Power consumption of OLED and μLED displays

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Abstract

High optical efficiency and low power consumption are critical for display devices. We have analyzed and compared the power consumption of AMOLED and AM-μLED displays for smartphones, notebooks and TVs under the same ambient contrast ratio. OLED exhibits a lower power consumption than μLED at low luminance, but μLED takes over at high luminance.

Keywords

Micro-LED, OLED, power consumption, quantum dots

1. Introduction

Emissive displays, such as organic light-emitting diode (OLED) and micro-LED (μLED) offer true black image, low power consumption, fast response time, thin profile, and freeform shape. However, OLEDs suffer from high fabrication cost and relatively short lifetime [1]. Recently, active matrix addressed μLED is emerging because it not only has similar advantages to OLED but also provides longer lifetime and higher brightness [2]. For mobile displays, power consumption is a critical issue. Ahmed [3] has studied the required efficiency of μLED in order to achieve lower power consumption than OLED. Wierer *et al.* [4] reviewed the challenges of μLED such as how to achieve high efficiency at lower current density and how to mitigate high surface states in small-size μLED. However, the electrical power consumption of devices and the effect of ambient light to displays are not considered. So far, the power consumption of OLEDs and μLEDs has not been compared comprehensively yet.

In this paper, we compare the power consumption of OLED and μLED displays for three major applications: mobile phones, notebooks, and TVs. The effect of μLED current injection area and color conversion efficiency on power consumption are analyzed. Moreover, by considering the tradeoff between efficiency and ambient reflection, the optimal μLED sizes for the lowest power consumption in different applications can be obtained.

2. OLED and μLED displays

To compare the power consumption of OLED and quantum dot-μLED (QD-μLED) fairly, their luminance should be defined. Here, the luminance is defined by matching the ambient contrast ratio (ACR) of both displays. As a key metric for supreme image quality, ACR can be calculated by [5]:

$$ACR = \frac{L_{on} + L_{ambient} \times R_L}{L_{off} + L_{ambient} \times R_L} \tag{1}$$

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

Usually, extra optical structures are required in both OLED and QD-μLED to reduce ambient reflection. In OLED, a broadband and wide-viewing-angle circular polarizer with ~42% transmittance is applied to eliminate ambient reflection from the bottom electrodes. In QD-μLED, color filters are coated on top of the QD color-conversion layer to prevent blue light leakage from the green and red subpixels and reduce ambient light excitation of QDs. Table 1 lists the ambient reflection of OLED and QD-μLED for smartphones, notebooks and TVs with different μLED sizes. We assume TVs with anti-reflection coatings has a surface ambient reflectance of 2%. For touch-panel phones and notebooks, they usually do not have anti-reflection layers so that the surface reflection is 4%. The μLED with smaller sizes has a smaller aperture ratio and thus the ambient reflection is smaller. To achieve the same ACR as OLEDs, we need to boost luminance of QD-μLED. Taking QD-μLED (20μm) for notebooks as an example, its luminance needs to be 1.287 times of OLED luminance in order to obtain the same ACR, as shown in Fig. 1.

TABLE 1 The ambient reflection of OLED and QD-μLED

	Phone	Notebook	TV
OLED	4.00%	4.00%	2.00%
μLED (5μm)	4.19%	4.07%	2.00%
μLED (10μm)	4.70%	4.29%	2.02%
μLED (20μm)		5.15%	2.06%
μLED (50μm)			2.42%

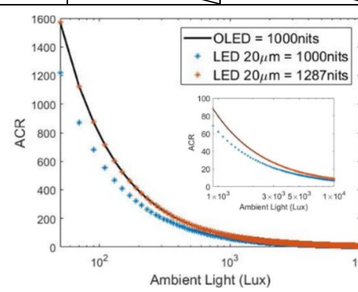

Fig. 1. ACR of OLED and μLED (20 μm) with different display luminance.

