Novel Design of Microstructure Package Design to Enhance Optical Efficiency of Micro-LED Displays

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Abstract

In this work, we propose a novel microstructured packaging design for Micro-LEDs. By using a high-refractive-index transparent resist, we enhance the light extraction efficiency of Micro-LEDs significantly. Additionally, a high-reflectivity white resin material combined with lens microstructures is adopted to converge the light from a wide viewing angle, increasing the brightness at the 0° viewing angle by approximately 53%. This novel design improves the light utilization efficiency and reduces color deviation issues caused by the strong sidewall light emission of Micro-LEDs. Furthermore, the patterned design of the black matrix cover layer reduces light loss and enhances the contrast of the display product, realizing high-quality image display for Micro-LED products. This paper provides a new scheme for enhancing the performance of Micro-LED display products and promotes the industrialization process of Micro-LED technology.

Author Keywords

Micro-LED; Microstructure Package; Optical Efficiency.

1. Introduction

Micro-LED generally refers to LED arrays with a single chip size of less than 50 μm, and is one of the most cutting-edge international display technologies today. Compared with LCD and OLED, Micro-LED has many advantages, such as high efficiency, good weather resistance, long lifetime, high resolution, and simple display structure[1-3]. It is known that light reflects multiple times from the upper and lower surfaces of the chips and emits from the sidewalls, causing the light emitting from Micro-LED chips is no longer conforming to the Lambertian far-field light distribution. However, as the size of Micro-LED pixels decreases, the ratio of sidewall area to the overall surface area increases. Then light intensity of Micro-LED chips emitting from side direction is much greater than that emitting from top direction. Therefore, when different colors of light emit from the side, their intensities are different due to the different refractive index and gradient angle among different color LED chips, thus leading to color deviation issues [4]. Moreover, this phenomenon reduces the overall light utilization efficiency because the light emitting from size direction is difficult to receive from human eyes. These limitations seriously restrict the application scenarios of Micro-LED display. Therefore, by adopting high-refractive-index transparent adhesive to enhance the light extraction efficiency of Micro-LED and using high-reflectivity white adhesive combined with lens microstructures to converge the wide-angle light of Micro-LEDs, we can adjust the light output angle and utilize the light emitting from sidewall of Micro-LED chips, thus significantly improve the optical efficiency of Micro-LED display products. In addition, the adoption of patterned design of the black matrix cover plate further reduces light loss and improves the contrast of display products. Therefore, this novel scheme consisting of transparent adhesive, white adhesive, lens array and patterned black matrix will achieve a high-quality image display for Micro-LED products, leading to a better performance in various application scenarios.

2. Experiment

Micro-LED chips are transferred to the backplane through ACF/eutectic bonding process. And a negative high-refractive-index transparent resist is coated on the chips and then patterned by photolithography. The distribution of exposure dose and the reaction mechanism during development process will affect the shape of the resist patterns. In negative photoresist, the edges are relatively easily etched due to the lower exposure dose and weaker crosslinking degree, resulting in an inverted trapezoidal shape (Micro-LED-Step 1). Next, a high reflectivity white resin material covers the surface of the substrate to ensure that the chips are fully filled with white resin (Micro-LED-Step 2), and then the excess white resin above the chips is removed by plasma to ensure that the light output is not blocked, forming an isosceles trapezoidal barrier between the chips (Micro-LED-Step 3). Moreover, high-precision alignment of lens is achieved above the chips through photolithography or nanoimprint, thus resulting in focusing the light (Micro-LED-Step 4). Finally, a BM cover glass is attached (Micro-LED-Step 5), which not only provides protection but also improves the contrast ratio of display products and enhances the display effect (Figure 1).

