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ABSTRACT

Micro-light-emitting-diode (μLED) displays with low power consumption are highly desirable for the mobile devices powered by batteries. However, since the smaller LED chip size corresponds to lower optical efficiency, this advantage is compromised. In this paper, we develop a model to evaluate the power consumption of micro-LED displays based on ambient contrast ratio. Then, the optimal μLED chip sizes to achieve the lowest power consumption for smartphones, laptop computers, and TVs, are obtained. Furthermore, we propose to employ different RGB chip sizes in μLED displays. In comparison with the optimal results with uniform LED chip size, our new design offers an additional 12% average power saving for real image contents.

Keywords: micro-LED display; power consumption; ambient contrast ratio

1. INTRODUCTION

Micro-light-emitting-diode (μLED) displays with high peak luminance, true dark state, high resolution, wide color gamut and long lifetime are emerging as next-generation displays[1-3]. In addition to above-mentioned properties, low power consumption is always desirable for μLED display to compete with its counterparts such as liquid crystal displays (LCDs) and organic LED (OLED) displays[4, 5]. Especially, low power consumption lengthens the operating time for the battery powered mobile devices. Although TVs and monitors are powered by the wall plugs, low power consumption helps to save the ecosystem. Even though high EQE (~70%) LED is common in large size LEDs used in lighting, the EQE for GaN μLEDs is mostly limited to 10%-30%[6, 7]. The main cause for the lower efficiency of small-size LEDs is sidewall defects[8-12]. Besides, the driving current density also affect the EQE of LED. To keep driving at high EQE region, pulse width modulation (PWM) is recommended for μLED displays[13-15]. In PWM, the driving current density stays at peak EQE, while the luminance is modulated by changing the duty ratio in each frame.

In this paper, we develop a model to evaluate the power consumption of μLED displays based on ambient contrast ratio (ACR). First, as the baseline for comparison, the power consumption of μLED displays (smartphone, laptop, and TV) with uniform chip size are analyzed, i.e. the LED chip size of RGB (red, green, and blue) subpixels is uniform. For TV applications, the LED chip size studied ranges from 5 μm to 50 μm. The optimal LED chip size is found to be 16 μm. At the optimal chip size, the power saving can reach 30–40%. Next, we extend our model to evaluate RGB subpixels with different chip sizes. Through the optimization procedures, our proposed μLED display with different RGB chip sizes further reduces ~ 12% average power consumption than that with uniform LED chip size.

2. DEVICE MODELING

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 completely dark ambient, so here we focus on analyzing the display performance under ambient lighting conditions. The contrast ratio of an emissive display such as OLED and μLED can exceed 10^6:1 at dark ambient, but in practical applications the effective contrast ratio is substantially affected by the ambient light and surface reflectivity of the display panel. The ACR is defined as[16, 17]:

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

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where L_{on} ($L_{off} \approx 0$) represents the on (off)-state luminance of the display, L_{am} is the ambient luminance, and R_L is the luminous ambient reflectance of a display panel.

To investigate the ambient reflection of RGB μLED displays, we build a ray-tracing simulation model based on LightTools. The device structure of our μLED display is depicted in Figure 1, where W_R, W_G, and W_B represent the chip size of RGB LEDs, respectively. The gap between micro LEDs is filled with black matrix to reduce ambient reflection. Because of the small aperture ratio of micro-LED displays, the circular polarizer normally used in OLED displays to reduce the ambient light reflection is not required here. The device structure of flip-chip RGB μLED is similar to that reported previously[18], and material characteristics of the flip-chip RGB μLEDs are summarized in Table 1, where *n* and *k* represent the real part and imaginary part of the refractive index of the corresponding material[19, 20].

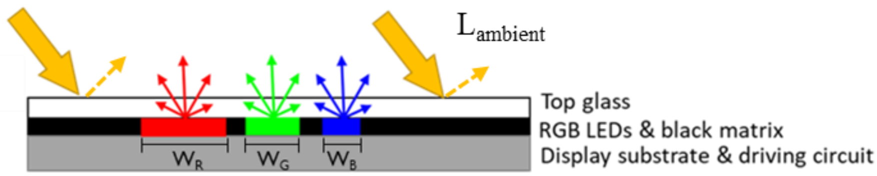

Figure 1. Device structure of our proposed RGB μLED display.

