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Uniform Illumination Realized by Large Viewing Angle of Gallium Nitride-Based Mini-LED Chip With Translucent Sublayer Pairs

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ABSTRACT The advent of mini-light-emitting diodes (mini-LEDs) represents a recent advancement in display technology. The biggest advantage of mini-LEDs over traditional backlight LED panels is that the LED array facilitates the local dimming of light intensity. This paper presents a large-view-angle (LVA) GaN-based mini-LED chip with batwing angular light distribution. By placing a translucent layer on the mini-LED, the angular light-intensity distribution can be modified from the Lambertian type to that resembling a batwing using translucent sublayer pairs. Compared to conventional mini-LEDs, the proposed mini-LED chip requires fewer LEDs and a shorter light-diffusing distance to maintain good uniformity without additional lens packaging. Further, the increased sublayer pair count in the translucent layer affords an increase in the radiation half-power angle from 137.5° to 173.2°. This increases the half-power angle of the mini-LED array from 47.4% to 89.1%. The findings of this study demonstrate significant potential for use in the development of ultrathin backlight panels, which are finding commercial utility in modern television designs. This work should provide the applications solution in mini-LED backlit and wide color gamut RGB backlight display.

INDEX TERMS Angular distribution, large view angle, mini-LED, translucent layer, television backlight.

I. INTRODUCTION

Mini-light-emitting diodes (mini-LEDs) have received significant attention owing to their high contrast, wide color gamut, low power consumption, etc. [1]–[4]. However, a backlight mini-LED panel requires an optical diffusing distance to ensure good surface luminance uniformity, which prevents an ultrathin backlight module [5]–[8]. Use of a dense mini-LED array can reduce the mixing distance; however, this method leads to high cost and a heat dissipation problem [9]–[11]. Another method is to tailor the angular distribution of light so that the light emitted from mini-LEDs can spread out faster. However, this requires complex modeling calculations and fabrication processes [12]–[14]. At present, research is being conducted to increase the light emitting angle on mini-LED backlights by using the lens package method with surface-mount (SMD) and chip-scale package (CSP) [16], [16], but there is no report on simply increasing the light emitting angle by changing the chip structure.

In this study, in order to control the light angle through the special chip structure, a chip with a wide light-emission angle has been designed for use in ultrathin backlight display applications. A translucent film layer with reflective and transmissive characteristics is placed atop the mini-LED chip. The angular light-intensity distribution can be modified from the Lambertian type to that resembling a batwing by adjusting the thickness of the translucent layers. Thus, the diffusion distance can be reduced without using a lens to provide uniformity, thereby realizing the objective of a low-optical-distance (low-OD) ultrathin backlight structure. The proposed large-view-angle (LVA) mini-LED chip is low-cost and practical for mass-production. It provides ultra-high light- angular distribution as well as an ultrathin direct backlight solution for use in mini-LED applications. To evaluate the effect of the

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LVA chip in backlight applications, this study compares the light uniformity of mini-LED arrays against those of normal mini-LEDs and LVA LEDs.

II. LVA MINI-LED FABRICATION PROCESS

GaN-based LEDs were grown on patterned sapphire substrates using the metal-organic chemical vapor deposition. The epitaxial LED structure comprised a 20-nm-thick AlN buffer layer, 3-μm-thick undoped GaN layer, 2.5-μm-thick Si-doped n-GaN layer, 120-nm-thick InGaN/GaN superlattice structure, 5 pairs of InGaN/GaN multiple quantum well, 48-nm-thick p-AlGaN/GaN electron-blocking layer, and 110-nm-thick Mg-doped p-GaN layer.

