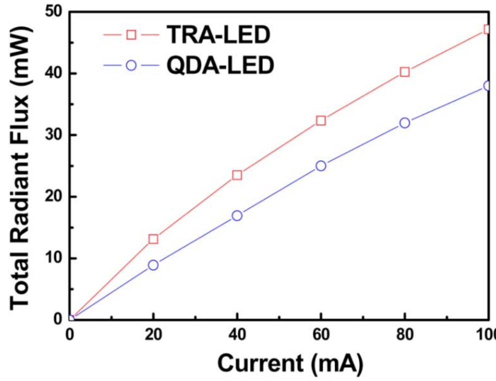

Fig. 4. Radiant flux characteristics $(L–I)$ of the TRA and QDA LED.

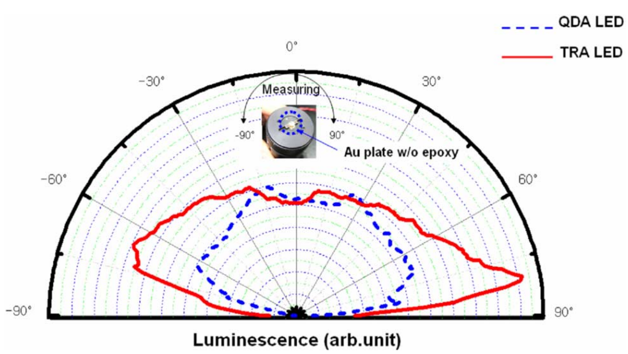

Fig. 5. Angle-dependent scan of the far field beam distribution of the TRA and QDA LED at a current injection of 20 mA. Inset shows a photo of the angle-dependent measurement of emitted light.

as shown in Fig. 4. The $L–I$ curves in Fig. 4 show that the optical output power of the TRA LED is larger than that of the QDA LED in the whole range of input current. The total radiant flux of the QDA and TRA LEDs measured in the integrating sphere was 8.9 mW and 13.2 mW at an input current of 20 mA and 38 mW and 47.2 mW at 100 mW, respectively. The enhancement of the total radiant flux of the TRA LED compared to that of the QDA LED was 48% at 20 mA and 24% at 100 mA. These results indicate that the optical power enhancement of the TRA LED can be attributed to a significant reduction in TIR.

Fig. 5 shows the angular dependence of the light far-field beam distribution of TRA and QDA LEDs at an injection current of 20 mA. To measure the light far-field beam distribution of photons emitted from the horizontal and vertical direction of LEDs, we packaged the LEDs using a flat Au plate without epoxy. Fig. 5 clearly shows that the emission intensities of QDA and TRA LEDs were almost identical in the vertical direction, but the emission intensity of the TRA LED in the horizontal direction was greater than that of the QDA LED. This indicated that the light emission from the TRA LED was enhanced in the horizontal direction due to the significant reduction of TIR at the sidewalls of the TRA LED. Therefore, this study showed that light extraction efficiency can be greatly enhanced in the TRA LED, with an increase in the probability of photon escape, by significantly reducing TIR at the three sidewalls of the TRA LED, compared to the QDA LED.

IV. Conclusion

The properties of the TRA LED were compared to those of a standard QDA LED. The enhancement in the total radiant flux of the TRA LED was 48% and 24% at 20 mA and 100 mA, respectively, compared to that of the QDA LED which was grown on PSS. In the light far-field beam distribution, the light extraction in the horizontal direction of the TRA LED was much greater than that of the QDA LED. The enhanced light output power was attributed to the increased light extraction of the TRA LED in the horizontal direction due to a significant reduction in TIR at the sidewalls of the TRA LED.

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