Table 1. Material parameters used in RGB μLED display simulations.

Material parameters	630 nm		530 nm		465 nm	
	n	*k*	*n*	*k*	*n*	*k*
Molding layer	1.48	0	1.49	0	1.50	0
Red LED chip	3.30	0	3.56	0.16	3.76	0.28
Blue/Green LED chip	2.35	4×10^{-5}	2.34	4×10^{-5}	2.42	4×10^{-5}
Bounding metal	0.15	3.52	0.44	2.29	1.43	1.85
Glass substrate	1.5	0	1.5	0	1.5	0

The simulated reflection spectrum from RGB LED chips illuminated by D65 white light source is plotted in Figure 2(a). Compared to GaN based green and blue LEDs, the AlGaInP based red LEDs have a stronger absorption in the green and blue spectral regions, thereby reducing ambient reflectivity. It is noteworthy that the low reflectance of GaN based LED in blue spectral region mainly result from the absorption of Au based electrode. The average luminous ambient reflectance of GaN based LED and AlGaInP based red LED is about 67% and 30%, respectively. The ambient reflection of a display can be separated into two parts: reflection from the surface cover glass and reflection from the display device (μLEDs). In a μLED display, the ambient light is firstly reflected by the front glass. Due to the small aperture ratio, only a small portion of the transmitted ambient light will be reflected by the μLED chips. The rest is absorbed by the covered black matrix. As a result, the total ambient reflectance of the μLED display can be derived by:

$$R_L = R_s + (1 - R_s) \times \sum_{i=RGB} R_{(i)} \times AP_{(i)} \times T_{sys} \tag{2}$$

where R_S is the surface ambient reflectance from cover glass, R_{RGB} is the luminance ambient reflectance from RGB LEDs, respectively, when the aperture ratio is 1, T_{sys} is the transmittance of display, and AP_{RGB} is the aperture ratio of RGB LEDs (the size of LED chip divided by the pixel size). For a touch-panel smartphone and laptop computer, the cover glass usually does not have anti-reflection (AR) coating. Thus, we assume their surface reflection is around 4%. However, most of TVs use remote control so that we can apply AR coating to reduce the surface reflection. Here, we assume their surface reflection is 1.2%.

In previous studies, the power efficiency of a display panel has mainly considered the optical efficiency (EQE/WPE) of the emission source (LED/OLED) and the transmittance of the display panel. However, in these models the influence of display's ambient reflectance on power consumption is not considered[21, 22]. Such an ambient light reflection may washout the image quality of the display. Boosting the brightness helps to improve the ACR, but the price paid is increased power consumption. In this paper, we compare the power consumption of displays when they provide same image quality (ACR) under same ambient conditions. Based on Equation 1, the on-axis brightness of the display for providing targeted ACR under different ambient light levels can be described by:

$$L_{on} = (ACR - 1) \times L_{am} \times R_L \tag{3}$$

where L_{on} ($L_{off} \approx 0$ for emissive display) represents the on (off)-state luminance of the display, L_{am} is the ambient luminance, and R_L is the ambient light reflectance depending on the display technologies.

Meanwhile, the power consumption is also affected by the efficiency of LED chips. Based on the luminance efficacy (K), average photon energy ($h\nu$), and EQE of the emission devices, the power efficiency (cd/W) can be derived as:

$$\eta_{RGB} = \frac{EQE_{RGB} \times T_{sys} \times K_{RGB} \times h\nu_{RGB}}{q \times V_{RGB} \times \alpha_{RGB}} \tag{4}$$

where V is the driving voltage, q is the elementary charge, and α is the conversion efficiency from luminance intensity [unit: cd] to luminous flux Φ [unit: lm].

