A 200-ppi Full Color Active Matrix Micro-LED Display with Low-Temperature-Poly-Silicon TFT Backplane

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ABSTRACT

A 1.8-inch 200-ppi full color active matrix micro light emitting diode (LED) display prototype has been developed with a low-temperature-poly-silicon (LTPS) TFT backplane. The frame rate of 240Hz and the luminance of 2000nits, both of which are promising attributes for a high motion image quality, and high dynamic range (HDR) applications, being superior to existing display technologies, were achieved by our LTPS TFT technology.

1 INTRODUCTION

Recently much attention for micro-LED displays as a next generation display, featuring in excellent visual performances and a low power consumption, has been paid for several applications: wearable, signage, virtual reality (VR), augmented reality (AR), automotive uses, and so on. Micro-LED displays have a potential of being superior to current high-end displays like existing organic light emitting diode (OLED) displays in luminance, color gamut, and motion picture quality [1].

Prior to micro-LED displays, conventional LED video walls, equipped with the PCB backplane, have been used at public spaces. The PCB backplane, on which passive matrix (PM) driving circuits are printed and LED chip packages are mounted, is relatively cost-competitive and allows to scale-up easily by tilling. However, the difficulty of achieving higher resolution due to the requirement of more driver ICs, resulting in cost increase, have been the drawback.

On the other hand, active matrix (AM) driving has a capability to drive a display with a higher resolution and a lower power consumption, although it is composed of more complicated circuits. In most of recent papers on micro-LED displays, the AM driving has been applied; for example, the complementary metal-oxide semiconductor (CMOS) backplane on c-Si has been studied mainly for VR or AR applications because high pixels per inch (PPI) can be easily obtained [2]. However, in terms of the limit of the size and the cost of the silicon wafer, the scale-up has been difficult.

Figure 1 is a graph showing the relationship between PPIs and display sizes for several applications. As shown in Fig.1, there is a gap of the ranges between the PCB and the CMOS on c-Si backplane can provide. In order to fulfill the gap, another approach is needed, and the AM driving with LTPS backplane has been considered to be the most suitable because of the high mobility and stability, allowing to supply a high current, and the scalability. So far there have been several papers based on LTPS backplane [3-4], but they are under 170ppi, which is not still adequate enough for several applications.

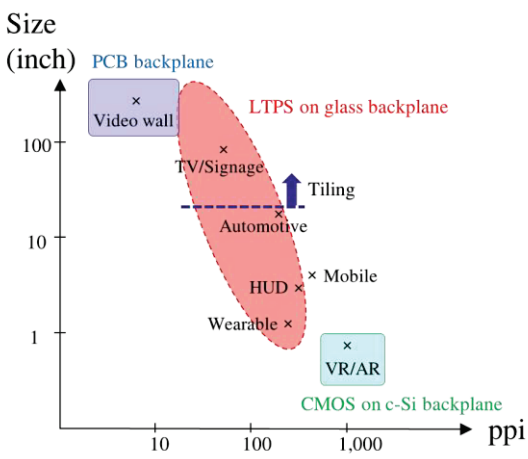


Fig.1 Relationship between PPIs and display sizes, and the range of the coverage of each backplane for LED displays

Extremely high luminance, as one of the features of micro-LED displays, and the excellent motion picture quality, are crucial for high-end HDR displays, being strongly related with each other. For example, the increase of black frame insertion (BFI) results in a better motion picture quality, but on the contrary, the decrease of the luminance is inevitable. According to the previous works on micro-LED displays with the LTPS backplane, most prototypes are capable to output 1000nits or above as the peak luminance, HDR10 requirement [5]. Hence, micro-LED displays are expected to exhibit the excellent motion picture quality, with a high luminance retained, but so far there have not been fully discussed.

In this work, we demonstrate the prototype of 1.8-inch

200-ppi full color active matrix micro-LED display with the LTPS TFT backplane to extend the range that LTPS backplane can provide [6], and discuss the matter on the relation between the luminance and the motion picture quality.

