Development of the World's Highest 5,644 PPI Full-Color MicroLED Micro-Display for Consumer AR Glasses

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Abstract
In this study, we present the world's highest 5,644 PPI single-chip full-color microLED micro-display. The 0.18-inch 720x720 display, with its ultra-compact design, is specifically suitable for augmented reality (AR) applications. Utilizing advanced microLED technology and optimized CMOS backplane design, it offers outstanding brightness and compact form factors ideal for consumer AR glasses.

Author Keywords
MicroLED; Micro-Display; Augmented Reality (AR); Quantum dot (QD); Color conversion.

1. Introduction

With advancements in Artificial Intelligence (AI) technology, Augmented Reality (AR) glasses are emerging as the most suitable interface for AI applications. AR glasses project symbols and images directly into the user's eyes, utilizing various sensors and cameras to manage these visual elements for AI assistant purposes. This allows users to access information seamlessly through AR glasses. At the core of AR glasses is the light engine, which comprises a micro-display module and an optical combiner responsible for directing images into the eye. The quality of the optical combiner largely determines the overall imaging performance of AR glasses. Currently, common optical combiner technologies include prisms, free-form optics, Birdbath optics, pin mirror and waveguides. The most important for consumer AI glasses is the lightweight and stylish.[1)] So, among these, waveguides stand out due to their advantages in lightweight design, thinness, larger eye-box, high transparency, compatibility with various shapes, and potential for mass production. However, waveguides also face a significant challenge: extremely low optical efficiency. In most cases, less than 1% of the light from the display actually reaches the user's eyes. To overcome this limitation, researchers are focusing on developing micro-displays with higher brightness, efficiency, resolution, and compact size. Among these, MicroLED micro-displays are considered the most promising due to their self-emissive nature and exceptional brightness, making them an ideal solution for the future of AR display technology. [2)] However, meeting the compact panel size requirements presents a challenge, as pixel density plays a crucial role and significantly increases the complexity of achieving full-color displays. One promising approach to addressing this issue is quantum dot (QD) color conversion (QDCC) technology. With this method, only monochrome blue MicroLED panels are needed, simplifying the manufacturing process by requiring just a single mass transfer step. [3)]

In this study, we present a full-color MicroLED micro-display utilizing QDCC, achieving a pixel density of 5,644 PPI. The display features a 0.18-inch panel with a 720 × 720 resolution. Each sub-pixel measures 3μm × 3.375μm, resulting in a full-color pixel pitch of approximately 4.5μm. The MicroLED chip size is around 2μm.

2. Experiments

The monochromatic blue microLED micro-display was fabricated using a conventional semiconductor manufacturing process. The device structure following the chip fabrication process is illustrated in Fig. 1(a). The 6-inch InGaN/GaN LED epitaxial wafers were grown on sapphire (Al_2O_3) substrates via metal-organic chemical vapor deposition (MOCVD), achieving a peak emission wavelength of 445 nm. After undergoing a standard semiconductor wafer cleaning procedure, an 80 nm-thick Indium Tin Oxide (ITO) film was deposited onto the epitaxial wafer using sputtering evaporation. This ITO layer served as both the transparent conductive layer (TCL) and the ohmic contact layer for the p-type GaN. Subsequently, the ITO film was thermally annealed at 575°C for 10 minutes in an O_2 ambient via rapid thermal annealing (RTA). The sub-pixel regions were defined through mesa etching, which was carried out using standard photolithography, followed by wet etching of the ITO and dry etching of the GaN epitaxial layer by inductively coupled plasma reactive ion etching (ICP-RIE). The chip dimensions were designed to be 2 μm × 2 μm, with an etch depth of 1.5 μm to fully expose the n-type GaN layer. A 300 nm-thick SiO_2 dielectric film was subsequently deposited by plasma-enhanced chemical vapor deposition (PECVD) to serve as a passivation layer. Contact openings for both the p-type and n-type regions were then formed using reactive ion etching (RIE). Finally, Cr/Al/Ti/Au multi-layer electrodes were deposited via electron-beam evaporation and patterned using standard photolithography and lift-off techniques to form the anodes and cathodes. The sapphire substrate was thinned from its initial thickness of 650 μm to 200 μm using a mechanical grinding process to facilitate the subsequent wafer cleaving step.