Here, because the PWM driving scheme is employed in our simulations to effectively drive LED, the EQE in Equation 4 represents the peak EQE of the LED and the voltage is fixed at the optimal driving condition. Generally, the peak EQE of LED depends on the chip size. Therefore, to investigate the power efficiency of different LED chip sizes, we also take this peak EQE variation into consideration. The peak EQE deceases as the μLED chip size decreases, resulting from the nonradiative recombination at the etched sidewall. The ratio of sidewall perimeter to the mesa area increases as the LED chip size shrinks. As a result, the sidewall effect becomes more significant when the LED chip size is smaller than ~100 μm. The chip size dependent efficiency of InGaN based μLEDs has been widely discussed in[8-11]. On the other hand, because AlGaInP exhibits a higher surface recombination velocity than InGaN, the efficiency drop of red μLED is more serious than the blue and green ones as the chip size decreases[12]. Detailed theoretical analyses and experimental results have been reported in[23, 24]. Using these published results, we plot the peak EQE as a function of LED chip size for RGB LEDs in Figure 2(b).

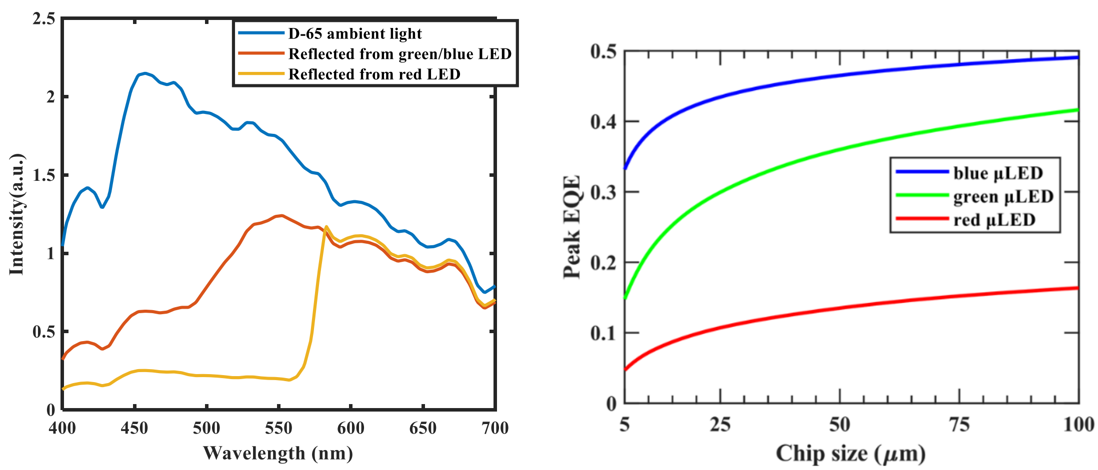

Figure 2. (a) The intensity spectrum of ambient light, ambient light reflected by AlGaInP based LED, and ambient light reflected by InGaN based LED. (b) Chip size dependent peak EQE of RGB μLEDs.

3. LED CHIP SIZE OPTIMIZARION PROCESS

3.1 Uniform LED chip size in RGB subpixels

As shown in Figure 2(b), the EQE of μLEDs gradually decreases as the chip size decreases. Therefore, a larger LED chip size is helpful to enhance the power efficiency. However, as shown in Equation 3, the μLED display with a larger LED chip size needs to deliver a higher luminance to maintain the same ACR because of its higher reflectance. Thus, based on the trade-off between display ambient reflectance and power efficiency, the optimal LED chip size with minimum power consumption can be found. Here, white image with color coordinate CIEx=0.312, CIEy=0.329 is applied as standard image to compare the power consumption of μLED display with different chip sizes. In addition, three kind of display applications under specific ambient condition are analyzed: 1) smartphone (PPI=460) under 2000-lux overcast daylight for ACR = 30:1, 2) Laptop (PPI=280) under 450-lux office lighting for ACR = 120:1, and 3) TV (PPI=68) under 200-lux living room lighting for ACR = 800:1. In the following, we define two functions P(x) and L(x) to describe the power efficiency and required luminance intensity of a μLED display at different LED chip sizes, respectively. Because the power consumption can be defined as the luminance intensity divided by the power efficiency, we can find the optimal LED chip size when the ratio of L(x) to P(x) has a minimum. Detail of these functions are discussed as follows. The required luminance intensity of a display is the product of display luminance and display area, and can be defined as:

