

Development of a Real 4K × 4K VR Display with Ultra-Wide Color Gamut and Panel Eye-Tracking Technology

Lutong Wang*, Wei Yan*, Jian Zhang, Peng Liang, Xinyu Wang, Jian Sun, Yanqing Chen, Jianyun Xie

*BOE Technology Group Co., Ltd., Beijing, China

Abstract

This paper describes a head-mounted display technology with ultra-high resolution of 2117 PPI and true 4K image quality, which uses quantum dot films to significantly improve color gamut performance. At the same time, the application of mini LED backlight technology enhances the brightness and contrast of the screen, further elevating image quality, and the VR headset also incorporates Foveated Rendering Display (FRD), markedly reducing overall power consumption and providing users with an optimised VR experience. The paper will discuss in detail the principles, advantages, and high PPI pixel design of these technologies.

Author Keywords

Real 4K; VR LCD; QD film; Mini-LED; FRD.

1. Introduction

In recent years, with the advancement of technology, virtual reality (VR) has gradually emerged as one of the most prominent topics, demonstrating significant potential across fields such as entertainment, education, and healthcare, enhancing the convenience and efficiency of human work and life. Head-mounted displays (HMDs) are critical components of VR technology, effectively bridging the virtual and real worlds and enabling users to interact with virtual environments. A key factor in providing users with an immersive experience through HMDs is the ultra-high-resolution display, which allows users to fully experience the virtual world's realism [1].

Color purity is a crucial factor in head-mounted displays (HMDs). To achieve optimal color performance, we incorporated a quantum dot film in the backlight structure. Compared to traditional LED RGB spectra, quantum dot films can emit narrower RGB peaks, enhancing color purity. Additionally, the narrower full width at half maximum (FWHM) minimizes spectral overlap between different colors, allowing for more precise representation of the RGB primaries and thereby improving color accuracy. As a result, the quantum dot film enables a broader color gamut, enhancing the display's color performance.

This prototype employs mini-LED backlight technology, supporting 500 local dimming zones. Mini-LED backlighting allows independent brightness adjustment for each zone, creating a distinct contrast between bright and dark areas on the screen, which significantly enhances display contrast. Due to the higher number of dimming zones compared to traditional LED backlighting, mini-LED technology enables finer control over brightness transitions, reducing halo effects caused by light leakage from bright to dark areas. Furthermore, the combination of mini-LED and quantum dot technology further enhances the display's color gamut, maintaining color accuracy even at increased brightness levels. Traditional LED backlighting often suffers from uneven brightness and light leakage in darker scenes, issues that the high-density and uniform distribution of mini-LEDs effectively mitigates.

Power consumption remains a major challenge in HMDs, as extended standby time is essential for user convenience, imposing stringent power requirements on displays. To reduce power consumption, the prototype incorporates eye-tracking functionality. By implementing line-by-line scanning in the area where the user's gaze is focused while scanning two lines simultaneously in non-gazed areas, the display achieves reduced power usage without compromising visual quality. In addition, for 4K high-resolution VR LCDs, the total scan time is longer, resulting in insufficient LCD response time, so for VR products with high PPI, the FRD function can be used to split the display into different resolutions, thereby reducing the overall scan time and reserving more time for the LCD response. This function is accomplished by adjusting the cascaded arrangement of the display's Gate on Array (GOA). Further details on the methodology, timing sequences, and experimental results will be provided in the subsequent sections.

In high-PPI displays, achieving stable pixel voltage is challenging due to reduced C_{st} capacitance from limited plate overlap. Adequate C_{st} is essential to prevent charge leakage, ensuring consistent voltage and image quality. Optimizing C_{st} design is, therefore, critical for maintaining display stability in high-resolution applications. Also, the design of the CITO opening region significantly affects liquid crystal optical efficiency. Proper electric field formation within this region is essential for accurate liquid crystal alignment, enhancing light transmission and overall display brightness, which is crucial for optimal image quality at high resolutions.