On the other hands, we custom-designed the Si-CMOS through a semiconductor foundry for 12-inch wafers. After the chip probing (CP) process, a metal micro-bump process was required, then we deposit the micro bump on the sub-pixels of CMOS backplane. A Cr/Au/In multi-layer was subsequently evaporated by thermal deposition, as shown in Fig. 1(b). To minimize the risk of short circuits, the thickness of the indium metal layer should be controlled to be less than 1μm. After finishing the microLED wafer and Si-CMOS wafer, further laser cutting and cleaving process was

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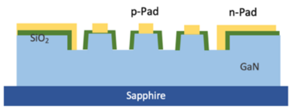
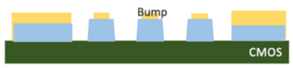
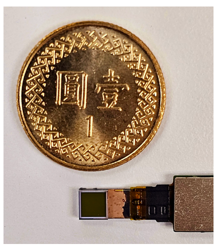
fabricated. Final testing and inspection are important to sort good dies for the precise alignment flip-chip die bonding. The microLED array was aligned and bonded to the CMOS backplane by a thermal-compression method. Highly bonding accuracy, within 0.5μm, is required to achieve high bonding yield. Following the monochrome blue panel fabricated, the QD technology was utilized for color conversion to realize full-color applications. After QD photolithography process, color filter material was used for filtering the blue light leakage. Then, glass was covered on the microLED micro-display for packaging. Finally, the fabricated panel was mounted on a flexible printed circuit by wire bonding and connected to a driver board, as shown in Fig. 1(c).



(a)



(b)



(c)

Figure 1(a) structure of microLED before bonding

Figure 1(b) structure of CMOS backplane before bonding.

Figure 1(c) 0.18-inch micro-display bonded with FPC

3. Results and discussion

Figure 2 illustrates the L-J characteristics of the 2μm microLED micro-display. The panel achieves a peak luminance of 523,300 nits with a sub-pixel driving current of 3.75 μA. The current density is about 90A/cm^2. For typical AI glasses use case, the display operated at a light-up resolution of 160 × 160, proximately 5% average pixel level (APL).

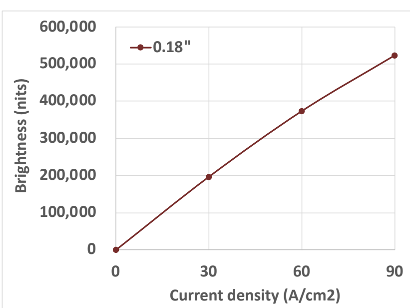
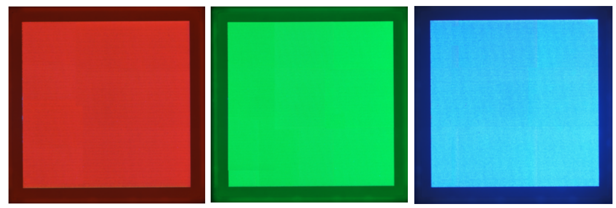


Figure 2 L-J characteristics of the 2μm microLED micro-display

Figure 3 presents the pixel yield analysis of a 720x720 resolution 0.18-inch microLED micro-display. The pixel yields for red, green, and blue sub-pixels are 99.50%, 99.47%, and 99.65%, respectively, with a total light-up yield as 99.54%. The main yield loss primarily comes from several factors:

1. Defects in the epitaxy process.
2. Contamination in the semiconductor process and defects in the photolithography process.
3. Peeling of electrode metal deposition, leading to electrode connection failure.

This is an underdeveloped R&D sample, where contamination in the semiconductor process can be mitigated through automated mass production, enhanced cleaning processes, and stricter photolithography yield control. Additionally, with proper surface treatment, adhesion can be improved, reducing the risk of metal pad peeling.



(a) (b) (c)

Figure 3(a) 99.50% light-up yield of Red sub-pixels
Figure 3(b) 99.47% light-up yield of Red sub-pixels
Figure 3(c) 99.65% light-up yield of Red sub-pixels

Figure 4 shows the spectral characteristics of the QDCC microLED micro-display. It is observed that color leakage is still present, which affects overall color purity. The color purity for red, green, and blue sub-pixels is measured at 89%, 86%, and 96%, respectively, indicating areas for further optimization in color filtering and spectral control.

