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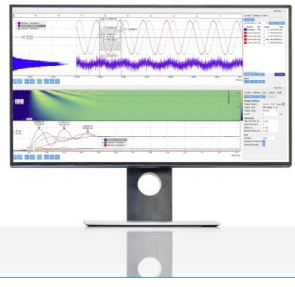

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ABSTRACT

We have demonstrated a vertical UV-C LED composed of the Ga-face *n*-contact electrodes using the circular shape holes on mesa. In order to understand the dependence of optical performance on the mesa hole density, we varied the number of holes. As the number of holes on mesa increased, both the light output power and the external quantum efficiency of vertical chips have enhanced while preserving the operation voltage. In spite of reduced active area, the efficiency of current injection could be improved by reducing the current density per hole. The increased mesa hole density of vertical chips induces the enhanced light extraction through the sidewall of holes.

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Aluminum gallium nitride (AlGaN)-based deep ultraviolet lighting emitting diodes (DUV LEDs) with wavelengths between 200 and 320 nm have drawn attention in industry due to its non-toxic atoms, low-voltage operation, flexible optical design, etc. The AlGaN-based DUV LEDs have potential industrial applications in water purification, surface disinfection, biomedicine, detection of material, phototherapy, UV curing, and plant growth lighting.[1–5] In spite of many promising potentials of DUV LEDs, its external quantum efficiency (EQE) is still much lower than that of mercury lamps.[6–10] To improve the poor EQE of DUV LEDs, highly reflective p-electrodes based on Al or Rh have been tried by researchers to improve the light output power (LOP).[11–13] In other attempts to improve the optical efficiency, researchers are testing p-AlGaN over p-GaN to reduce the optical absorption losses. Unfortunately, the high Al content in a p-AlGaN layer results in poor electrical conductivity due to high Mg activation energy, not to mention the relatively high work function makes it difficult to obtain an Ohmic contact.[14,15] In addition to these drawbacks, high resistance of the *p*-AlGaN layer induces the current crowding effect in the periphery of the n-type electrode that results in majority of light emission in DUV LEDs occurring at the electrode boundary.[16,17] Such current crowding effect around *n*-type electrodes results in the LOP degradation by Joule heating and EQE reduction by the increased local current density. In spite of such difficulties, research to enhance the light extraction efficiency in the vertical type GaN LEDs has shown promising results in the area of visible high power LEDs.

In general, GaN LEDs with laterally injected current have poor heat dissipation due to low thermal conductivity of the sapphire substrate.[18,19] On the other hand, GaN LEDs with vertical current injection show an improved junction temperature due to the thermally conductive substrate that results in the enhanced light extraction efficiency through the textured n-(Al)GaN surface.[18–21]

In the vertical LED structure, there are two types of n-Ohmic contact designs that are currently available: the first type is the conventional *n*-contact on N-face and the second type is the n-contact on Ga-face that can be done by drilling holes. The current flow of the latter type is similar to that of a flip chip, and it has several advantages in terms of the light extraction enhancement and heat dissipation compared to the former type.[22–24] The current crowding phenomena in this vertical chip can be improved by optimizing the *n*-contact hole density for homogenous current injection. In general, the hexagonal arrangement of n-contact electrodes allows a uniform current distribution between the holes.

In this study, we investigate the optoelectronic properties of vertical UV-C LED by varying the hole density of a Ga-face n-contact on the mesa. We suggest the optimum design concerning the gap between

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holes for the efficient optical performances of UV-C LEDs by improving current spreading.

