Mini-LED, OLED or Micro-LED: Who Wins?

En-Lin Hsiang,[1] Yi-Fen Lan,[2] and Shin-Tson Wu[1]

Email: swu@creol.ucf.edu

[1]College of Optics and Photonics, University of Central Florida, Orlando FL 32816, USA

[2]AU Optronics Corp. Hsinchu Science Park, Hsinchu 300, Taiwan

Keywords: High dynamic range, mini-LED backlit LCD, OLED, micro-LED

ABSTRACT

Recently "LCD, OLED or μLED: who wins?" is a heated debatable question. In this review, we give a comprehensive overview of these three display technologies. The pros and cons of each technology are analyzed, and their future perspectives are discussed.

1. INTRODUCTION

Display technology is an important human-machine interface. Its applications include smart watches, smartphones, pads, computers, TVs, and vehicles, just to name a few. With continuous innovations in new materials and device structures, and heavy investment in manufacturing technology, thin film transistor (TFT)-based LCDs have displaced cathode ray tubes as a dominant flat panel display technology since 2000s. However, LCD is a non-emissive display, it requires a backlight. The depolarization effects from TFT, LC layer, and color filters limit the LCD's contrast ratio (CR) to ~5000:1. Recently, mini-LED backlit LCD (called mLCD), which provides adequate local dimming zones to suppress the halo effect, has been demonstrated to have comparable CR with OLED [1]. In addition, because the panel's brightness can be modulated from the low-resolution mini-LED backlight array and high-resolution LCD, an mLCD can achieve over 12-bit gray levels relatively easily. Thus, high dynamic range (HDR) mLCDs have sparkled another round of widespread applications.

As an emissive display, OLED offers several advantages, such as ultra-thin profile, unprecedented CR, fast material response time, and vivid colors. With continuous development in new materials and device structures, OLED's performance has been improved significantly and it has become a strong contender to LCD in smartphones and TVs. Because of its ultra-thin profile, bendable, rollable, and foldable OLED displays are emerging [2]. However, the burn-in and lifetime issues, and high cost of OLED displays remain to be overcome.

Recently, micro-LED (μLED) with high peak brightness, true black state, and long lifetime holds potential to become a disruptive display technology, if its cost can be more affordable [3]. One big advantage of μLED display is its ability to provide high luminance with ultra-small chips. As a result, the μLED's aperture ratio can be made as small as 1%. That means, 99% of the pixel area can be covered by either black matrix (for sunlight readable displays) or by transparent material (for transparent displays). Presently, the application of μLED display is still limited due to its high cost resulting from complicated manufacturing process, including mass transfer and pixel repair. In addition, the emission wavelength shift of μLEDs under different driving currents increases the difficulty of driving circuit design [4]. The reduced efficiency as the chip size decreases also compromises the advantages of μLED displays.

Overall, each technology has its own pros and cons. To fairly compare different displays is by no means easy. Here, we use following nine performance metrics for comparisons: (1) a high ambient contrast ratio (ACR), including high dynamic range, (2) lifetime including burn-in issue, (3) a wide color gamut, (4) resolution density, especially for augmented reality and virtual reality applications, (5) a wide viewing angle and an unnoticeable angular color shift, (6) a fast motion picture response time (MPRT) to suppress motion image blur, (7) low power consumption, which is particularly important for battery powered mobile displays, (8) a thin profile, freeform, and flexibility, and (9) low cost.

2. DEVICE STRUCTURES

Active matrix LCD is a non-emissive display; therefore, it requires a backlight unit. Two types of backlight units have been developed: (1) edge-lit backlight and (2) direct-lit backlight. The former offers a thin profile, which is particularly attractive for portable displays such as smartphones and notebook computers. However, this configuration is relatively difficult to adopt local dimming technology so that its contrast ratio is limited. Recently, with the rapid development of mini-LED technology, direct-lit backlights accompanying local dimming functions can also be made reasonably thin. As a result, both high dynamic range and thin profile can be achieved simultaneously. Meanwhile, four popular LC operation modes, depending on the molecular alignments and electrode configurations, have been developed: (1) twisted nematic mode, (2) vertical alignment (VA) mode, (3) in-plane switching (IPS) mode, and (4) fringe-field switching (FFS) mode. Their pros and cons have been analyzed in [5].