2. Application and simulations

(a) Quantum Dot Film

Quantum dot (QD) display technology primarily consists of an LCD module, a quantum dot film, and LED backlighting. Quantum dots are semiconductor nanostructures that confine excitons in three-dimensional space, and the size of photoluminescent quantum dots determines their fluorescence properties. When excited by short-wavelength light, quantum dots emit different colors. Combined with the blue light from the backlight, the quantum dot film produces red and green light, which, together with the transmitted blue light, creates white light [2]. To achieve a broader color gamut, the full width at half maximum (FWHM) of the emission peaks for the primary colors (RGB) needs to be sufficiently narrow. Due to the high density of chemical bonds within the lattice structure of quantum dots, they can achieve a smaller FWHM for their emission peaks [3], significantly enhancing the color gamut of LCD displays.

The backlight module in this prototype employs a quantum dot film and has undergone a series of optical simulations. As shown in Figure 1, the mini LED backlight with a QD film exhibits narrower FWHM at RGB wavelengths. Compared to conventional nitride-based backlighting, the QD film backlight more effectively utilizes energy for color display, resulting in higher transmittance. As illustrated in Figure 2, backlighting with

a QD film achieves a broader color gamut than standard nitride backlighting, the color gamut coverage can reach 98% under the DCI-P3 color gamut standard, 103% under the NTSC color gamut standard, and the transmittance can reach 1.49%.

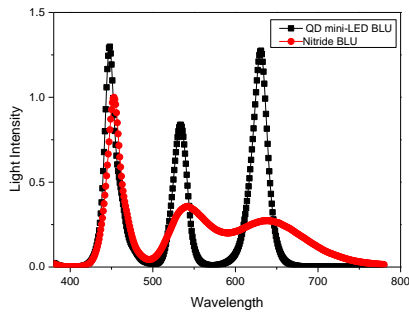


Figure 1. Comparison of the spectra of QD film backlight with common nitride backlight.

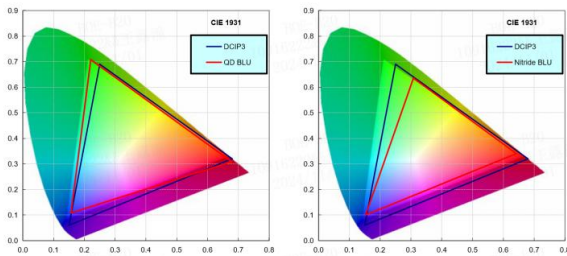


Figure 2. Color gamut comparison between QD film backlight and ordinary nitride backlight.

(b) Mini-LED Backlight

Common backlight structures include edge-lit and direct-lit configurations. As a direct-lit type, the mini-LED backlight, in combination with a quantum dot film, enables superior color display performance. In the backlight module, the mini-LED panel is positioned at the base of the module structure, with a diffuser, quantum dot film, and prism film placed above it. A mini-LED backlight in LCD typically uses blue light, which is converted to uniform white light after passing through the diffuser and color-converting quantum dot film.

The smaller emission area of mini-LED (75 - 300 μm) and their denser arrangement (300 μm < pitch < 1 mm) enhance the uniformity of the backlight module’s illumination. With support for 504 dimming zones, mini-LED back-lighting enables precise multi-zone dynamic dimming, achieving higher contrast ratios and addressing issues like low contrast caused by the inability of LCD to produce true black images [4].

(c) Eye-Tracking Functionality

This prototype employs an 18T3C GOA driver circuit, as shown in Figure 3. The circuit uses a single-stage dual-drive design to optimize layout space and support a 2117 PPI pixel pitch. Due to the higher resolution requirements of VR products, which impose a greater load per row of pixels, this GOA separates the transistors used for cascading from those connected to the pixels. Specifically, transistors T3, T4, T12, and T13 drive the pixels, while T3’, T4’, T12’, and T13’ are used for cascading the next GOA stage. Since the cascading transistors are not directly connected to large loads, they can be smaller in size. This design not only conserves space but also avoids inaccuracies in the

output signal of the subsequent GOA stage caused by prolonged rise/fall times due to excessive loading.

Figure 4 illustrates the cascading approach that enables eye-tracking functionality. In this design, the OUTPUT_N+7 signal resets the first-stage GOA, with OUTPUT_N+7 corresponding to CK8, which does not overlap with CK2. This setup achieves the PU delay reset function depicted in Figure 6, ensuring proper OUTPUT_N+1 signal output. Using a 12CLK staggered cascade configuration for PU delay reset prevents premature coupling of the next-stage GOA by the PU signal, ensuring correct signal output.