The AlGaN-based UV-C LED epi structure was grown on a 4-in. sapphire substrate using a metal organic chemical vapor deposition system. The epi structure is composed of 3 μm-thick AlN, 200 nm-thick AlN/$Al_{0.5}Ga_{0.5}N$ for a sacrificial layer of laser liftoff (LLO) formation, 2.5 μm-thick Si-doped n-$Al_{0.7}Ga_{0.3}N$, 0.5 μm-thick n-$Al_{0.6}Ga_{0.4}N$, five pairs of $Al_{0.4}Ga_{0.6}N/Al_{0.64}Ga_{0.36}N$ multiple quantum wells (MQWs), 35 nm-thick Mg-doped p-AlGaN electron blocking layer, and 30 nm-thick Mg-doped p-AlGaN Ohmic contact layer with graded Al composition from 65% to 50%. After the UV-C LED epi structure growth, five vertical chips of 1×1 mm^2 in size with different mesa hole numbers were fabricated for the experiment. Figure 1 shows (a) three-dimensional tilt image [(a) part of the DUV LED structure illustrating the carrier injection path from two n-contact holes to active layer] and (b) schematic plane images that include the p-contact metal and n-contact holes for each chip, where the hole diameter is 60 μm. The number of n-contact holes (N_h) for each vertical chip (denoted

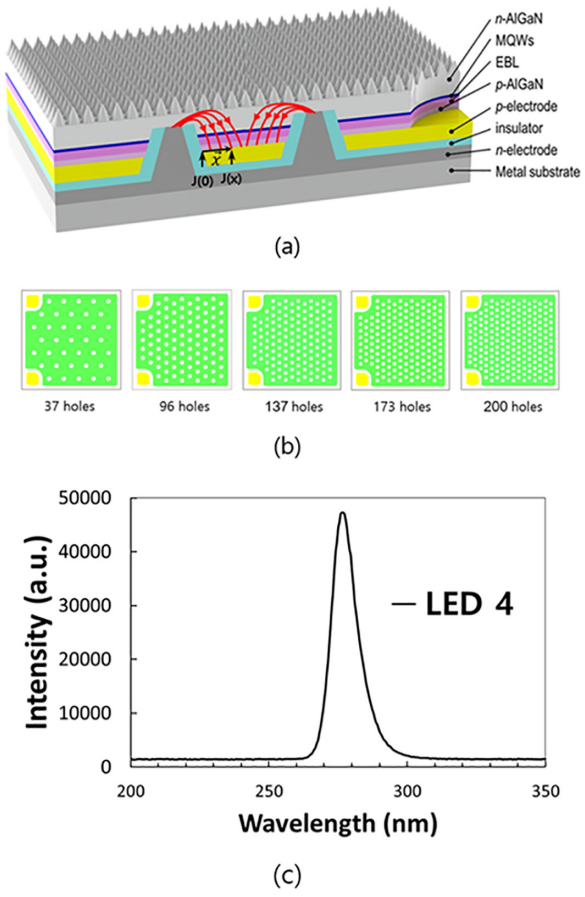

FIG. 1. Schematic of (a) three-dimensional tilt image [(a) part of the DUV LED structure illustrating the carrier injection path from two n-contact holes to the active layer] and (b) plane images based on the number of holes in the vertical chip. The number of holes in each vertical chip was 37 (LED 1), 96 (LED 2), 137 (LED 3), 173 (LED 4), and 200 (LED 5), respectively. (c) The emission peak wavelength of LED 4 in the spectrum is 276.8 nm at 350 mA.

LED 1, LED 2, LED3, LED 4, and LED 5) are 37, 96, 137, 173, and 200, respectively. Detailed fabrication processes of UV-C vertical chips were published elsewhere.[13] The emission peak wavelength of LEDs is around 276 nm, and the full-width at half-maximum is about 11 nm. Figure 1(c) shows the emission spectrum of LED 4 at 350 mA, which has the peak wavelength of 276.8 nm.

Table I shows the active area, the length of the p-type electrode between the holes, and the current density at an injection current of 350 mA according to the N_h. The active area of each vertical chip is 0.65 mm^2 for LED 1, 0.47 mm^2 for LED 2, 0.35 mm^2 for LED 3, 0.26 mm^2 for LED 4, and 0.18 mm^2 for LED 5. For LED 1, LED 2, LED 3, LED 4, and LED 5, the distance between neighboring holes is 88, 27, 13, 7, and 4 μm, respectively.