For an emissive display, no external light source is required so that its device structure is simpler. In an OLED display [6], the emission layer for emitting light is composed of a dopant and a host material with high quantum efficiency and high carrier mobility. Other layers such as hole and electron transport layers, and hole and electron injection layers are also used to improve current injection efficiency. However, an OLED display needs a circular polarizer to reduce the ambient light reflection from the bottom electrodes. The negative side is that it reduces the output OLED brightness by ~50%. In μLED displays, red LEDs are usually produced by growing AlGaInP epitaxial layers on GaAs substrates, and green and blue LEDs are produced by depositing InGaN epitaxial layers on sapphire substrates. Through mass transfer technology, millions of μLED chips are transferred from the corresponding semiconductor wafers to the display substrate [7]. For a μLED display, whether a circular polarizer is needed remains controversial because it depends on the aperture ratio and the required ambient contrast ratio.

3. RESULTS

In the following sections, we briefly discuss the above-mentioned nine performance metrics for LCD, mini-LED backlit LCD (mLCD), OLED, and μLED displays.

3.1 Ambient Contrast Ratio (ACR)

High dynamic range (HDR) refers to a display with peak brightness >1000 nits, black state <0.005 nits, and over 10-bit gray levels. However, a display is rarely used at totally dark ambient, so here we focus on high ambient contrast ratio (ACR). The contrast ratio of an emissive display such as OLED and μLED can exceed 10^6:1, but in practical applications the effective contrast ratio is substantially affected by the ambient light and surface reflectivity. The ACR is defined by [8]:

$$ACR = \frac{L_{on} + L_{ambient} \times R}{L_{on} + L_{ambient} \times R} \qquad (1)$$

where L_{on} ($L_{off} \approx 0$) represents the on (off)-state luminance of the display, $L_{ambient}$ is the ambient luminance, and R is the ambient light reflectance.

Based on Eq. (1), a display with high peak brightness and low reflectance would exhibit a larger ACR under the same ambient condition. Here, we use a large size TV as an example. Under a typical 50% APL (average picture level), the peak brightness of LCD-TV, OLED-TV and μLED TV is 1015 nits (Vizio P series, 2019)), 328 nits (LG C8 OLED, 2018)), and 1600 nits (Samsung The Wall, pitch=0.8mm), respectively. The peak brightness of the display depends on the APL of the displayed image. For example, when APL= 2%, the peak brightness of LCD-TV and OLED-TV increases to 1800 nits and 979 nits, respectively. Under a checker-board pattern, the LCD's contrast ratio is 5414:1, and when the local dimming function is enabled, the contrast ratio increases to 14,743:1. If the local dimming zone number is designed properly, such an mLCD's CR can also reach 10^6:1. The ambient reflectance of display is calculated based on the data reported in [9]. The same anti-reflection coating (R=1.5%) is applied to all display panels and the aperture ratio of μLED is assumed to be 1%.

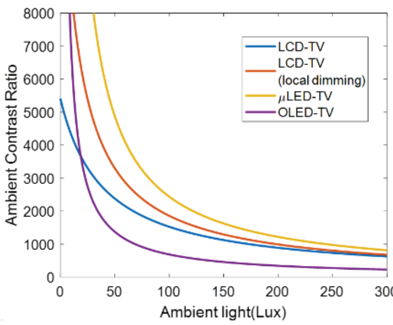

Fig. 1. Calculated ACR as a function of different ambient light conditions for LCD, OLED, mLCD, and μLED.