Figure 5 displays the CLK signal configuration for the eye-tracking feature, enabling single- or dual-line output switching. As shown in Figure 6, the display performs normal single-line scanning in the region where the user’s gaze is focused, while non-gazed areas undergo dual-line scanning. This approach reduces overall display scanning time and conserves power[5].

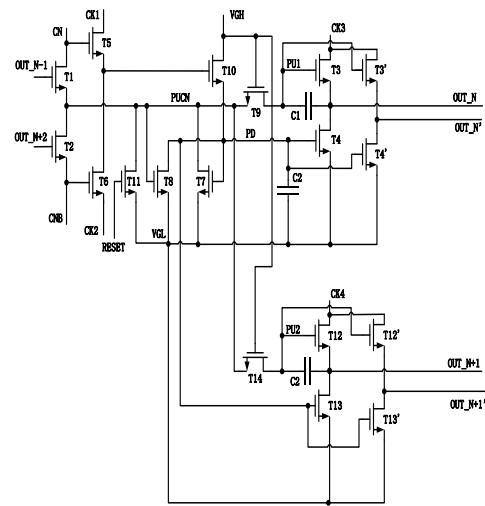


Figure 3. 18T3C GOA circuit structure diagram

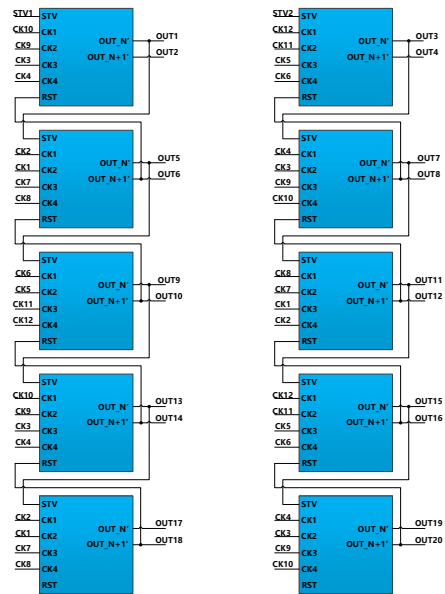


Figure 4. GOA cascade diagram

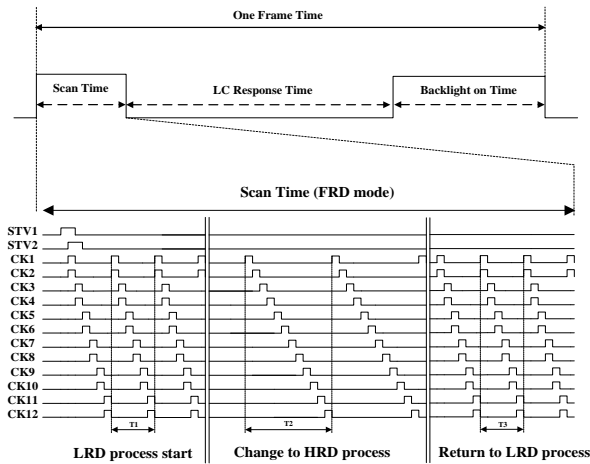


Figure 5. The CK timing under FRD mode of Fig.6 case B

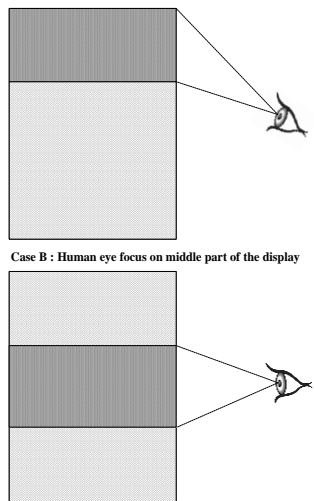


Figure 6. The schematic diagram of human eye tracking display under FRD mode

(d) Pixel Design

This 2117 PPI demo utilizes a COA structure with a C-Metal disconnection design in the AA area. As shown in Figure 7, C-Metal (CMT) and 2ITO are stacked in the AA area and share the same signal. The 2ITO layer is designed with an angled opening that forms an electric field around the opening area. If C-Metal is configured as a continuous strip, it overlaps with 2ITO at the upper and lower corners, as illustrated in Figure 8(a). This overlap disrupts the electric field, preventing proper liquid crystal alignment and resulting in dark spots that negatively impact optical efficiency, as shown in Figure 9(a). Therefore, this demo adopts a disconnection design for C-Metal, as shown in Figure 8(b), enabling a well-formed electric field around the 2ITO opening, as demonstrated in Figure 9(b), significantly improving optical efficiency[6]. Simulation results show that the liquid crystal optical efficiency can be increased by 2.2% to 53%, and the metal disconnect design can increase the transmittance from 1.49% to 1.84%.

C_{st} , the storage capacitor for maintaining the liquid crystal pixel voltage, is crucial in TFT-LCDs, with 1ITO and 2ITO serving as the upper and lower plates of the capacitor. For high-PPI displays, the pixel pitch for real RGB is only $4 \times 12 \mu m$, resulting in a