Since green and red colors in QD-μLED are down-converted from the blue LED, the conversion efficiency of the QD layer is very important. There are mainly two methods to fabricate QD color-conversion layers. One is inkjet printing [6] which can deposit a thick QD film. However, achieving good uniformity remains a challenge. The other is photolithography [7] which can provide high resolution and uniformity, but can hardly realize enough thickness. Around 40% of blue light will transmit through the QD layer. However fortunately, with the help of other optical structures (e.g. DBR and scattering structure) [8, 9] color-conversion efficiency can be improved. Herein, we sweep green and red QD efficiency, defined as the number of emitted green or red photons divided by the number of incident blue photons, from 30% to 70% in our simulation.

 ISSN 0097-996X/20/4803-0528-$1.00

The efficiency of OLED and QD-μLED devices is closely related to the power consumption of display panels. Here, we use the high performance RGB OLEDs reported by Semiconductor Energy Laboratory (SEL) in our simulation [10, 11]. While the efficiency of OLEDs is not influenced by the pixel size, the peak external quantum efficiency (EQE) of μLED declines as LED size decreases. The EQE drop is caused by high-density surface states which increase the Shockley-Read-Hall (SRH) recombination. Besides, this non-radiative recombination also leads to peak EQE shifts to higher current densities [12]. Here, the widely used ABC model is applied to evaluate the characteristics of LED. In such a model, considering the size effect, the internal quantum efficiency can be calculated by [13]:

$$IQE = \frac{B\times n^2}{A\times\frac{p}{s}\times n+B\times n^2+C\times n^3}, \tag{2}$$

where A is the SRH recombination constant, B is the radiative recombination constant, C is the Auger recombination constant, p is the perimeter of the LED, s is the surface area of the LED, and *n* is the carrier density. Experimental data of 10-μm μLED presented by PlayNitride [14] are fitted by this model, as plotted in Fig. 2(a). After fitting, we use Eq. (2) to model μLED with different sizes, as shown in Fig. 2(b). From Fig. 2, the EQE of the μLED is highly dependent on the driving current. Therefore, driving range of QD-μLED is important to define efficiency. To define the driving range of μLED, we must know the required brightness of R, G, B subpixels for displaying a white image (D65). Fig. 3 depicts the emission spectra of QD-μLEDs and OLEDs. From color mixing principles, the ratio of [R, G, B] is [27%, 66%, 7%] for QD-μLED and [25%, 68%, 7%] for OLED to generate the white point D65.

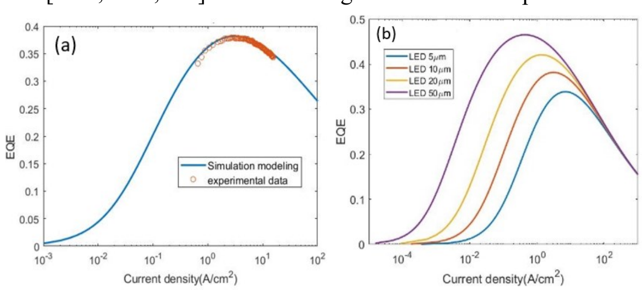

Fig. 2. (a) Measured EQE-*J* curve and the fitted result. (b) Calculated EQE-*J* curves for μLEDs with various sizes.

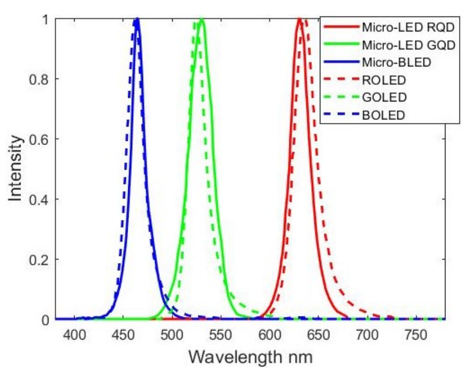

Fig. 3. Emission spectra of OLEDs and QD-μLEDs.

The panel luminance of different colors can be calculated by Eq. (3). Here, we assume the angular distribution of QD-μLED and OLED is Lambertian.

$$L_{R,G,B} = J_{R,G,B} \times \frac{A_C}{q} \times EQE_{R,G,B} \times \eta_{R,G,B} \times h\nu \times \frac{\frac{K}{\pi}}{A_{pixel}} \tag{3}$$

In Eq. (3), J is the current density, A_c is the current injection area, q is elementary charge, $h\nu$ is photon energy, K is luminance efficacy, A_{pixel} is the pixel area, L is the luminance, and η is the optical efficiency.