2 DISPLAY DESIGN AND SPECIFICATION

Figure 2 shows the block diagram of our prototype micro-LED display. The prototype has a resolution of 256 x 256 pixels, V and H driver circuits, integrated by the LTPS backplane technology, and a driver IC on a glass substrate. The video signal inputs from the outside via FPC PAD are converted to control signals of each micro-LED chips through the driver IC. The circuits on the glass enable the display to drive at the frame rate of 240Hz. A pixel of the prototype includes 3 anode pads for a red, green, and blue LED chip, and a cathode pad, respectively.

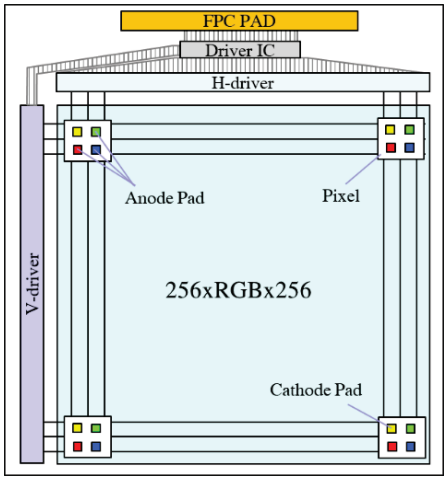


Fig 2. Display block diagram

The micro-LED chips that we have adopted are a vertical configuration type, which has a potential of being superior to a flip-chip type in terms of resolution. Each color LED chip was mounted on the corresponding anode pad, and then coated with insulator, on which a contact hole was formed. The cathode, the top side of the LED chip, was connected to the cathode pad through the contact hole.

Table 1 shows the specification of our prototype. Our prototype could output a high luminance not only of the peak white, 3000nits, but also of the all-white, 2000nits. The color gamut of our prototype, plotted in Fig.3, was 81% of Rec.2020 area ratio while 113% by DIC-P3 area ratio. The response time was measured by displaying a row line on the screen, consisting of a single pixel in column direction, and taking the value from 90% to 10% gray-scale and the opposite. Since the response time of the LED chip itself is significantly fast, the measured response time is considered to be attributed mainly to the driving circuit operation.

Table 1 Specification of 1.8" prototype

Items	Specifications	Remarks
Backplane	LTPS	-
Screen size	1.8-inch	-
Resolution	256 x 256	-
Pixel size	127μm x 127μm	-
PPI	200	-
Frame rate	240Hz	-
Luminance	All white: 2000nits Peak white: 3000nits	White: D65
Contrast ratio	> 1,000,000:1	-
Color gamut	81% (Rec.2020) 113% (DIC-P3)	Area ratio
Viewing angle	> 178 deg.	-
Response	7μsec or less	$T_r + T_f$

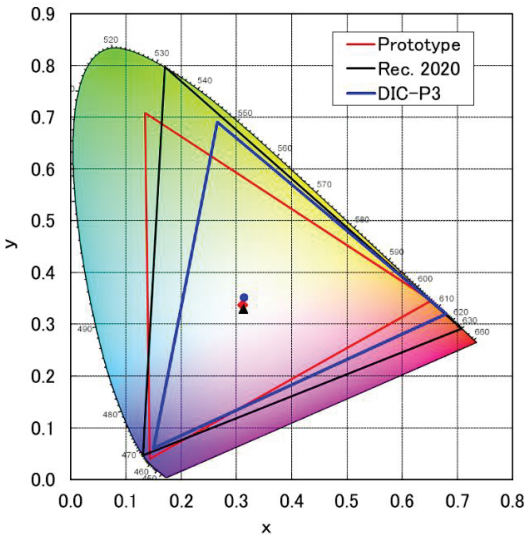


Fig 3. CIE1931 chromaticity diagram

3 IMAGE QUALITY

Figure 4 shows pictures of our prototype, which were taken from different viewing angles. As shown in Fig 4, luminance and color change were not seen, supporting that our prototype has a wide viewing angle.

