LETTER

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Enhancing the light extraction of AlGaN-based vertical type deep-ultraviolet light-emitting-diodes with an internal reflector

Youn Joon Sung1,2, Young-Gyeong Lee1, Hwankyo Kim1, Hyun-Soo Lim1, O-Min Kwon1, Sunghan Choi1, Yong-Tae Moon1, Rak-Jun Choi1, Myung-Hoon Jung1, Jeong-Tak Oh1, Dong Woo Kim2, and Geun Young Yeom2,3

1Department of LED Business, Chip development group, LG Innotek, Paju, 10842, Republic of Korea
2School of Advanced Materials Science and Engineering, Sungkyunkwan University, Suwon 16419, Republic of Korea
3SKKU Advanced Institute of Nano Technology (SAINT), Sungkyunkwan University, Suwon 16419, Republic of Korea

E-mail: gyyeom@skku.edu

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Abstract: The light extraction of deep-ultraviolet (DUV) light-emitting diodes (LEDs) with an internal reflector has been shown to lead to a significant improvement in light output power (LOP). Here, we report on Ga-face vertical UV-C LEDs fabricated with a hexagonal internal reflector. The LOP of the vertical LED with an internal reflector is 1.27 times higher than that of the vertical LED without an internal reflector.
Following the LLO process, the sapphire substrate is removed. The UV-C LED structure on the carrier wafer is dipped into a HCl solution to remove Al and Ga droplets. Next, the $n$-AlGaN is roughened by an alkali solution, and each chip is isolated by dry etching. The chips, which are not encapsulated by resin or lenses, are attached to the 6060 PKG. The LOP of the vertical LED is measured using an integrating sphere.

Figures 1(a) and 1(b) show schematic drawings of the vertical LEDs without and with an internal reflector, respectively. Optical microscopic images of vertical LEDs made without and with an internal reflector are also shown in Figs. 1(c) and 1(d). The circular shapes in the chip are the $n$-electrode image shown in Figs. 1(c) and 1(d), while the honeycomb-shaped hexagonal lines surrounding the $n$-electrodes in Fig. 1(d) are the internal reflectors.

Figure 2 shows a cross-sectional SEM image of the internal reflector region. Internal reflector comprises SiO$_2$ and highly reflective Al.

Figure 3 shows the (a) LOP–current–voltage ($L$–$I$–$V$) and (b) current–external quantum efficiency ($I$–EQE) characteristics of the UV-C vertical LEDs with/without an internal reflector. As shown in Fig. 3(a), the LOPs are 14.3 mW for the vertical LED without an internal reflector and 18.2 mW for the vertical LED with an internal reflector at an injection current of 200 mA with a peak wavelength of about 280 nm. The voltages of the vertical LED without and with an internal reflector were 5.94 V and 5.89 V at the same current, respectively. The voltage differences between the two structures are negligible because the current is concentrated mainly at the mesa edge area by the current crowding effect not at the internal reflector area which is located far from the mesa hole. The vertical LED with an internal reflector has a LOP that is 27% higher than that of the vertical LED without an internal reflector. The improvement in the LOP of the vertical LED with an internal reflector indicates an increase in the number of photons extracted by reflecting TM-polarized light. In the propagation of light to the surface direction, the light propagating with an incident angle greater than the escape angle is re-entered to the LED direction due to the total internal reflection effect. The re-entry light can be further extracted by reflecting on the etched plane of the internal reflector. The vertical LED with an internal reflector increases the LOP due to an improvement in the reflectivity. Figure 3(b) shows that the EQE of the vertical LED without and with an internal reflector are 1.60% and 2.07% at an injection current of 200 mA, respectively. These results show that the vertical LED with an internal reflector improves the
Fig. 3. (Color online) (a) Light output power–current–voltage ($L-I-V$) and (b) $I$-EQE characteristics of UV-C vertical LEDs without and with an internal reflector.

Fig. 4. (Color online) Transmittance of UV-C LED (light) on sapphire as a function of p-GaN layer thickness. Each solid is the measured transmittance of different wavelength for different p-GaN thickness. Each solid line indicates the fitting line for different wavelength obtained from Eq. (1).
EQE compared to the vertical LED without an internal reflector, which is attributed to the increased LEE.