$$L(x) = L_{display} \times A_{display} = L_{ambient} \times R_L \times (ACR - 1) \times p^2 \times N \qquad (5)$$

where p is the pixel width and N is the number of pixels. From Equation 2, R_L is a function of LED chip size.

For the function P(x), because the peak EQE of RGB subpixels is different as shown in Figure 2(b), thus the efficiency of a display strongly depends on the image contents. Moreover, different colors can be obtained by mixing the ratios of RGB primaries. Therefore, the power efficiency of a mixed color can be determined by:

$$\frac{1}{P(x)} = \frac{1}{\eta_{pixel}} = \frac{\gamma_R}{\eta_R} + \frac{\gamma_G}{\eta_G} + \frac{\gamma_B}{\eta_B} \qquad (6)$$

where η is the power efficiency and γ represents the luminance intensity ratio of RGB primaries.

Let us firstly focus on the TV applications. From Equation 5, the total luminance intensity (L(x)) of the display as a function of LED chip size is plotted by the blue color in Figure 3. As the LED chip size increases, the higher ambient reflectance results in a higher luminous flux to maintain the same ACR. On the other hand, From Equation 6, the power efficiency (P(x)) of the μLED display as function of LED chip size is plotted by the orange color in Figure 3. The larger LED chip size brings out a higher EQE and power efficiency. Then, the optimal LED chip size with minimal power consumption can be found when the ratio of L (x) to P (x) has a minimum as plotted by the yellow color in Figure 3. Compared to 50 μm and 5 μm chip sizes, the optimal LED chip size (16 μm) can save 48% and 26% power consumption, respectively. These results manifest the advantage of using optimized LED chip size. With the same analysis process, we find the optimal LED chip size for smartphone is 6 μm and for laptop is 8 μm.

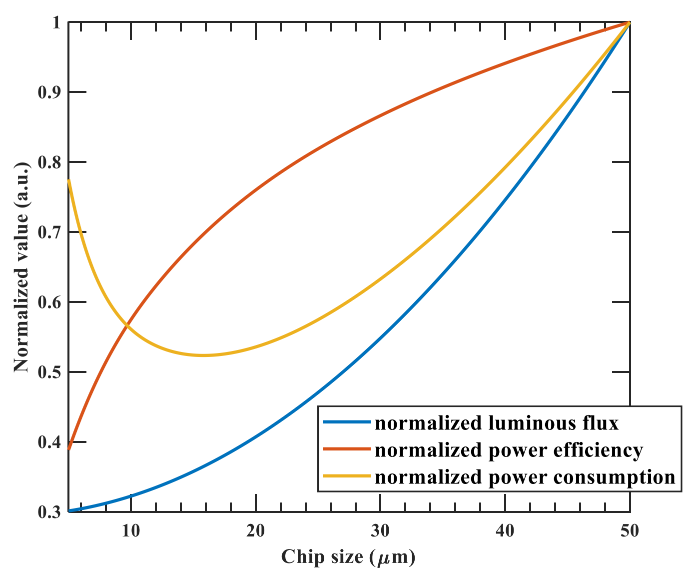

Figure 3. Normalized power efficiency fitting function (orange line), normalized luminous flux (blue line), and normalized power consumption function (yellow line).