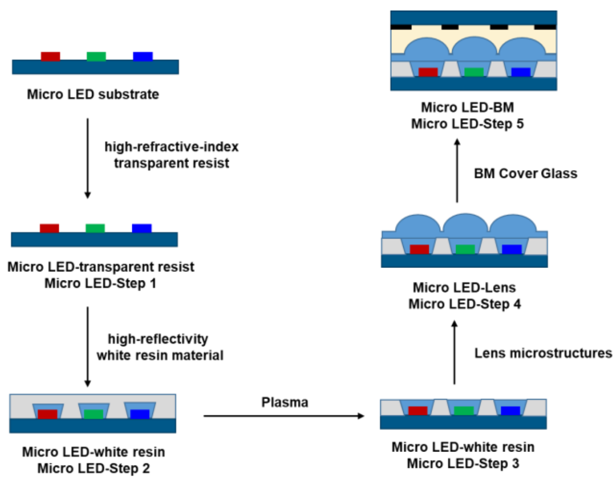

Figure 1. Micro-LED display microstructure package design process.

3. Results and Discussion

Firstly, we take the flip-chip Micro-LED as an experimental model. The structure of Micro-LED chips is shown in Figure 2a, which consists of p/n-contact, P-GaN, MQWs, N-GaN and PSS[5]. As the size of Micro-LED chip decreases, the sidewall area increases, so the sidewall luminescence has a large impact in the Micro-LED display.

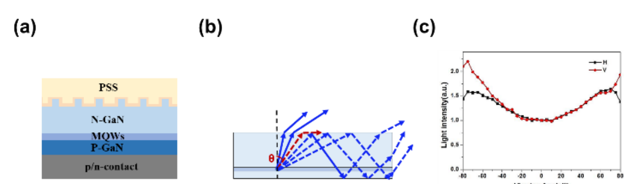

Figure 2. Micro-LED structure (a), chip internal light emission direction (b) and light distribution (c).

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It is well-known that the refractive index of GaN is around 2.3. When the light emitted from the MQWs reaches the surface of the chip and exits into air with a refractive index of 1, due to the relatively large difference in refractive indices at the interface, the critical angle θ can be calculated using the formula for total reflection. The light will directly exit from the top surface when the incident angle is less than θ=25°. When the incident angle is greater than θ=25°, the phenomenon of total internal reflection occurs, a portion of the light emitting upward exits from the top surface directly. Another part of the light emitting upward is reflected downward and exits from the sidewall, resulting in a relatively higher intensity of light emitted from the sidewall (Figure 2b). Meanwhile, we tested the light pattern of Micro-LED chips (Figure 2c). It is indicated that the light emission of Micro-LED is not a conventional Lambertian distribution, and the light intensity increases with the viewing angle in both vertical (V) and horizontal (H) directions. Therefore, enhancing the light utilization efficiency under wide viewing angles is an important approach to improve the light efficiency of Micro-LED displays.

To solve the severe total reflection issue, we introduce a new packaging scheme consisting of three different kinds of transparent resist layer with refractive indices of 2.1/1.9/1.7 and a OCA layer with a refractive index of 1.5. The transparent resist layer is regarded as refractive index transition layer and the OCA layer is regarded as packaging layer. With the introduction of this gradual refractive index structure, the critical angle is significantly improved to 65.9°/55.7°/47.6° (corresponding to 2.1&1.9&1.7 refractive indices), thereby enhancing the light extraction efficiency from the top surface. As shown in Figure 3, a simulation was conducted taking the H direction of Micro-LED emitting light as an example. The light extraction efficiency is highest when the refractive index of the transparent resist is 2.1, leading to a significantly enhancement of top emitting intensity.

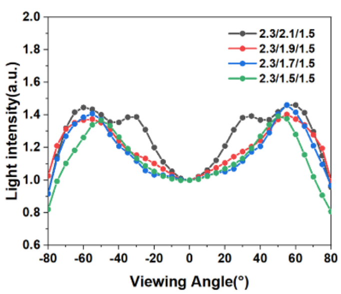

Figure 3. Light distribution curves of high refractive index transparent resists with refractive indices of 2.1/1.9/1.7.