Although the light propagation to the surface direction is extracted as mentioned above, most of the light propagating to the direction of the $p$-GaN is absorbed. Because the removal of the $p$-GaN may partly increase the LOP by reducing the absorption effect, the effect of $p$-GaN thickness on transmittance and absorption may need to be investigated. Figure 4 shows the transmittance of UV-C LED (light) as a function of the remaining $p$-GaN thickness. The transmittance is measured until the 450 nm thick $p$-GaN is removed by etching the $p$-GaN of the UV-C LED on sapphire. The results show that the transmittance decreases as the wavelength is shortened, and the light of 254 nm wavelength is almost 0%. Initially, the transmittance for the 450 nm thick $p$-GaN is 0%, but as the $p$-GaN is gradually removed, the transmittance increases. Specifically, for the light of 278 nm, the transmittance increases significantly when the remaining...
$p$-GaN thickness is less than 60 nm. The transmittance is expressed as follows

$$T = Ae^{-\alpha x},$$

where $A$ is a coefficient, $\alpha$ is an absorption coefficient ($\text{cm}^{-1}$), and $x$ is the thickness of the material. Fitting the experimental data leads to the following equation $T = 18.7e^{-\left(1.25 \times 10^5\right)x}$, where $x$ is the thickness of $p$-GaN. According to this equation, we obtain an absorption coefficient of $1.25 \times 10^5 \text{ cm}^{-1}$ at 278 nm, which is consistent with the absorption coefficients of approximately $1.5 \times 10^5 \text{ cm}^{-1}$ reported by Muth et al.\textsuperscript{31}

Figures 5(a)–5(c) show the charge-coupled device (CCD) emission image [Fig. 5(a)], the line-profile of the emission distribution [Fig. 5(b)], and the three-dimensional emission distribution [Fig. 5(c)] of the vertical LED without an internal reflector at an injection current of 200 mA. The CCD emission image, the line-profile of the emission distribution, and the three-dimensional emission distribution of the vertical LED with an internal reflector are shown in Figs. 5(d)–5(f), respectively.

As shown in Fig. 5(a), locations on the edge of the chip away from the hole, such as the right top area of chip, exhibit lower intensity. This indicates that highly resistive UV-C LEDs are affected by the current crowding. In Fig. 5(b), the red line (B-B)\textsuperscript{′}, which is the line-profile of the active area, exhibits similar intensity except for the chip edge, similar to the midpoint between the holes of A-A\textsuperscript{′}. Figure 5(c) shows a three-dimensional distribution of emission intensity. As shown in Figs. 5(b) and 5(c), only the area around the hole has high emission intensity.

In Fig. 5(d), the area with an internal reflector shows the brightest image. In Figs. 5(d) and 5(e), the blue line (C-C)\textsuperscript{′} is the line-profile of emission in the horizontal direction passing through the mesa hole. As was the case in Fig. 5(b), the emission intensity is high at the mesa edge. However, the emission intensity at the internal reflector, which is the midpoint between the holes, is higher than that at the mesa edge. Similarly, in the red line (D-D)\textsuperscript{′}, the line-profile of emission at the active area with no holes shows the highest emission intensity at the internal reflector, and the areas with the internal reflector show nearly the same emission intensity. This indicates that the hexagonal internal reflector surrounding the hole increases the light reflection. Figure 5(f) shows the three-dimensional distribution of emission intensity for the vertical LED with an internal reflector. The emission intensity is the highest at an internal reflector, so higher emission is observed at an internal reflector compared to the vertical LED without an internal reflector shown in Fig. 5(c).

In conclusion, we have demonstrated a UV-C chip design that is composed of a Ga-face $n$-contact type vertical LED with an internal reflector. The internal reflector in the vertical LED is designed in the form of a hexagon surrounding a $n$-electrode, and is fabricated using a SiO$_2$/Al reflector. The LOP of the vertical LED with an internal reflector is 1.27 times higher than that of the vertical LED without an internal reflector. The increased light emission for the vertical LED with an internal reflector is attributable to the effective light reflection on the internal reflector as well as improved local reflectivity.

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