As Figure 1 depicts, ACR decreases sharply and then gradually saturates as the ambient light brightness increases. Under all ambient lighting conditions, the μLED display with high peak brightness and high intrinsic contrast ratio shows the highest ACR. Unlike a μLED display which can achieve high peak brightness by increasing the current, boosting the peak brightness of an OLED display would compromise its lifetime and efficiency. From Fig. 1, there is a crossover point for OLED and LCD at around 20 lux. Below 20 lux, OLED shows a much higher ACR than LCD. But the situation is reversed as the ambient illuminance exceeds 20 lux. This is because the dark level (signal) of the display panel is washed out by the surface reflection (noise) of the ambient light. A typical family room lighting is about 100 lux and an office lighting is about 300 lux.

3.2 Lifetime

Both LCD and μLED displays use inorganic materials as emitting light sources. Their device lifetime is usually longer than 50,000 hours. However, the emission source of OLED displays is organic materials which are more sensitive to moisture and air, and DC current. Therefore, a special protective film is needed to prevent it from environmental damage. In addition, the luminance of OLED decreases due to the degradation of organic materials during long-term operation [10]. This phenomenon is more obvious in blue OLEDs with larger band gaps [11]. The lifetime of blue phosphorescent OLED is around 20x shorter than that of red and green ones. However, several new materials and novel device structures (stacked blue OLED layers) have been proposed recently, the lifetime of OLED displays is expected to be gradually improved.

3.3 Motion Picture Response Time (MPRT)

Even the response time of an LCD (ms) is much slower than that of OLED (μs) and LED displays (ns), we cannot conclude that LCD will suffer more severe motion blurs. This is because the visual perception of a moving object depends not only on the response time of the display material, but also on the TFT frame rate. The widely accepted MPRT is jointly determined by the pixel response time (τ) and frame rate ($f = 1/T_f$) as [12]:

$$MPRT = \sqrt{\tau^2 + (0.8T_f)^2} \qquad (2)$$

Figure 2 shows the MPRT as a function of material response time at 60, 120 and 240 frames per second. At a given frame rate, reducing the response time will cause the MPRT to first decrease linearly and then gradually saturate. Here, we take a display with 120 Hz frame rate as an example to compare the MPRT of the three display technologies. From Figure 2, as long as the LC response time is less than 2ms, the MPRT of the TFT LCD is almost the same as that of OLED and μLED displays. High frame rate is important for achieving a fast MPRT, but this alone is still inadequate to eliminate the image blurs. In addition, a lower duty ratio (e.g. 10%-20%) plays a key role for suppressing the motion image blurs. The major drawback of low duty ratio is its compromised brightness [12].

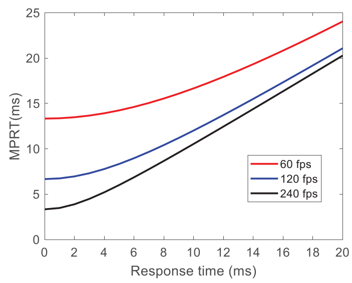

Fig. 2. Calculated MPRT as a function of LC response time at three different frame rates.

3.4 Color Gamut

Vivid color is another important requirement for display devices. Before comparing the color performance of each display technology, let us first discuss the relation between color gamut and total light efficiency. From [13], as the color gamut exceeds 85%-90% Rec. 2020 color space, the total light efficiency of the display begins to decline noticeably. Therefore, it is reasonable to set the target color gamut at 90% Rec. 2020 when comparing different display panels. For LCDs, the color conversion materials have been improved from yellow YAG phosphor, two-color phosphors (green: β-sialon: Eu2+ phosphor; red: KSF phosphor) to quantum dots [14]. The corresponding color gamut is expanded from 50%, 70% to 85% Rec. 2020. In an LCD, the converted white light is further filtered by the RGB color filters to generate three primary colors. However, since the RGB transmission bands of the pigments-based color filters are wide and do not completely match the emission spectra from the LCD backlight, the crosstalk is appreciable especially for the blue channel. A narrow band color filter with less crosstalk would increase the color gamut to about 90% Rec. 2020, but the larger absorption reduces the optical efficiency.