The detailed fabrication process of the proposed LVA mini-LED chip is as follows. Inductively coupled plasma (ICP) etching was used to etch n-type holes with BCl_3/Cl_2 gas until the n-GaN was exposed. Electron beam evaporation was used to deposit a 100-nm-thick indium tin oxide (ITO) layer on p-GaN as a transparent conductive layer and annealed at 550 °C in a N_2 atmosphere. Subsequently, Cr/Al/Ti/Au/Pt (2/100/30/500/100-nm-thick, respectively) metal layers were deposited on the ITO and n-GaN layers as the n- and p-electrodes, respectively. Distributed Bragg reflector (DBR) layers comprising 20 alternating pairs of SiO_2/TiO_2 were deposited on the chip via ion-beam sputtering and holes formed via ICP using CF_4/O_2 gas. Ti/Al/Ti/Al/Ti/Au (50/500/50/500/50/40 mm, respectively) metal layers were deposited on the p- and n-type holes as p and n pads, respectively; subsequently, the wafer thickness was reduced to 90 μm via lapping and polishing. A translucent light-emitting layer was deposited onto the sapphire substrate of the mini-LED via ion-beam sputtering with different pairs of SiO_2/TiO_2. Finally, the wafer was sliced into mini-LED chips measuring 100 × 200 μm. Figs. 1(a) and 1(b) depict the normal and LVA mini-LED configurations, respectively.

III. LVA MINI-LED PARAMETERS

A. STRUCTURE OF LVA MINI CHIP

Fig. 2 (a) shows scanning electron microscope (SEM) images of the LVA mini-LED. The cross-sectional image obtained via milled by focused ion beam (FIB) along the c-c plane reveals the DBR layer to cover the surface of the luminous region [Fig. 2(c)]. To control the light-emission angle, a translucent layer was placed onto the sapphire surface of the mini-LED chip. The selected layer materials with high and low refractive index included TiO_2 and SiO_2, respectively [Figs. 2(b) and (d)], and the Essential Macleod commercial software was used to design and simulate the analysis of the translucent layer. For the 455-nm dominant wavelength, 2, 3, 4, 5, and 20 pairs of SiO_2/TiO_2 translucent sublayers were designed, and the thickness of each SiO_2 ($n = 1.47$) and TiO_2 ($n = 2.3$) layer was maintained at 80 nm and 45 nm, respectively.

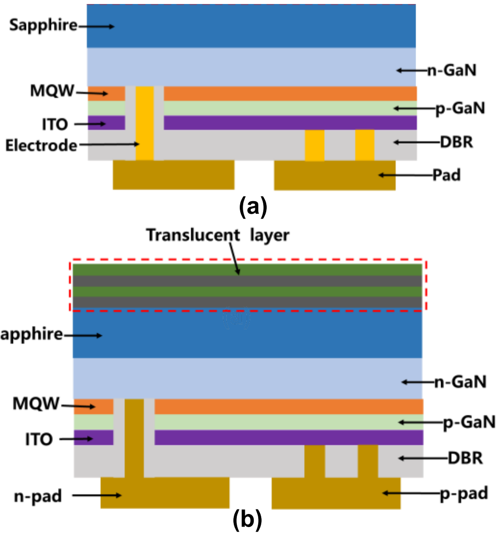
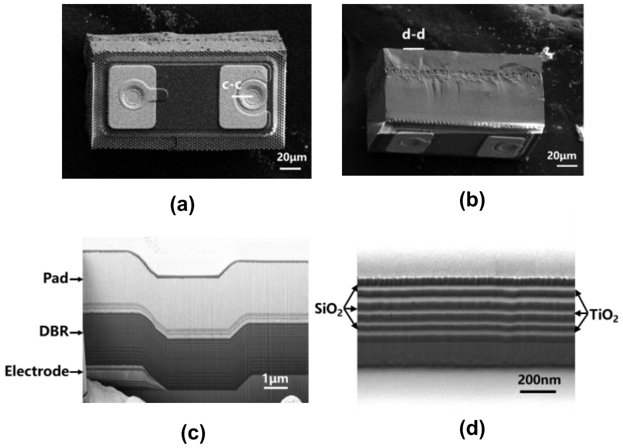


FIGURE 1. Schematic of (a) normal and (b) LVA mini-LEDs.



(a) (b)

(c) (d)

FIGURE 2. SEM images of LVA-LED—(a) top-view image, (b) lateral-view image, (c) cross-sectional SEM image of LVA-LED milled by FIB along c-c plane, (d) cross-sectional SEM image of LVA-LED milled by FIB along d-d plane.