In Fig. 2(a), the N_h dependent LOPs of each LED at an injection current of 350 mA increase until the N_h of up to 173. When the N_h increases above 173 holes, the LOP of UV-C LEDs no longer increases whereas the operating voltage increases with the mesa hole density. It seems that the insignificant difference in operating voltage with different hole densities is due to the low transverse current spreading in the n-AlGaN layer with high Al composition. Therefore, it is assumed that the N_h increase enables a laterally uniform current injection into the active layer of DUV LEDs. Although the active area is reduced when N_h is increased from 36 to 173 holes, the wall-plug efficiency (WPE) also increases up to 5.6%, as shown in Fig. 2(b). Such result can be explained by certain device aspects of physics. The increased mesa hole edge area can contribute to extraction efficiency of light from the adjacent active region.[25,26] Li *et al.* have reported the light extraction efficiency enhancement of the 290 nm nanoporous LEDs gets enhanced when the nanoporous is introduced.[27] They have addressed that it not only improves the extraction efficiency of top-emitting transverse-electric (TE) polarized light but also improves the efficiency of side-emitting transverse-magnetic (TM) polarized light. We assume that n-contact hole structure can enhance TE/TM light extraction in proportion to the number of n-contact hole, which might have attributed to the increased scattering by the increased sidewall area of mesa. To investigate the relative extraction efficiency enhancement of TM-polarized light compared to TE polarized light, we measured the normalized intensity of TM/TE polarized light depending on the UV-C LED structures, as shown in Fig. 3. The reference sample, Blue LED, is a vertical chip type blue wavelength (441 nm) LED. In the case of LED 4, when compared to the conventional flip chip type UV-C LED, the TM polarized light is enhanced up to 29.4%. However, part of the TM

TABLE I. Active area, distance between holes, and current density depending on the number of holes.

Number of holes	Active area (mm^2)	Hole to hole distance (μm)[a]	Current density (A/cm^2) at 350 mA
37	0.65	88	53.8
96	0.47	27	74.5
137	0.35	13	98.8
173	0.26	7	134.6
200	0.18	4	190.6

[a]Hole to hole distance is the distance between the nearest neighboring holes.

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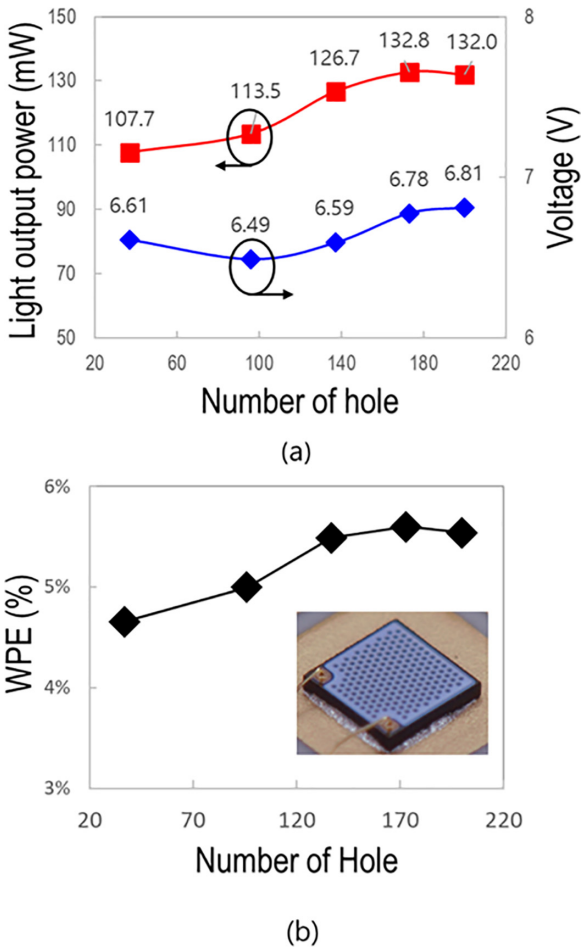