In Micro-LED-Step 2 shown in Figure 1, a high reflectivity white resin material (ref. ≥60%) is filled into the gap between Micro-LED chips using bonding process. Then plasma process is adopted to remove residual adhesive resin on top of LED chips shown in Micro-LED-Step 3. Then a positive trapezoidal pattern is formed based on the shape of transparent resist. The gradient angle of the trapezoid's side can be adjusted through the lithography process in Micro-LED-Step 1. As shown in Figure 4a, when the gradient angle is 60°, the light has a good convergence effect with a 27% increase in light intensity at a 0-degree viewing angle. Furthermore, a higher trapezoid can be achieved by controlling the thickness of the photoresist and resin materials. The greater the height of the trapezoid exceeds the chips, the greater the improvement in optical efficiency (Figure 4b). The microscope images before and after the plasma treatment to clear the residual adhesive above the LED chips are shown in Figure 4c and 4d. As shown in Figure 4e, if the residual adhesive is not removed, the light intensity will decrease by over 20%, further indicating that plasma process is necessary in white resin material fabrication.

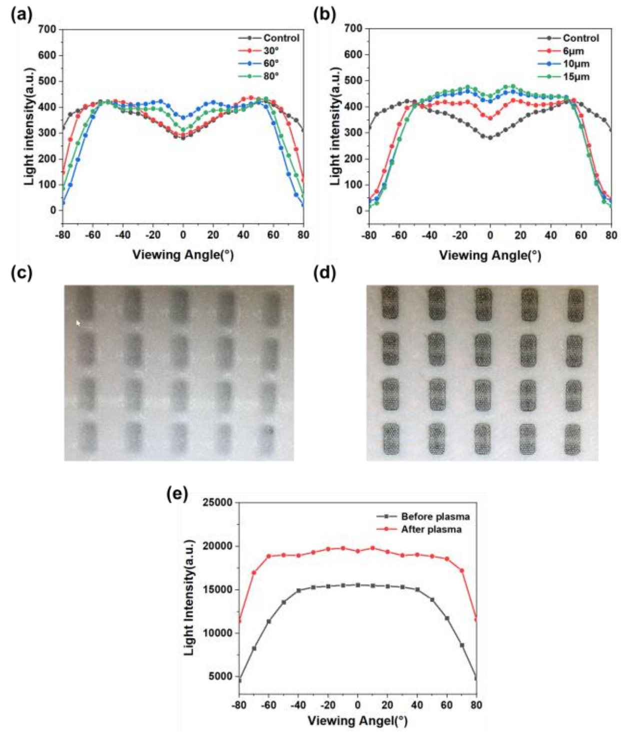

Figure 4. Light distribution with different gradient angles (a) and heights (b) of high reflectivity white resin material. Microscope images of Micro-LED chips with plasma process (d) and without plasma process (c) after bonding with the white resin material. (e) Light intensity of the module with and without plasma process.

High reflectivity white resin material can converge the viewing angle to ±60° (at this time, the light intensity at 60° viewing angle decreases to half of the intensity at 0° view angle) when the gradient angle is 60° and the height is above 6 μm. The micro-structure of the lens has been introduced to narrow the viewing angle more efficiently and further enhance the brightness at the 0° viewing angle. Firstly, making lens array directly on the Micro-LED chip has poor effect on improving light efficiency. It is shown in Figure 5a that a new light intensity peak is observed at ±75°, indicating that the direct lens design on LED chips has disadvantages of light leakage and crosstalk at large viewing angles. Therefore, in this design, the high reflectivity white resin material is introduced to preliminarily converge the light at large viewing angles, and then the light is further focused by the high precision aligned lens, then achieving an optical effect with high collimation and efficiency shown in Figure 5b. As shown in Figure 5c, the lens micro-structure is fabricated by the photolithography process with great surface morphology and periodicity, leading to a good effect of light convergence.

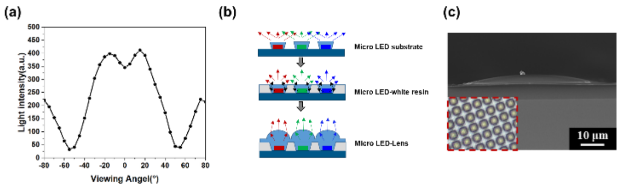

Figure 5. (a)The light distribution after the lens is directly attached to the chip. (b) The light propagation path of the microstructured packaging design. (c) SEM image of Lens.