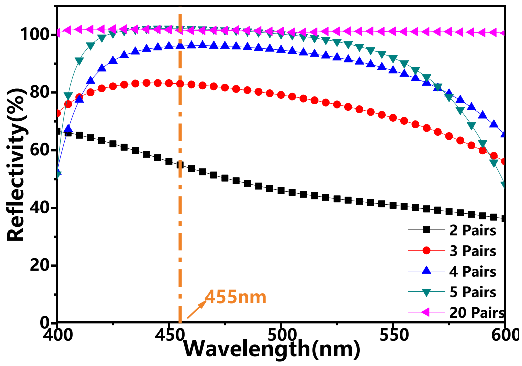


FIGURE 3. Observed reflectivity trends when using 2, 3, 4, 5, and 20 pairs of SiO_2/TiO_2 translucent sublayers, as measured by fiber spectrometer.

Fig. 3 shows the reflectivity observed when using different numbers of sublayer pairs within the translucent layer. as can be seen, the observed reflectivity equals 53.2%, 81.5%, and 94.6% when using 2, 3, and 4 sublayer pairs, respectively, in the translucent layer at 455-nm wavelength; the reflectivity further increases to 99.5% when considering 5 pairs. This is because very little light is reflected from each sublayer interface. The reflection at the interface occurs owing to the high and low refractive indexes of SiO_2 and TiO_2, respectively [17], [18].

In accordance with matrix optics theory, the reflectivity R can be deduced as follows when direction of incident is normal to the interface [19].

$$R = \left[\frac{1 - \frac{n_i}{n_0}\left(\frac{n_1}{n_2}\right)^{2p}}{1 + \frac{n_i}{n_0}\left(\frac{n_1}{n_2}\right)^{2p}} \right]^2 \tag{1}$$

Here, n_1 and n_2 denote the refractive indexes of translucent layer, n_0 and n_i denote the refractive indexes of the incident and exit planes, respectively, and p denotes the number of translucent-layer pairs. An increase in the number of SiO_2/TiO_2 sublayer pairs (p) causes an increase in the reflectivity of the translucent layer (R). This results in increased intensity of the light exiting laterally out of the mini-LED chip. When the number of SiO_2/TiO_2 translucent sublayer pairs increases from 5 to 20, the reflectivity does not improve further; therefore, increasing the number of translucent sublayer pairs beyond 5 is recommended when using light with 455-nm wavelength. The 455-nm wavelength was selected because it facilitates the realization of a higher phosphor excitation efficiency in the backlight module.

B. LVA MINI-LED OPTICAL PARAMETER MEASUREMENT

Multiple pairs of translucent sublayers were utilized to increase the scattering angle. The far-field radiation pattern was measured using the distributed photometer (Everfine LED 626). The distance between the mini-LED and detector equaled 316 mm during far-field measurements.

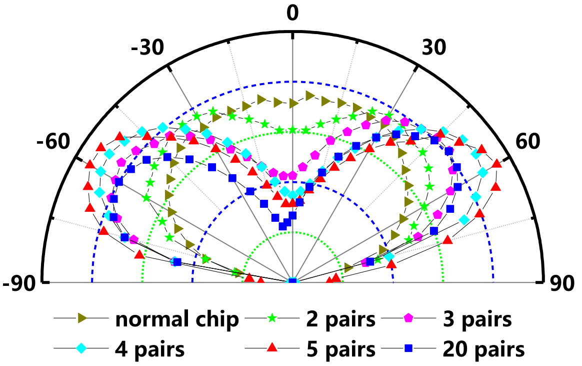


FIGURE 4. Far-field radiation patterns obtained for 2, 3, 4, 5, and 20 pairs of SiO_2/TiO_2 translucent sublayers, as measured using distributed photometer.

As depicted in Fig. 4, the angular light distribution of the LED alone differs from the Lambertian type. As observed, the axial and lateral light intensities decrease and increase, respectively, corresponding to an increase in the number of translucent sublayer pairs. Accordingly, the angular light-intensity distribution gradually spreads from the Lambertian-type to that resembling a batwing. Table 1 lists the observed values of the radiation half-power angle and luminous efficiency corresponding to a 5-mA current. The presence of partially reflective translucent sublayer pairs on the emitting surface causes the axially incident light to be reflected along the lateral direction. This increases the intensity light emitted through the side of the chip, thereby increasing its radiation half-power angle.