As emissive displays, the color gamut of OLED and µLED displays mainly depends on the emission spectrum of the RGB emitters. Among OLED displays, deep blue fluorescent and deep red phosphorescent OLEDs have recently been released. In addition, the optical cavity formed by adding a multilayer film and a bottom reflective electrode can provide high transmittance in a certain wavelength range, and therefore can further reduce the FHWM of emitted lights. With the help of these new materials and optical cavity, the color gamut of OLED displays can also achieve over 90% Rec. 2020 [15].

In a µLED display, the emission spectrum is mainly defined by the band structure of multiple quantum wells. The FWHM of the red and blue emission spectra is usually below 20nm, and the green is 30nm. Therefore, the color gamut of RGB µLED can also cover about 90% Rec. 2020. However, the color performance of LED displays is affected by the center wavelength shift under different driving currents. Generally, as the driving current increases, the center wavelength of the LED will blueshift due to the quantum-confined Stark effect, and then redshift due to increased junction temperature. To solve the wavelength shifting problem in a µLED display, the pulse width modulation (PWM) driving method that drives with a fixed current and modulates the grayscale by the LED emission time is adopted. However, it is challenging for PWM to achieve a short emission time in low gray levels, especially at a high frame rate. Therefore, a hybrid (digital and analog) driving method for µLED displays has also been proposed [16].

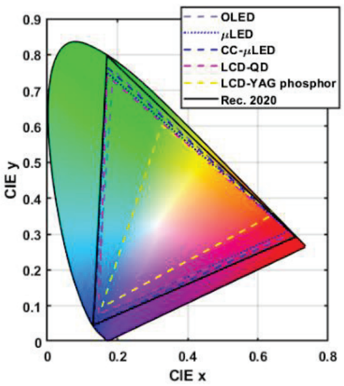

Fig. 3 Chromaticity (x, y) of LCD/µLED/OLED displays in comparison with Rec. 2020.

By adding color conversion materials such as QD or perovskite on top of the emission source (blue OLED or µLED) [17], full color can also be achieved. According to the emission spectrum of the color conversion material with an ultra-narrow FWHM, a color gamut greater than 95% Rec. 2020 can be achieved in theory. However, some key issues remain to be solved, e.g. blue light leakage would reduce the color purity of the display, the power conversion efficiency of the color conversion layer, and the ambient light excitation of the color conversion layer placing at top of the display panel. Figure 3 summarizes the color gamut of different displays studied.

3.5 Viewing Angle

For TVs and public displays, wide viewing angle is a key requirement. Two factors affect the viewing angle of a display: decreased contrast ratio and color shift. The root causes of angular color shift in LCD, OLED, and µLED are quite different. Therefore, different optical design should be employed to minimize the angular color shift for each technology.

In an LCD, the gray level of each sub-pixel is determined by the transmitted backlight. However, when the backlight traverses the LC layer at different incident angles, the accumulated phase retardation varies. Such a phase difference causes the angular color shift. To expand the viewing angle, compensation films are widely used in TN LCDs. In a VA LCD, multi-domains and compensation films are required for achieving wide view. In IPS and FFS modes, the LC directors are arranged homogeneously, thus, with multi-domain and phase compensation, a very wide viewing angle and indistinguishable color shift can be achieved [18].

In an emissive display, each pixel is directly modulated by the driving current. However, color shift could still appear at different viewing angles. In an OLED display, two factors are responsible for the observed angular color shift: the microcavity effect and unmatched RGB emission patterns. As the viewing angle increases, the emission spectrum shifts toward a shorter wavelength due to the microcavity effect. Moreover, if the RGB sub-pixels have unmatched radiation patterns, then color shift will also occur. Through optimizing the microcavity of an OLED device structure, angular color shift can be mitigated [19]. In a µLED display, the cavity effect is weak, so the central wavelength of the RGB sub-pixels basically remains unchanged with viewing angles. However, the LED chip size is small so that the surface effect increases, and the red LED material is different from the green and blue ones. As a result, the red LED has a different radiation pattern from the green and blue ones. To reduce the mismatched angular radiation patterns between RGB µLEDs, a specially designed black matrix, LED taper angle, and optical structure have been proposed [20].