In OLEDs, due to the use of a circular polarizer, the optical efficiency is 42%. In μLEDs, the optical efficiency of blue color is 81%, determined by the transmittance of the blue color filter, while the optical efficiency of red and green colors is the product of QD efficiency (0.3~0.7) and corresponding color filter transmittance (86%, 96%). All the parameters in Eq. (3), except current density and EQE, are constant for each specific application. Therefore, to achieve a certain value of L, the product of current density and EQE is a constant, defined as β. Here, taking a 10-μm blue μLED as an example, to obtain the target luminance (L_B), β is 0.00425, 0.0112, and 0.192 for TV, notebook, and phone, respectively. The corresponding EQE-*J* curves for those β values are plotted in Fig. 4(a), as the yellow, orange, and blue lines indicate. The intersection of the β curve and the μLED EQE curve is the driving point for each application. Driving the LEDs at a high EQE range is desired for lower power consumption. To achieve this goal, a current confinement layer can be applied [15]. As exhibited in Fig. 4(b), for a smaller current injection area, the driving point shifts toward higher EQE values, which in turn lowers the power consumption. In a more general case, to obtain the current of a full pixel, we can sum up $I_{R,G,B}$ which can be acquired by Eq. (3).

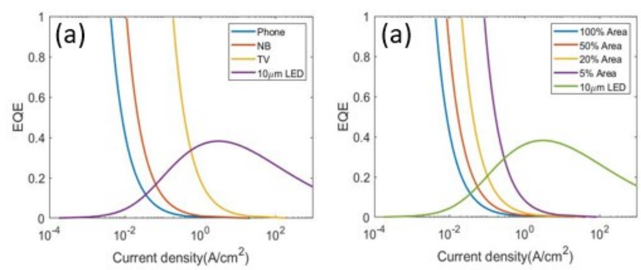

Fig. 4. (a) EQE-*J* curves for different β values (corresponding to different applications) and for the μLED. (b) Effect of the current injection area on the driving range.

3. Power Consumption Evaluation Model

For an AM display shown in Fig. 5(a), the power can be consumed by the timing controller, source driver, gate driver, thin-film transistors, emissive devices and wiring dissipation, etc. The system of OLEDs and QD-μLEDs is almost the same except the different emissive devices. Therefore, we only need to consider the power consumption of the display array, including thin-film transistors (TFTs), emissive device, and wiring, to make a fair comparison between them. The calculation model of the power consumption is adopted from [16]. Since the power consumption of the display array is dominated by the static power, the efficiency of the emissive device is important. As shown in Fig. 5(b), when the display is on, the drain-to-source voltage (V_{DS}) of the driving TFT that operates at saturation region can be expressed as follows:

$$V_{DS\_i} = \sqrt{\frac{2\times I_{sub\_i}}{\mu\times Cox\times\frac{W}{L}}}, i = R, G, B \tag{4}$$

where μ, *Cox*, W and L are the field-effect mobility, oxide capacitance, channel width, and channel length of the TFT, respectively, and I_{sub_i} is the current of R, G, and B subpixels we calculated above. Hence, the voltage across each subpixel can be obtained by the following equations:

$$V_{RED} = V_{DS\_R} + V_{DEVICE\_R} \quad (5)$$

$$V_{GREEN} = V_{DS\_R} + V_{DEVICE\_G} \quad (6)$$

$$V_{BLUE} = V_{DS\_B} + V_{DEVICE\_B} \quad (7)$$

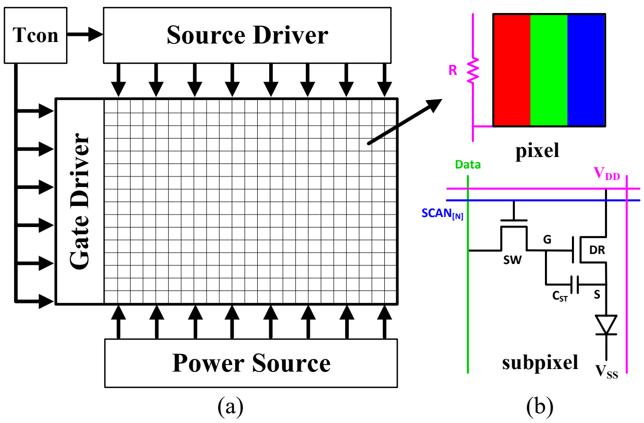

Fig. 5. (a) System diagram of AM displays. (b) Pixel diagram.