TABLE 1. Observed radiation half-power angles when using different number of translucent sub-layer pairs.

	Normal chip	2 pairs	3 pairs	4 pairs	5 pairs	20 pairs
Radiation half-power angle (°)	137.5	153.9	165.0	168.4	173.2	173.4
Luminous efficiency (lm/W)	9.3	9.02	8.80	8.71	8.52	7.88
Wavelength (nm)	455.2	455.4	455.3	455.4	455.2	455.3

It should be noted that the luminous efficiency of chips fell from 9.3 lm/W for the normal chip to 8.52 lm/W for 5 pairs of sub-layers on the LVA chip and to 7.88 lm/W for the 20-pairs sample. This happens because: As the light bounces back and forth inside the chip, some light is lost at each reflection surface as well as through absorption in the GaN defects and multiple quantum wells [20]. Finally, as the light comes out of the side of the chip, the area burned by the laser cutting can also cause a certain loss of light.

TABLE 2. The light intensity with different light degree measured by distributed photometer.

Light degree (°)	Normal chip (cd)	2 pairs (cd)	3 pairs (cd)	4 pairs (cd)	5 pairs (cd)	20 pairs (cd)
-60	1.287	1.538	1.71	1.826	1.938	1.704
-30	1.629	1.737	1.619	1.602	1.479	1.322
0	1.652	1.413	1.217	1.163	1.104	1.029
30	1.631	1.704	1.672	1.582	1.486	1.501
60	1.292	1.428	1.752	1.866	1.952	1.817

The light intensities corresponding to the −60, −30, 0, 30, and 60 degree angles were measured in order to further investigate the principle behind LVA mini-LED chips, as shown in Table 2. The light intensity of a normal chip is much higher than that of the different pairs of LVA chips at the 0 light degree angle. However, for a 60 degree light angle, we can see clearly that the LVA chip showed a higher light intensity, especially with 5 pairs of translucent sublayers. As seen from the microscopy images of a normal mini-LED and LVA-LED in Fig 5, in a traditional mini-LED, most of the exiting light remains perpendicular to the chip and no light is emitted from the side of the chip (Fig. 5(a)). In contrast,

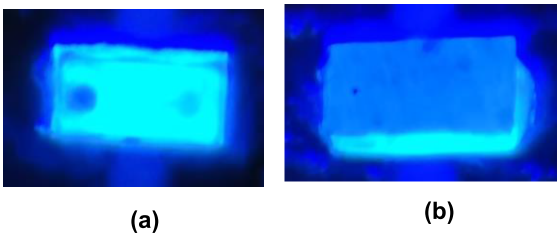


FIGURE 5. Microscopic imaging of (a) normal mini-LED and (b) LVA-LED.

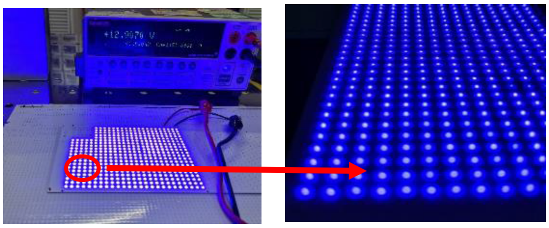


FIGURE 6. Square lattice on backlight mini-LED panel.

at the interface between the sapphire and translucent layer, part of the light emitted by the LVA-LED undergoes total internal reflection. This reflected light exits from the side of the chip [21], [22]. The translucent layer reflects light back towards the chip. After subsequent reflection from the p-side of the DBR layer, this light is returned towards the translucent layer. After multiple such internal reflections, the light is finally emitted from the side of the chip, thereby increasing the emission angle of the mini-LED chip (Fig. 5 (b)).