3.2 Different LED chip sizes in RGB subpixels

In this section, we analyze the power consumption of RGB μLED displays with different LED chip sizes. In an RGB μLED display, as the chip size decreases, the power efficiency declines for the RGB micro-LEDs, but the decreasing rate of red μLED is more noticeable than that of green and blue, due to its faster surface recombination rate. For example, as the LED chip size decreases from 15μm to 5μm, the power efficiency of red, green, and blue LEDs drops 46.23%, 41.52%, and 18.69%, respectively. Therefore, using different chip sizes (with red being the largest) could improve the overall power efficiency. In addition, as mentioned above, increasing the LED chip size leads to enhanced display luminance for maintaining the same ACR. However, from Figure 2(a), the ambient reflectance of red μLED is smaller, due to its higher absorption of AlGaInP material. Therefore, among the RGB primaries, the enhancement of display luminance originated from enlarging the chip size is the smallest for the red micro-LED.

By lifting the restrictions on micro-LED chip size, we conducted a systematic optimization for achieving the lowest power consumption. The optimal LED chip size in RGB subpixels is (10, 5, 5) μm, respectively, for the smartphone, (14, 7, 5) μm for the laptop, and (26, 13, 8) μm for the TV studied. Next, we compare these power consumption results with that of uniform chip size. The power saving at different chromaticity coordinates in DCI-P3 color space is shown in Figure 4. Overall, the power saving covers about 94.46% of DCI-P3 color space. More specifically, the power saving over 10% covers 68% area of the DCI-P3 color space.

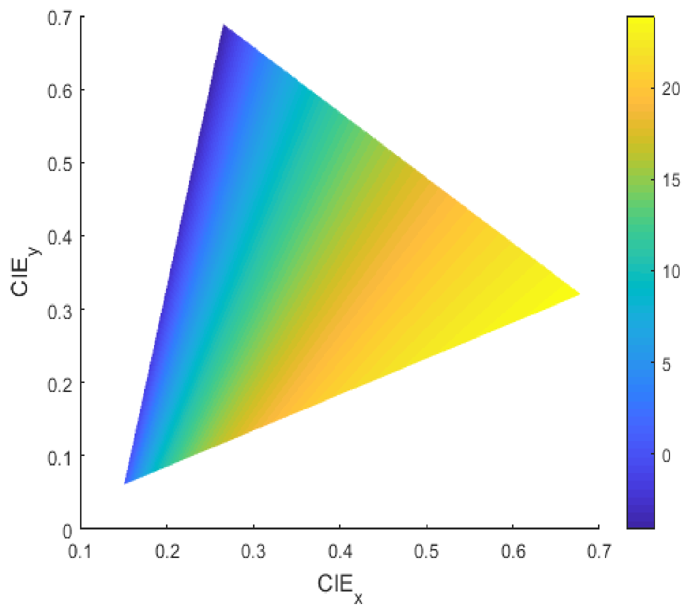

Figure 4. The decreased power consumption (unit: %) of RGB micro-LED displays with different chip sizes and uniform chip size.

We also evaluated some frequently displayed images for smartphones, laptop computers, and TVs. For smartphones, we compared the image contents of Facebook homepage, Google map, Google search, YouTube homepage, and iPhone homepage with app icons. Due to copyright issue, we do not show these images here. The average power saving is 12.9%. For laptop computers, we evaluated the image contents of Amazon homepage, Gmail, Facebook homepage, YouTube homepage, and computer game PUBG, and the average power saving is 13.2%. For TVs, we evaluated the image contents of CNN news, NBA game, football game, TV show, and weather forecast, and the average power reduction is 11.7%. Therefore, by employing various RGB micro-LED chip sizes, we can obtain about 12% average power saving in all the three intended applications.

4. SUMMARY

We developed a model for evaluating the power consumption of μLED displays. In the model, we investigate the power efficiency and luminance ambient reflection of RGB subpixels in a μLED display. The optimal chip sizes corresponding to the lowest power consumption are found in three application scenarios: smartphones, laptop computers, and TVs. The major findings are twofold: 1) For TV applications, the optimized chip size (16 μm) leads to 48% and 32% power saving, as compared to uniform LED chip size at 50μm and 5μm, respectively. 2) Our proposed μLED display employing different RGB LED chip sizes further reduces ~12% average power consumption over the optimized RGB micro-LED display with uniform LED chip size.

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