FIG. 2. (a) Characteristics of LOP and operating voltage and (b) wall-plug efficiency (WPE) at an injection current of 350 mA as a function of mesa hole density.

polarized light can be extracted by mixing with TE polarized light through the cone-shaped surface as shown in Fig. 1(a); hence, it is difficult to reveal the exact TM/TE polarization extraction ratio. Furthermore, the optimum value for N_h acts to reduce the active area, which does not contribute to the light generation due to low electron/hole carrier mobility in UV-C LEDs. Such compact arrangement of the n-contact electrode is necessary for efficient current injection into the whole active region. However, as in the case of LED 5, too much N_h results in the decreased effective active area for light emission, which in turn decreases the LOP. For such reasons, further study is needed to understand the exact TM/TE polarized light extraction ratio depending on the vertical UV-C LED structure.

Figure 4(a) shows LOP and EQE characteristics of vertical LEDs as a function of injection current for the representative LED 1, 2, and 4. Figure 4(b) represents *I*–*V* characteristics of vertical LEDs. As it can be seen in Fig. 4(a), the saturation current of LED 1 is about 1.7 A. On the other hand, the LOP for both LED 2 and 4 increases until 2 A. Moreover, LED 4 has a high slope efficiency of 0.35 compared to LED 2, and the saturation current for LED 4 is higher than LED 2. As shown in Fig. 4(a), the peak of EQE for the LED 1(LED 4) is 7.58%

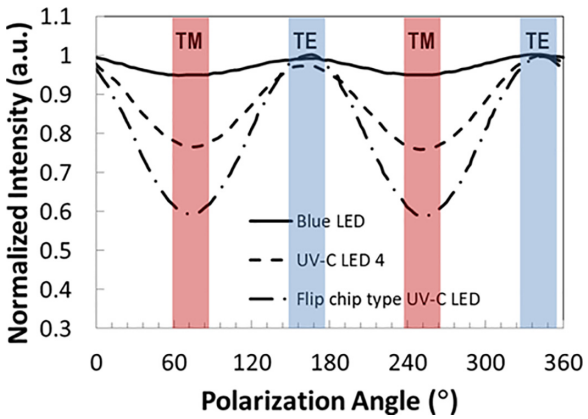

FIG. 3. TM/TE polarized light intensity depending on the UV-C LED structures. Blue LED is a vertical type blue wavelength (441 nm) LED as a reference sample.

(9.59%) at an injection current of 30 mA and 6.89% (8.61%) at an injection current of 350 mA, respectively. Obviously, the LOP for the LED 4 at an injection current of 350 mA is 132.8 mW. The difference in the active layer area due to varying N_h causes a difference in the current injection density. However, comparing the saturation current point of each UV-C LEDs with different N_h is necessary for understanding the device properties such as comparing wall-plug efficiency, thermal resistance calculation, and circuit and/or package design. In Table I, it can be seen that the current density changes in proportion to N_h, which is correlated with the active area. This implies the saturation point of LOP for LEDs depends on N_h in the vertical chip. Figure 5(a) shows the characteristics of LOP as a function of current density. The vertical chip with a large number of n-contact holes enhances LOP for higher current densities compared to vertical chip with low N_h. Such implies a large number of n-contact holes reduce current injection density per unit hole that acts to increase the saturation current level. Figure 5(b) shows the characteristics of current density-LOP per unit hole curves for LED 1, 2, and 4, respectively. It can be confirmed that the saturation current point of the LOP per hole increases as the number of holes increases. In addition, as the number of holes increases, the LOP per unit hole decreases on the contrary to the increase in LOP. This result indicates that the amount of current being injected per unit hole is smaller and the local current density is lower near the hole edge as the number of holes increases. Such property relieves the current crowding around the n-electrodes and enough emission is achieved between the holes, implying the amount of current being injected per unit hole is small and the local current density is low near the hole edge. Figure 5(c) shows the characteristics of current density-EQE curves for LED 1, 2 and 4, respectively. The efficiency drop of vertical LEDs improves rapidly in accordance with the increased mesa hole density, which implies the light extraction efficiency is improved by means of the increased mesa hole density.