IV. OPTICAL PARAMETERS OF LVA MINI-LED ARRAY

The batwing-shaped angular distribution of backlight mini-LED panels spreads light over a much wider region area compared to the Lambertian distribution. Therefore, the introduction of the LVA mini-LED chip in the backlight system could facilitate a reduction in the panel thickness and mini-LED count.

To assess the effect of the LVA chip in backlight-panel applications, mini-LEDs measuring 100 × 200 μm were arranged as a 3-mm pitch square chip lattice (Fig. 6). An optical power meter (Konica Minolta LS-110) was used to test the light uniformity of the mini-LED array for the normal mini-LED and LVA-LED lattices using a 5-mA injection current. The power meter is fixed on the bracket with the OD of 1.6mm from the backlight-panel, and moved to 9 points located on the panel respectively to record the power of each point. A nine-point method was used to determine the uniformity of the mini-LED array. The light uniformity was calculated using the following relation [23].

$$\text{uniformity} = 1 - \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}} \tag{2}$$

where $I_{\max}$ and $I_{\min}$ denote the maximum and minimum illuminances in the power meter, respectively.

Fig. 7 depicts the uniformity and power-output trends pertaining to the LVA mini-LED array comprising different numbers of translucent sub-layer pairs. As can be seen, an increase in the radiation half-power angle causes a corresponding increase in the light uniformity of the mini-LED array from 47.4% (normal chip) to 89.1% (chip containing 5 translucent sub-layer pairs). However, the luminous efficiency correspondingly decreases. The loss in light output increases from 0 (normal chip) to 10.1% (chip containing 5 translucent sublayer pairs). The chip containing 20 translucent sublayer pairs suffers 18.7% loss in emitted light. This demonstrates the importance of the tradeoff between light uniformity and emission loss in actual mini-LED backlight-panel applications. Overall, the LVA mini-LED containing 5 translucent sublayer pairs represents the optimum tradeoff between the desired light uniformity and emission loss. The use of a chip with a large viewing angle results in good light uniformity while requiring only a small mixing distance in the system.

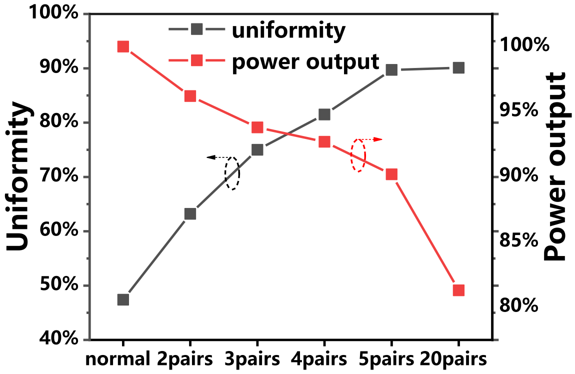


FIGURE 7. Uniformity of mini-LED array when using different number of translucent sublayer pairs.

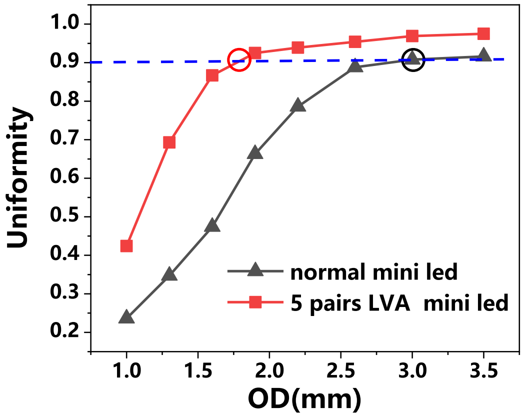


FIGURE 8. Light uniformity of LVA mini-LED array and normal mini-LED array containing 5 translucent sublayer pairs with different OD.

The below discussion explains how the large viewing angle influences a backlight mini-LED panel. To realize a target light uniformity of 90%, the minimum OD values corresponding to an LVA mini-LED array containing 5 translucent sublayer pairs and normal mini-LED array equal 1.7 and 3 mm. respectively. These cases are marked by the red and black circles, respectively, in Fig. 8. As can be seen, the LVA-LED configuration is thinner (by 1.3 mm) compared to the normal-LED configuration. Alternately, for the same uniformity, the LVA-LED panel requires a smaller LED count compared to the normal-LED configuration. This reduced thickness of the backlight module makes it suitable for use in ultrathin backlight-panel applications.