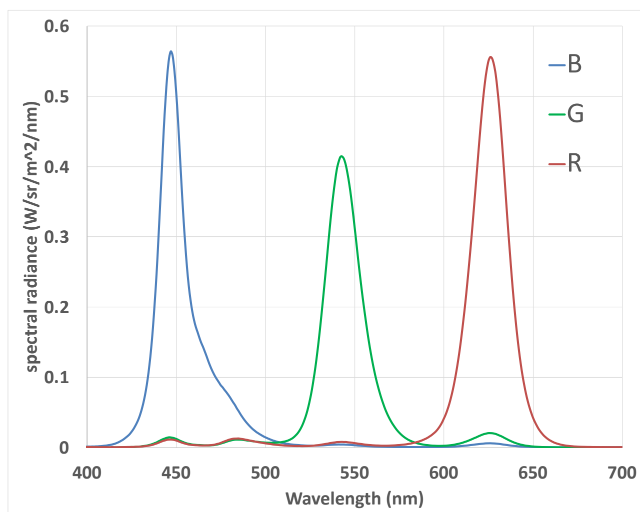


Figure 4 spectral characteristics of the QDCC microLED micro-display

Fig. 5 and Table 1 depicts the color gamut performance of the QDCC microLED micro-display. The display achieves a color gamut coverage of 91.30% DCI-P3 and 87.72% NTSC, shown its potential for vivid color reproduction. The coordinates are (Rx, Ry) = (0.654, 0.309), (Gx, Gy) = (0.282, 0.662), (Bx, By) = (0.155, 0.036), respectively.

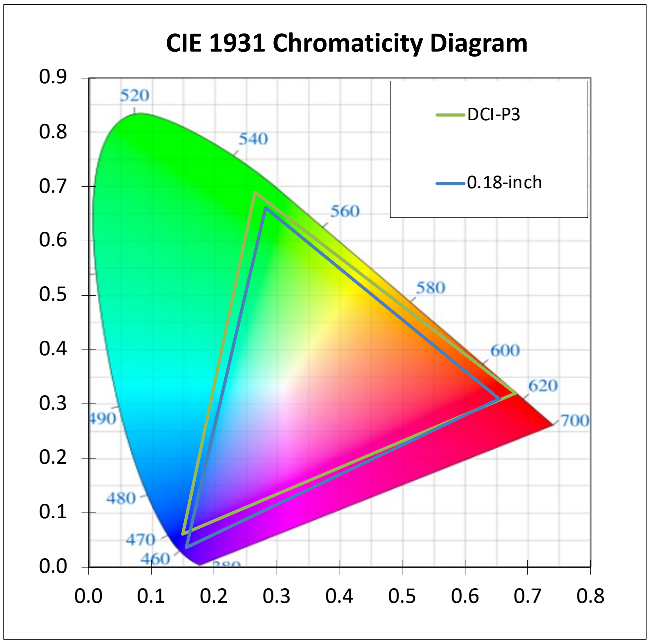


Figure 5 color gamut performance of the QDCC microLED micro-display

Rx	0.654
Ry	0.309
Gx	0.282
Gy	0.662
Bx	0.155
By	0.036
DCI-P3	**91.30%**
NTSC	**87.72%**

Table 1 Color coordinates and the color gamut coverage of the QDCC microLED micro-display

4. Conclusion

In this study, we demonstrate a full-color microLED micro-display employing quantum dot color conversion (QDCC), achieving an ultra-high pixel density of 5,644 pixels per inch (PPI) with a pixel pitch of 4.5 µm. The fabricated display features a compact 0.18-inch diagonal panel with a resolution of 720 × 720 pixels. Under a sub-pixel driving current of 3.75 µA, the panel exhibits a peak luminance of 523,300 nits. The sub-pixel yields for the red, green, and blue pixels were measured to be 99.50%, 99.47%, and 99.65%, respectively, resulting in an overall light-up yield of 99.54%. Furthermore, the color purity of the red, green, and blue sub-pixels, enhanced via a color filter coating process, was determined to be 89%, 86%, and 96%, respectively.

5. References

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