Figure 5 shows an image displayed on the 1.8-inch prototype, on which the measured luminance and the representative gray-scale value were inserted at a certain point. The peak luminance of D65 white, shown in Table 1, was 3000nits, but the luminance measured on the image, shown in Fig 5, was 4600nits. The grayscale value of the point with 4600nits was RGB (135, 224, 240), while the D65 white point of the prototype was set at RGB (255, 255, 255). The reason why the measured

luminance was higher than that shown in Table1 is considered to be attributed to the decrease of the current through the red LED chips, resulting in the increase of the current through the relatively efficient blue and the green LED chips.

Although not at D65 white, our prototype could output 4000nits or above that is required for Dolby Vision [7], and has been so far difficult for other existing displays. It supports the idea that micro-LED displays are well suited to the HDR displays especially in luminance.

Fig 4. Pictures of 1.8-inch prototype at different viewing angles

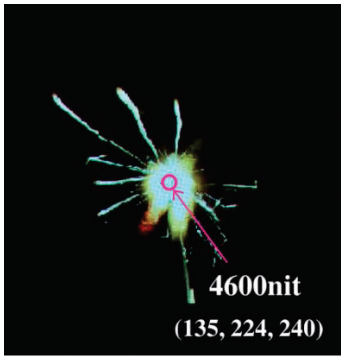


Fig 5. Picture of an image displayed on 1.8-inch prototype

4 MOTION PICTURE QUALITY VS. LUMINANCE

Motion picture response time (MPRT) has been proposed to evaluate image blurs [8], and considered to be adequate for assessing the motion picture quality. Originally MPRT measurement has been performed by using the pursuit camera, however, recently, the analytic equation has been proposed as follows [9];

$$MPRT \approx \sqrt{\tau^2 + (0.8T_f)^2}\,. \qquad (1)$$

, where τ is the response time and T_f is the display frame rate, the inverse of frame rate ($f=1000/T_f$). Based on Eq. (1), the following equation can be derived from the assumption that the response time is fast enough (i.e. $\tau \approx 0$), as shown in Table 1, and the MPRT decreases according to the BFI ratio [9];

$$MPRT \approx 0.8 \times BFI \times T_f\ . \qquad (2)$$

By using Eq. (2), the relationship between the BFI ratio vs. the MPRT was plotted in Fig 6. In the graph, the dotted line, indicating the cathode ray tube (CRT) like MPRT ($\approx$ 1.5 ms) [9], was also inserted; here, the impulse-driving CRT was chosen as a reference of the display with a supreme motion picture quality. According to Fig 6, when the display frame rate is 240Hz, at which our prototype can operate, 55% BFI ratio is required to achieve the CRT-like MPRT. In order to comprehend the capability of our prototype, we assessed a current commercially available OLED TV set as a reference among latest high-end displays. In this case, the frame rate is 120Hz and the BFI ratio is 50% [10]; thus, according to Fig 6, the MPRT becomes approximately 3.3ms, which is not sufficient to reach the level of the CRT. For obtaining the equivalent motion picture quality, 78% BFI ratio is required, but it has not been implemented because the increase of the BFI ratio results in a significant decrease of the luminance, as illustrated in Fig 7.