3.6 Power Consumption

Power consumption affects the ecosystem and is a critical issue. To compare the power consumption fairly, we should set the display to have similar image quality. Recently, a power consumption model based on ACR has been proposed, which provides a meaningful comparison on the power efficiency of different display devices. Figure 4 shows the relationship between the power efficiency of different display devices and the LED chip size. The image content is a white image (D65) with APL=100%. Three display applications (smartphones, laptops, and TVs) are evaluated, their corresponding pixel sizes are (50µm, 90µm, and 375µm), and the ambient light levels are (1500 lux, 500lux, and 150 lux). The targeted ACR is (40:1, 100:1 and 1000:1), respectively.

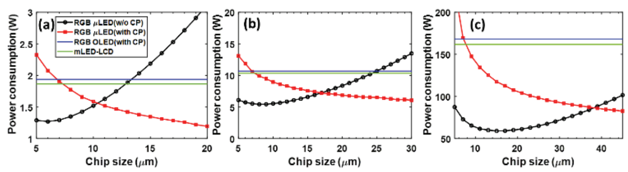

Fig. 4 Simulated power consumption of different display technologies. (a) 6.5” smartphone, (b) 15.6” NB computer, and (c) 65” 4K TV.

As mentioned above, whether a µLED display requires a circular polarizer (CP) is debatable. Here, we examine this issue in terms of power consumption. First, when a CP is used to eliminate the ambient light reflection from display panel, the ambient light reflectivity will not change with the µLED’s aperture ratio. Thus, as the chip size increases, the EQE of the μLED will increase, thereby reducing power consumption. However, the use of CP will reduce the power efficiency of the system by more than 50%. On the other hand, if the CP is removed, then a larger chip size will not only increase the EQE of the μLED, but also increase the reflectivity of ambient light. Therefore, as the μLED chip size increases, the corresponding power consumption will decrease first due to higher EQE, and then rebound due to higher ambient light reflectivity. Based on this trade-off, the optimal LED chip size with the lowest power consumption can be found. In our calculations, in most applications the power consumption of μLED is better than that of OLED and mLCD. These results are based on the PWM driving of μLED display, and the driving point is in the peak EQE region. However, under PWM driving, especially at a high frame rate, it is still challenging to obtain such a short emission time in low gray levels.

3.7 Panel Flexibility

Due to the excellent flexibility of organic materials, a rollable AM-OLED display has been released commercially, such as LG rollable TVs. A flexible μLED display was demonstrated by PlayNitride, on a polyimide substrate. For LCDs, due to the requirement of a backlight, their flexibility is limited. Lately, FlexEnable demonstrated a rollable LCD using organic TFT, called OLCD. At Touch Taiwan 2019, Innolux exhibited an impressive 3-fold splicing display with 3 borderless LCDs.

3.8 Resolution Density

The required display resolution depends on the viewing distance and field of view. So far, in most display applications, such as TVs and monitors, the display resolution is adequate due to the relatively long viewing distance. However, in AR/VR displays, the viewing distance is short. To avoid the screen-door effect, a resolution density over 2000 pixel-per-inch (ppi) is required. The resolution density of an LCD is determined by the TFT and color filter arrays. In 2017, Samsung demonstrated an LCD with 2250 ppi for VR displays. In 2019, Sony developed a micro-OLED display with 3000 ppi for AR applications [21].

3.9 Cost

Cost is often a decisive factor for consumers to purchase a display product. Active matrix LCDs have been developed since 1980s. Nowadays, LCD's cost has declined substantially. After 30 years of development, OLED technology is also reasonably mature, especially for small-sized displays. The manufacturing yield has been greatly improved. With continuous innovations in materials and device structures, and advanced manufacturing processes, such as inkjet printing, OLED's cost should continue to decrease. For an μLED display, its cost is related to the chip size. Minimizing LED chip size help increase the number of chips per wafer, but the mass transfer yield could be compromised. A lower mass transfer yield would lead to a higher repair cost and longer led time [22].