minimal overlapping area between 1ITO and 2ITO. Consequently, the resulting C_{st} capacitance is only 8 fF, insufficient to prevent charge leakage and maintain display stability, falling well short of normal charge-holding requirements. Therefore, as shown in Figure 7, this pixel design introduces an additional SITO layer connected to CITO at the periphery and overlapping PITO across a large area. Simulation results show that this increases C_{st} from 8 fF to 24 fF, ensuring stable screen operation. Furthermore, the design incorporates a PLN planarization layer, adding an FITO layer on top of PITO and directly connecting with PITO, further increasing the overlapping area with CITO. Figure 10 shows the comparison of the effects of SITO and FITO on the luminous efficiency and adjacent electric field of the liquid crystal. It can be seen that the addition of SITO and FITO layers has no adverse effects on the luminous efficiency and electric field of the liquid crystal.

In addition, in order to solve the problem of light leakage in the ILD hole, LS block light leakage as shown in Figure 7 was added. Figure 11 shows the comparison of light efficiency after adding the LS layer, and it can be seen that light leakage in Figure 11(b) is significantly reduced.

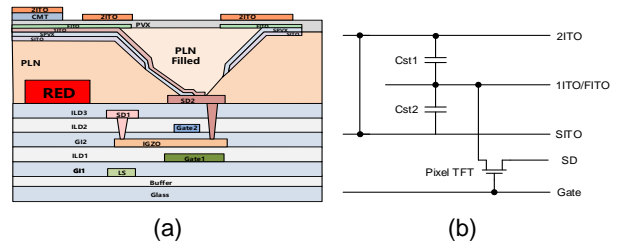


Figure 7. (a) Pixel structure cross-section (b) Pixel circuit diagram

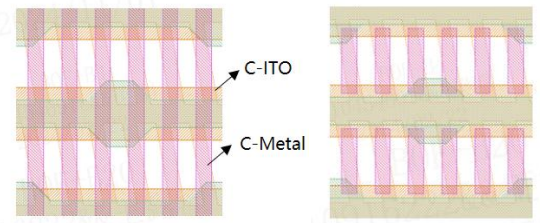


Figure 8. Different morphology design of C-Metal.

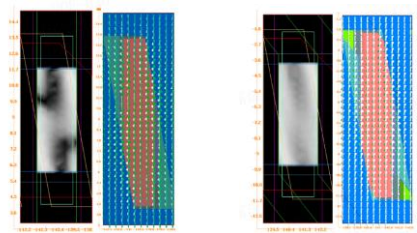


Figure 9. Light effect map.

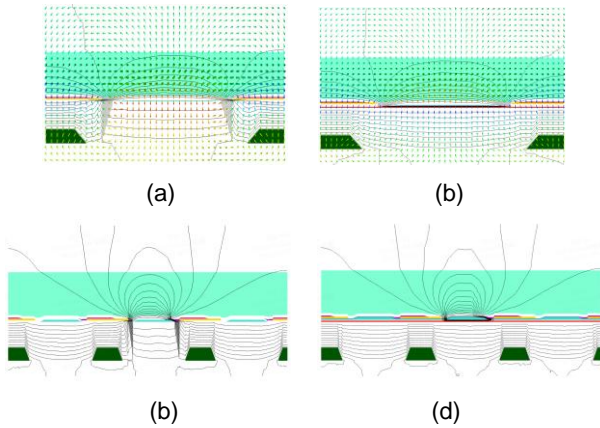


Figure 10. (a) LC light efficiency simulation of normal structure (b) LC light efficiency simulation of SITO structure (c) Simulation of adjacent electric fields by normal structures (d) Simulation of adjacent electric fields by SITO structures