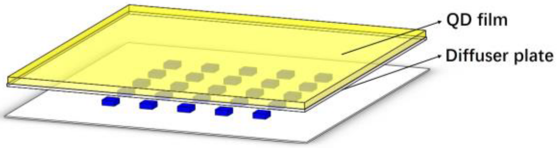


FIGURE 9. White backlight structure with mini led array.

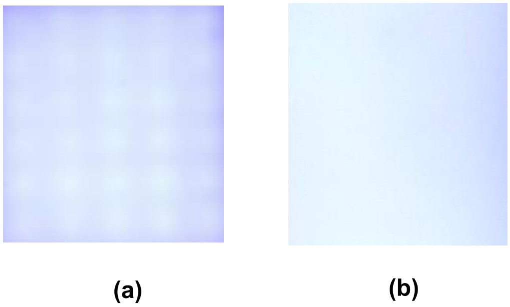


FIGURE 10. (a) Light distribution images of normal mini-LED; (b) light distribution images of LVA-LED with 5 translucent sublayer.

Fig. 9 displays the white backlight structure, which consists of 3-mm pitch square mini-LED chip lattice, diffusion plate and QD films. OD films were fabricated using CdSe/ZnS core-shell, which is used to convert the colour of light from blue to white. A diffuser sheet was inserted below the QD sheet to realize high uniformity. The effective optical distance (OD) between chip and diffusion plate is set as 1.8 mm in order to obtain good spatial uniformity. Fig. 10(a)(b) shows the light distribution images of the normal mini-LED array and LVA mini-LED array with diffusor and QD films at OD = 1.6 mm, it can be seen that the normal mini-LED array shows the stripe patterns visibly, but as a comparison, the horizontal and vertical stripes disappear for the LVA mini-LED array, which has a better uniform planar light compared to the normal chip. It is significant for the ultra-thin display technology in the future.

V. CONCLUSION

In this study, a chip with large light-emitting angle was designed for use in ultrathin backlight mini-LED applications. A translucent film layer with reflective and transmissive characteristics was placed atop a mini-LED chip, and the transmittance of translucent sublayer pairs were adjusted to control the levels of axial and lateral light emission by adjusting the emission angle of the chip. The angular distribution of light intensity can be changed from the Lambertian type to one that resembles a batwing by adjusting the number of translucent sublayers. The radiation half-power angle could be changed from 137.5° to 173.2° by increasing the number of sublayer pairs in the translucent light-emitting layer. Measuring the light uniformity of the normal and LVA mini-LED arrays in backlight panels revealed the radiation half-power angle of the mini-LED array to have increased from 47.4% (normal chip) to 89.1% (chip containing 5 translucent sublayer pairs). However, this increase in the radiation half-power angle resulted in a corresponding decrease in luminous efficiency. The loss in output light increased from 0 (normal chip) to 10.1% (chip containing 5 translucent sublayer pairs). An analysis of the tradeoff between light uniformity and emission loss revealed the LVA mini-LED configuration with 5 translucent sublayer pairs as optimum.

The LVA LED chip described in this paper can be employed in ultrathin backlight display applications, thereby significantly reducing the OD between the mini backlighting source and LCD screen. The angular light intensity distribution can be modified from the Lambertian type to one resembling a batwing, thereby reducing the mixing height without the need for optical lenses to meet uniformity requirements. This would enhance the economic feasibility of mini-LED applications. This work should not only find applications in mini-LED backlit LCDs but also shed light on wide color gamut RGB backlight display.

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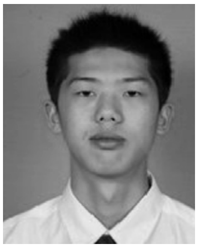

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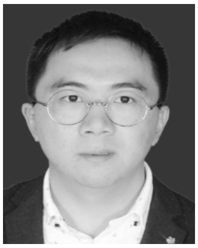

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