4. CONCLUSIONS

We have briefly reviewed the latest developments in OLED, mini-LED backlit LCD, and micro-LED displays. Each technology has its own pros and cons. We summarize the nine display performance metrics in Figure 5. Overall, the lifetime of OLED displays remains to be overcome for high-brightness applications, such as sunlight readable displays. The relatively low contrast ratio degrades the image quality of LCDs at dark ambient. However, considering the ambient light effect, an LCD can have a higher ACR than an OLED display because of its higher peak brightness. As HDR display becomes mainstream, the competition between OLED and mini-LED will further intensify. Finally, μLED displays show an excellent ACR in almost all ambient conditions, thanks to its high peak brightness. However, the complex driving circuitry and manufacturing process still impede its widespread applications. As the cost continues to decline, μLED displays will gradually move toward the center stage.

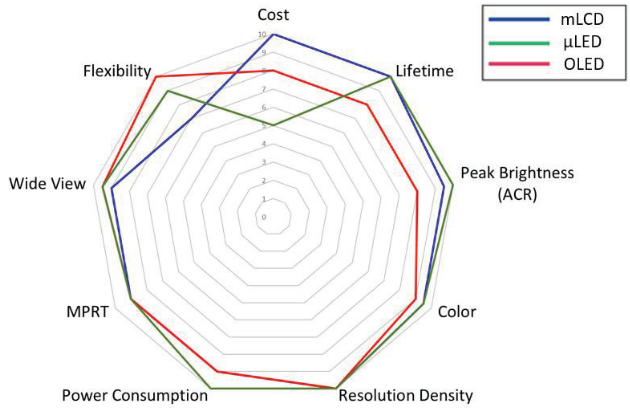

Fig. 5 Display performance metrics comparison between mLCD, RGB OLED, and RGB micro-LED displays.

5. ACKNOWLEDGMENT

The UCF group is indebted to a.u.Vista, for the financial support.

REFERENCES

[1] Hoffman, D. M., et al. J. Soc. Inf. Disp. 24, 216–228. **2016**

[2] Tsujimura T. OLED Display: Fundamentals and Applications 2nd ed. Hoboken, NJ, USA: John Wiley & Sons. **2017**.

[3] Lin, J. Y., et al. Appl. Phys. Lett. 116, 100502. **2020.**

[4] Guo, W., et al. IEEE Trans. Electron Devices 66, 2263. **2019**.

[5] Chen, H. W., et al. Light Sci. Appl. 7, 17168. **2018**.

[6] Tang, C. W., et al. Appl. Phys. Lett. 51, 913-915. **1987.**

[7] Corbett, B., et al. Prog. Quantum. Electron. 52, 1-17. **2017**.

[8] Lee, J. H., et al. Opt. Express 13, 9431-9438. **2005**.

[9] Huang, Y., et al. Light Sci. Appl. 9, 105. **2020**.

[10] Scholz, S., et al. Chem. Rev 115, 8449-8503. **2015.**

[11] Lee, J. H., et al. J. Mater. Chem. C 7, 5874. **2019**

[12] Peng, F. L., et al. J. Appl. Phys. 121, 023108. **2017**.

[13] Chen, H. W., et al. Light Sci. Appl. 6, e17043. **2017.**

[14] Jang, E., et al. Adv. Mater. 22, 3076-3080. **2010**.

[15] Hosoumi, S., et al. SID Symposium Digest 48, 13-16. **2017**.

[16] Tamaki, M., et al. SID Symposium Digest 51, 111-114. **2020**.

[17] Liu, Z., et al. Light Sci. Appl. 9, 83. **2020**.

[18] Lu, R., et al. Opt. Express 14, 6243-6252. **2006**.

[19] Kim, E., et al. Organic Electronics 48, 348-356. **2017**.

[20] Gou, F., et al. Opt. Express 27, A746-A757. **2019.**

[21] Motoyama, Y., et al. J. SID 27, 354-360. **2019.**

[22] Virey, E. H., et al. SID Symposium Digest 50, 129-132. **2019**.