Figures 6(a)–6(c) show two-dimensional (2D) light emission image of vertical UV LED at the injection current of 1 A, (d)–(f) a cross-sectional intensity profile of 2D UV light emission of each vertical LED, respectively. Two-dimensional intensity profiles were observed by an UV bandpass filter in the wavelength range between 250 and 300 nm. In Figs. 6(d)–6(f), the cross-sectional intensity profile

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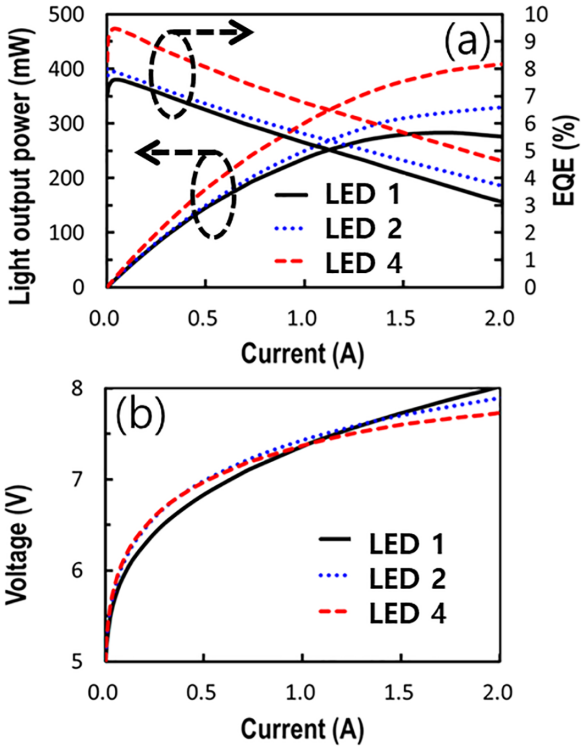

FIG. 4. (a) Current–LOP (*I–L*) and I-EQE characteristics of vertical LEDs depending on mesa hole density. (b) I–V characteristics of each vertical LEDs.

of LED 1 forms a valley between the nearest two *n*-electrodes whereas for LED 2 and LED 4, the same features appear as hill shape at the center between the n-contact holes. Such indicates LED 1 does not have sufficient current spreading due to a wide-spaced gap between n-electrodes. In Figs. 6(d)–6(f), ***A*** is the light intensity at the edge of the hole and ***B*** is the light intensity at the center of the gap. Figure 7 shows the intensity of each ***A*** and ***B*** including the value of ***B/A*** ratio as a function of N_h. The ratio of ***B*** to ***A*** increases as the gap between holes narrows in Fig. 7, which result supports the previous idea that light extraction becomes more efficient on account of the increased hole density. This result can be explained that the improved current spreading according to the reduced n-contact distance can enhance the light intensity at the center of gap between n-electrodes. Figure 8 shows one-dimensional current density distribution between n-contact holes by calculating Eqs. (1) and (2)[28]

$$L_s = \sqrt{(\rho_c + \rho_p t_p) t_n / \rho_n}, \tag{1}$$

$$J(x) = J(0)\exp(-x/L_s), \tag{2}$$

where L_s is the diffusion length, ρ_c is the n-contact resistivity, ρ_p and ρ_n are the resistivity of the p-, n-AlGaN layer, respectively, t_p and t_n are the thickness of the n-, p-AlGaN layer, respectively, J(x) is the current density in the plane of active layer, and J(0) is the current density at the edge of active layer in contact with each n-contact hole. Equation (1) represents the diffusion length of the flip-chip type LEDs. In this experiment, the shape of DUV LED is a vertical type, but the