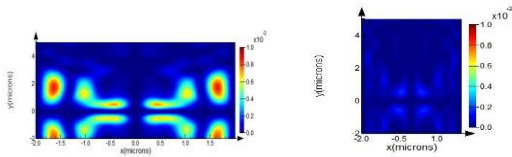


Figure 11. (a) Light effect simulation without LS block (b) Light effect simulation with LS block

3. Panel Specifications and Performances

The following table details the specifications of the 2117 PPI real 4K VR LCD prototype. This demo achieves a peak brightness of 500 nits, providing vivid and immersive visuals suitable for VR environments. Despite the high resolution, the display maintains a manageable total power consumption of approximately 1.4W, making it efficient for extended use. Additionally, the color gamut reaches 95% of the DCI-P3 standard, allowing for a broad and accurate color reproduction essential for realistic imagery. With a transmittance of 2%, the display efficiently outputs light, contributing to a clear and vibrant viewing experience in high-performance VR applications.

Table 1. 2.487 VR LCD display specification

Real 4K*4K 2117PPI VR LCD DEMO	
Size	2.487”
Pixel pitch	4*12μm
Resolution	3600*REAL*3840
Brightness	500 nits
Power consumption	1.4 W
Color Gamut (DCI-P3)	95%
Transmittance	2%
Number of partitions of Mini-LED backlight	504

4. Conclusion

This paper presents a prototype with a 2117 PPI display that incorporates a quantum dot film mini-LED backlight and an 18T3C GOA circuit. The prototype has been successfully developed, achieving both eye-tracking functionality and an ultra-wide color gamut, effectively addressing the challenges of color accuracy and power efficiency in high-PPI LCD displays. The use of quantum dot film enables an expanded color gamut and improved color accuracy without sacrificing transmittance, enhancing the display’s overall brightness and color fidelity. The integrated eye-tracking technology further optimizes power consumption and scanning time by adjusting the active display area according to the viewer’s gaze, significantly lowering energy use. Additionally, improvements in pixel design have increased the C_{st} capacitance and enhanced the liquid crystal optical efficiency, contributing to a more stable and vibrant display performance. These advancements combine to offer users a more convenient and immersive experience, meeting the stringent requirements of next-generation high-resolution displays for VR applications.

5. References

- Hachiya A, Aman M, Chiu Y H, et al. 46-1: 1218 ppi Quest 3 Display by Hybrid Backplane with Highly Reliable IGZO TFTs [J]. SID Symposium Digest of Technical Papers, 2024, 55(1):615-618.
- Ji H, Xu H, Jiang F, et al. 37.5: Hybrid Backlight System based on Blue, Red LEDs and Perovskite Quantum Dots for Liquid Crystal Display Application [J]. SID Symposium Digest of Technical Papers, 2019, 50(S1):411-413.
- Li Jijun, Nie Xiaoming, Zhen Wei, et al. Comparison and new progress of display technology [J]. Chinese Journal of Liquid Crystals and Displays, 2018, 33(01):74-84. (in Chinese)
- Zhang H, Fang Y, Xie J, et al.5-3: Invited Paper: Development of fast LCD with Mini-LED BLU for VR application [J]. SID Symposium Digest of Technical Papers, 2023, 54(1):40-43.
- Sun J, Wang Z, Yan W, et al. 46-2: Reliable Gate Driver for Eye-Tracking in High PPI VR Display Using LTPS TFTs [J]. SID Symposium Digest of Technical Papers, 2024, 55(1). DOI:10.1002/sdtp.17600.
- Xie J, Chen Y, Fang Y, et al. 90-3: Invited Paper: Ultra High PPI VR Display Devices [J]. SID Symposium Digest of Technical Papers, 2024, 55(1):1266-1270.