where V_{DEVICE} represents the driving voltage of the emissive device as listed in Table 2. Notably, the voltage across the terminal pixel of the display array is determined by the maximum voltage across the R, G, and B subpixels, which is given by:

$$V_{MAX} = \max\{V_{RED}, V_{GREEN}, V_{BLUE}\} \quad (8)$$

This maximum voltage must ensure that the driving TFTs in each subpixel are operating at saturation region when the panel is working at the peak luminance. It is worth pointing out that although the model [16] mentioned that there is a voltage drop of V_{DD} line over the panel, this effect was not considered. Since the wiring line has a parasitic resistor, the voltage across each pixel will be reduced gradually from the left side to the right side of the display array. To evaluate the power consumption more accurately, we modify the calculation of the wiring power. Finally, the power consumption of the display can be expressed as:

$$P_{TOTAL} = [(I_{PIXEL} \times V_{MAX}) \times M \times N] + P_{LINE} \quad (9)$$

where I_{PIXEL}, M, N, and P_{LINE} are the total current of a pixel, the row number of the display and the column number of the display, and the power consumption of the power line respectively.

Next, we use the modified model to evaluate the power consumption of AMOLED and QD-µLED displays for mobile phone, notebook, and TV. Table 3 lists the corresponding parameters and panel specifications. Herein, phone and notebook are based on low-temperature polycrystalline silicon (LTPS) TFTs, while TV is amorphous indium-gallium zinc oxide (a-IGZO) TFTs. Our simulated power consumption for the 4.8" OLED panel (resolution 320x480) is 2.35W at 700 nits, which agrees with the measured value (2.40W) well [16].

4. Results and Discussion

Normally, a larger size µLED has a higher EQE and thus can achieve lower power consumption, as Fig. 6(a) shows. However, as illustrated in Fig. 6(b)-6(d), the sizes of µLED that achieve the lowest power consumption for phone, notebook, and TV are 5 µm, 5 µm, and 20 µm, respectively. In fact, there is a tradeoff when considering real applications. As the size of µLED increases, the aperture ratio becomes larger and thus results in higher ambient reflection. Therefore, to maintain a certain ACR, higher luminance is required. On the other hand, when the size of µLED increases, the µLED can achieve higher efficiency due to less SRH recombination. Because of the tradeoff, we can find the optimal µLED size for TV.

TABLE 2

DRIVING VOLTAGE OF OLED AND µLED

	Red	Green	Blue
V_{OLED}	4	3.4	3.2
$V_{\mu LED}$	1.95	2.34	2.75

TABLE 3

PARAMETERS OF PHONE, NOTEBOOK, AND TV

	6.5" phone	15.6" NB	65" TV
W/L of TFT (µm/µm)	3/12	3/15	20/10
Mobility (cm²/V·s)	100	100	10
Resolution	1242 × 2688	3840 × 2160	3840 × 2160
Luminance (cd/m²)	769	1000	1000

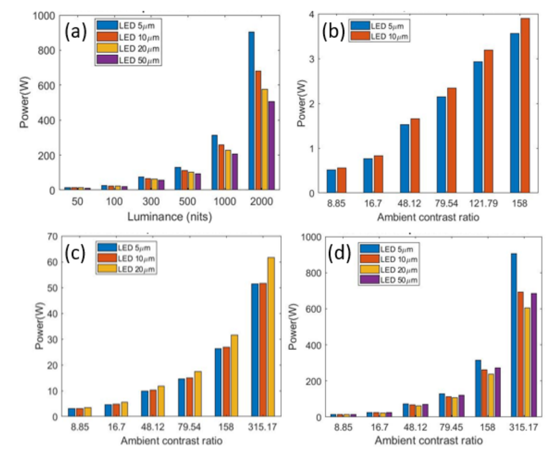

Fig. 6. Size effect of µLEDs on (a) power consumption of TV as a function of luminance and (b-d) power consumption as a function of ACR for (b) phone, (c) notebook, and (d) TV applications, where the illuminance of ambient light is 500 lux and the QD efficiency is 30%.