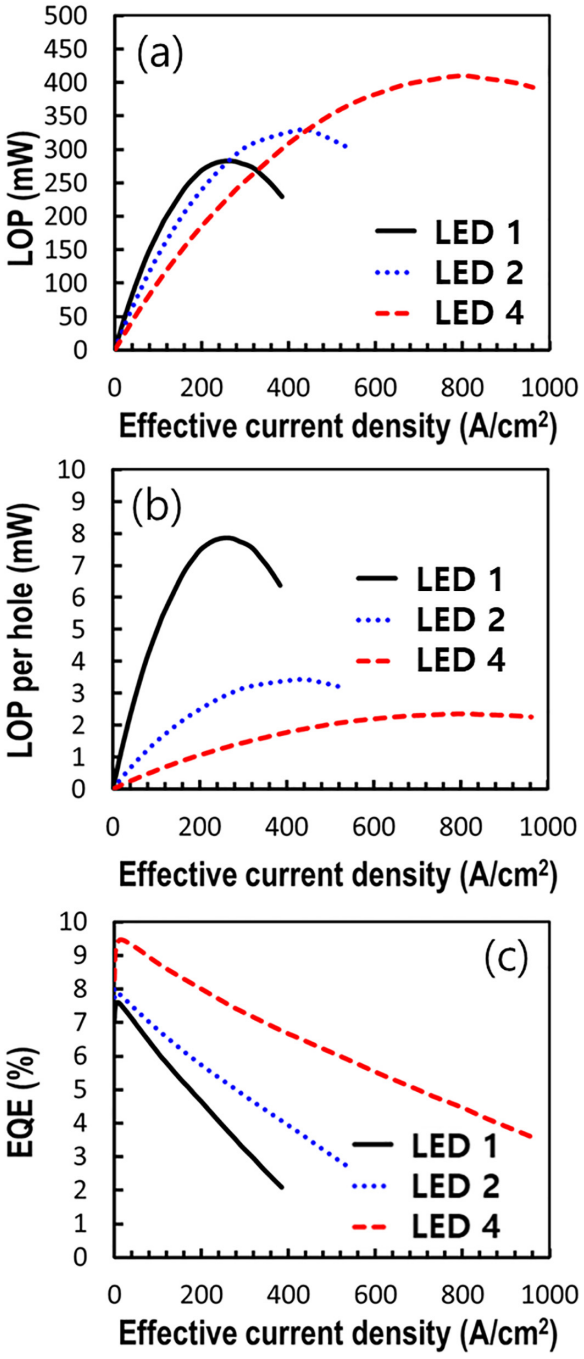

FIG. 5. Characteristics of (a) LOP as a function of current density, (b) LOP per unit hole as a function of current density, and (c) EQE as a function of current density, respectively.

carrier injection path from the n-contact hole to the active layer is the same as that of the flip chip type LED. As it can be seen in Fig. 8, the current spreading is improved as the distance between n-contact holes is decreased. It indicates the LOP enhancement in LED4 could be

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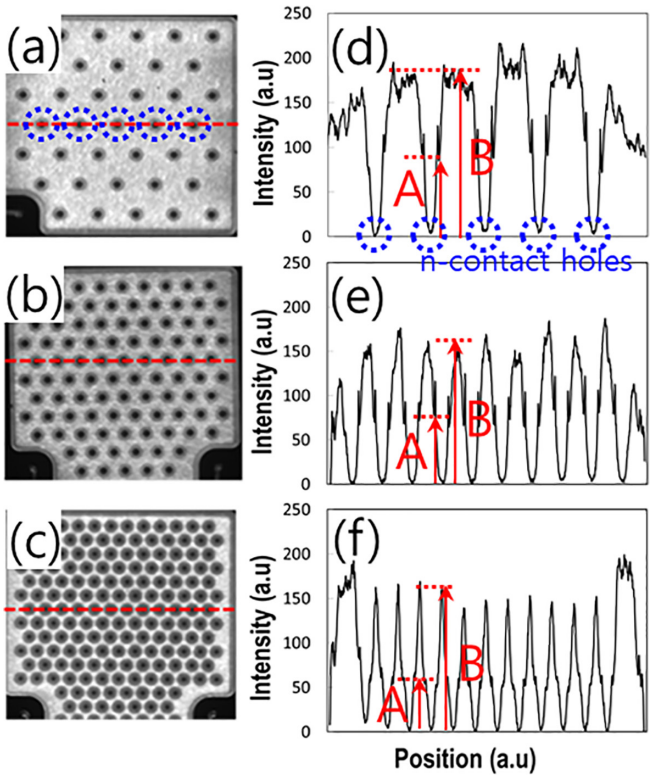