Meanwhile, the morphology and refractive index of the lens have a great impact on the light extraction efficiency of Micro-LED chips. Optical simulations were conducted on different curvatures of the lens shown in Figure 6a. The results indicate that when the curvature increases from 0.025 to 0.03, the increase in light intensity is not obvious, but the viewing angle is significantly narrowed from ±40 °to ±25 °. This phenomenon is caused by the fact that the lens concentrates the light excessively in local areas which should be collected uniformly, leading to the insufficient light in other areas. As the curvature increases further to 0.035, more light undergoes total internal reflection at the lens interface, leading to a result that the light that should continue to propagate through the lens is trapped inside the lens and unable to emit normally. Moreover, based on the lens with a curvature of 0.03, optical simulations were carried out with the change of refractive indices of lens. As shown in Figure 6b, the higher the refractive index is, the greater the degree of light convergence will be, and the more obvious the improvement in light intensity will be. When the refractive index is 1.85, the light intensity is 53% higher than that of the Micro-LED chip without lens structure.

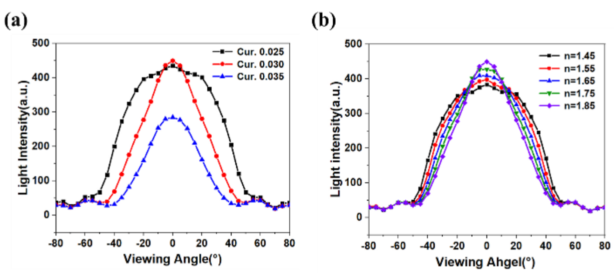

Figure 6. (a) Light shape of Micro-LED chips with different curvature of lens. (b) Light shape of Micro-LED chips with different refractive index of lens.

Additionally, in order to enhance the reliability of Micro-LED encapsulation and improve its surface hardness, wear resistance, and resistance to water and oxygen, a glass cover is adopted to encapsulate and protect the module. Besides, due to the issue that high reflectivity white resin material used in this packaging scheme will reduce the ambient ratio, we introduce a black photoresist layer to improve the ambient contrast ratio and the display quality. Moreover, patterned black matrix is formed by photolithography process based on this black photoresist material. The black layer on top of the LED area is removed to reduce the loss of emitted light and the brightness of the module will be improved. As tested by the CM700D color analyzer, when the proportion of black matrix area to the luminescent area reaches 80% or more, the surface reflectance can be reduced to less than 6%. Then a cover glass with a OCA layer is adopted to further reduce the surface reflectivity. As shown in Table 1, when the transmission is reduced to 55%, the surface reflectivity reaches 1.95%. And a high contrast ratio of over 20000:1 is realized with the introduction of patterned black matrix layer and OCA layer, resulting in a high-quality display performance for Micro-LED products.

Table 1. Surface reflectivity with different OCA layer transmittance.

Transmittance	Reflectivity
98%	4.83%
93%	4.10%
80%	3.57%
55%	1.95%

4. Conclusion

Micro-LED is a new generation of display technology due to its high resolution, high brightness and long lifetime. However, as the size of Micro-LED chips decreases, the side light intensity is significantly greater than the top light intensity, which not only results in the loss of light energy but also makes it more prone to color deviation after the mixing of different colors of light. In this paper, we designed a new microstructure encapsulation scheme consisted of transparent adhesive, white adhesive, lens array and patterned black matrix layer. By utilizing high-refractive-index transparent adhesive to enhance the light extraction efficiency of Micro-LED chips and leveraging the converging effect of high-reflectivity white adhesive and lens microstructures on the light from large viewing angles, the optical efficiency is improved and the light output angle of Micro-LED chips can be adjusted, thereby significantly improving the brightness of Micro-LED display products. In addition, the patterned design of the black matrix cover can reduce light loss and enhance the ambient contrast ratio of the display products. Therefore, high-quality image display for Micro-LED products is achieved based on such novel packaging scheme. This novel design is expected to achieve faster development and broader application in future Micro-LED displays.

5. Acknowledgements

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