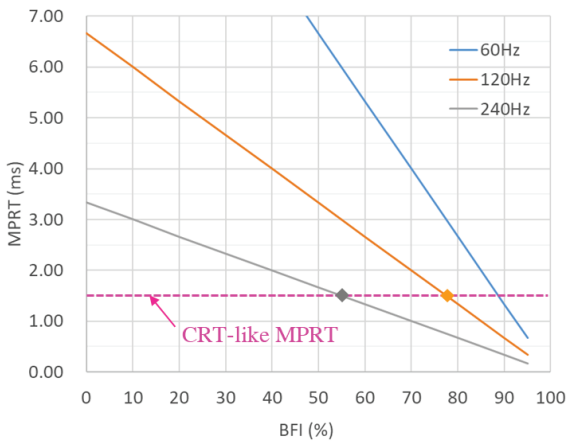
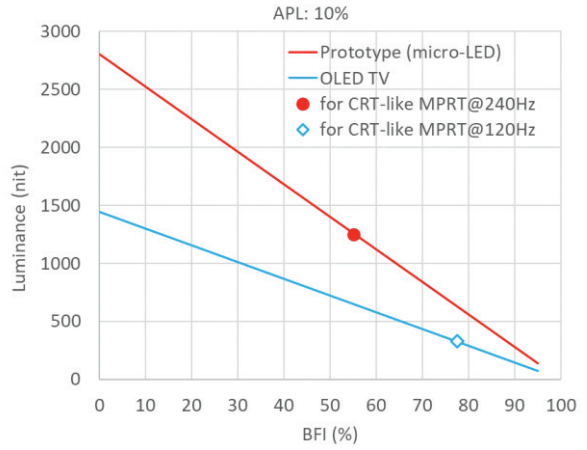


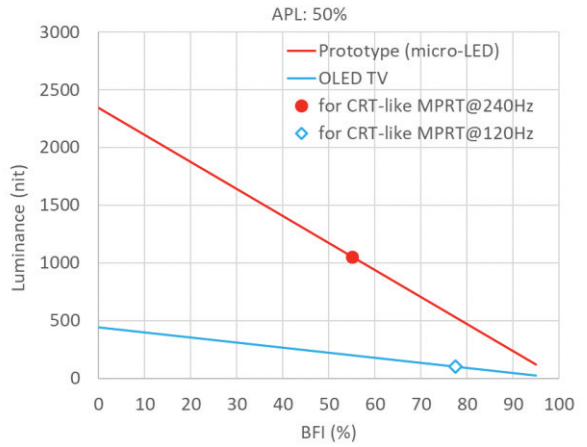
Fig 6. Relation between BFI vs. MPRT when the response time is fast enough

Figures 7 show the relations between the BFI ratio vs. the luminance of the OLED TV and our prototype, at the condition of (a)10% and (b) 50% average picture level (APL): APL is defined as a percentage of the range between blanking and reference white level. The luminance of the OLED TV was taken from the commercially available TV set [11], and the value of our prototype was taken from the measured one in Table 1. While the open dots, inserted on the line of the OLED TV, indicate the BFI ratio required for the CRT-like MPRT at 120Hz, the solid dots on the line of our prototype indicate those at 240Hz. As shown in Fig 7(a) and (b), the luminance decreases with the increase of the BFI ratio. As mentioned above, the OLED TV with 120Hz frame rate needs 78% BFI ratio for the CRT-like MPRT; thus, available luminance decreases to 330nits when the APL

is 10%. On the other hand, our prototype is capable to output 1250nits luminance, which exceeds the HDR10 requirement. When the APL is 50%, as shown in Fig 7(b), the luminance of our prototype becomes 1050nits, which still meets the HDR10 requirement, while that of the OLED TV decreases to 100 nits. This result indicates that the high luminance of all-white of our prototype is effective for retaining the luminance even when the APL is high.



(a)



(b)

Fig 7. Relation between BFI vs. Luminance at the condition of (a) 10% and (b) 50% APL

5 CONCLUSIONS

1.8-inch 200ppi full color micro-LED display prototype with the LTPS backplane has been demonstrated in this work. Our prototype has extended the range of PPIs to which the previous works using LTPS backplane have not achieved. Furthermore, our prototype has presented excellent features as a next generation HDR display such as 3000nits as the peak white (D65), 2000nits as the all-white (D65), and 81% Rec.2020 area ratio. It was also indicated that the higher luminance is effective for achieving the CRT-like motion picture quality because of the capability of inserting higher percentage of the black frame, which has been difficult by conventional display technologies such as OLED displays. Finally, we conclude that our 1.8-inch prototype has made sure that micro-LED displays are well fitted to the next generation HDR display.

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