FIG. 6. (a)–(c) Two-dimensional near field image of vertical UV LED at the injection current of 1 A, (d)–(f) a cross-sectional intensity profile of 2D UV light emission of each vertical LED, respectively.

accounted for improved overall current injection efficiency in LED 4. We have evaluated the junction temperature (T_j) to determine the effect of heat on different saturation current levels. With the ambient at 25 °C, T_j of LED 1, 2, and 4 at an injection current of 350 mA is 81.2 °C, 80.1 °C, and 79.3 °C, respectively. It can be noticed that T_j decrease gradually as N_h increases. Based on such results, it can be concluded that decreased current density per hole plays more important role in T_j than the effective active area that gets decreased with increased N_h. Consequently, it indicates that increased n-contact area reduces the thermal resistance.

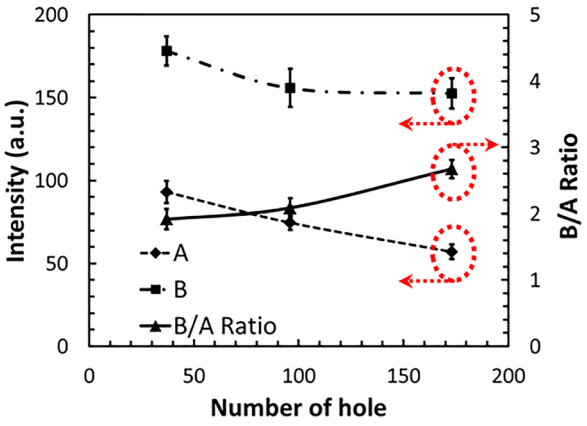

FIG. 7. Intensity of each A and B including B/A ratio as a function of number of holes.

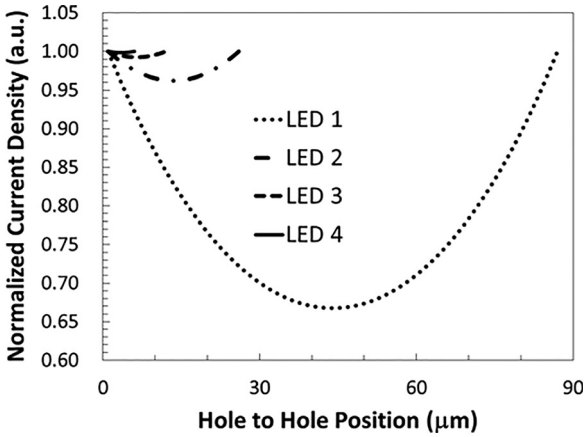

FIG. 8. One-dimensional current density distributions between n-contact holes for each LED 1, 2, 3, and 4, respectively.

We have demonstrated the light output power dependence on the hole density for vertical UV-C LEDs with the circular hole shape *n*-contact electrodes on the Ga-face of mesa. We obtained the optimum hole density for enhancing the light output power of vertical chips. More efficient emission was achieved by increasing the light extraction through the sidewall of holes despite the reduced active area. By increasing the number of holes on mesa from 36 to 173, the LOP of vertical chips at an injection current of 350 mA could be increased from 107.7 to 132.8 mW, which is an improvement of 23.3%. Such result indicates an EQE enhancement from 6.89% to 8.61%. In addition to these improvements, increased mesa hole density of vertical chips was also shown to have advantages in the thermal management during the high current driving.

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DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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