Other than the size of µLED, the QD efficiency also affects the power consumption of µLED displays. By setting the µLED size to the optimal size discussed above, the QD efficiency is swept from 0.3 to 0.7. As shown in Fig. 7(a)-7(c), power consumption can be reduced as QD efficiency increases. However, such advantage gradually saturates. To make a comparison, power consumption of OLED is also plotted in Fig. 7(a) and 7(b), where the TFT characteristics are the same for both OLED and µLED. At low luminance that is low ACR in Fig. 7(a)-(b), the OLED can obtain lower power consumption than µLED. However, at high luminance µLED shows better efficiency. This phenomenon can be explained by Fig. 7(d), where the optical efficiency ($EQE_{R,G,B} \times \eta_{R,G,B}$) of blue OLED and µLED as a function of luminance is depicted. For µLEDs, defects and surface states cause low efficiency at low current density. As the current density increases, the influence of defects is diminished and thus the efficiency increases. Comparing to µLEDs, OLEDs usually have high EQE at low current density and EQE rolls off at high current density. Therefore, the optical efficiency-luminance curves of OLED and µLED will intersect at certain luminance in Fig. 7(d). In Fig 7(d), the intersection point only indicates where efficiency of blue OLED and µLED crosses over. To find the crossover point of total power consumption, we have to consider the operation voltage for each color. An OLED TV normally uses white OLED with color filters, which is different with the RGB OLED, so the power consumption of OLED TV is not calculated in this paper. As mentioned before, a current confinement layer can effectively shift the driving range to higher EQE. To study how much it improves the efficiency, we also sweep the current injection area of µLED displays for phones. As shown in Fig. 8(a), power consumption can be reduced by restricting the current injection area, and the effect is more obvious at lower luminance. Fig. 8(b) shows as the injection area decreases, the cross point moves to lower luminance.

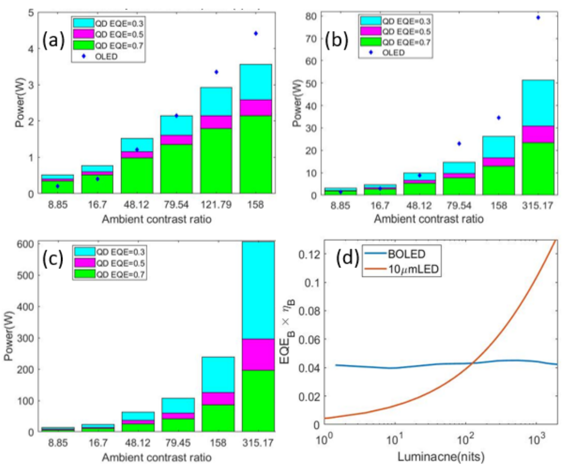

Fig. 7. The effect of QD efficiency on power consumption of (a) phone, (b) notebook, and (c) TV as a function of ACR (ambient light is 500 Lux and µLED is the optimized size in each application) (d) The optical efficiency of blue OLED vs. blue µLED at various luminance.

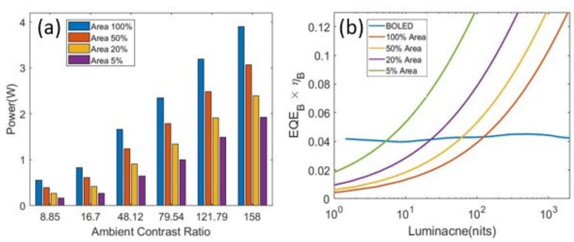

Fig. 8. The effect of current injection area on (a) power consumption of µLED (10µm) as a function of ACR; (b) The optical efficiency of blue OLED and blue µLED as a function of display luminance.

5. Conclusion

We have analyzed power consumption of OLED and µLED. OLED is more efficient than µLED at low luminance. However, by confining current injection area of µLED, the driving range can shift to a higher EQE. Therefore, µLED can be more power-efficient than OLED even at low luminance. Moreover, considering ACR and size effect, we found the optimal size of µLED (5µm in NB and phone, 20µm in TV) with the lowest power consumption.

6. Funding

a.u.Vista, Inc.

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