Ambient Light Excitation in Quantum-Dot-Converted MicroLED Displays

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Abstract

Ambient light excitation in quantum dots-converted micro-LED displays is analyzed and the calculated results agree well with simulations. By depositing a layer of color filter and reducing the area ratio of quantum dots, the display's ambient contrast ratio can be improved to adequately readable under full daylight.

Author Keywords

Micro-LEDs; color conversion; quantum dots; ambient contrast ratio.

1. Introduction

Micro-LED is considered as the next generation display technology because of its outstanding features such as low power consumption, true black state, high dynamic range and wide color gamut [1-3]. Although the commonly used fabrication method is to assemble individual red (R), green (G) and blue (B) micro-LED pixels from semiconductor wafers to the same driving backplane through mass transfer process, it is still challenging to achieve high manufacturing yield. In addition, RGB micro-LED displays suffers from angular color shift issue because of the epitaxial material difference [4]. In order to avoid these issues, alternative approach by employing blue or UV micro-LED to pump the color converters is proposed [5-7]. This method only needs one type of LED epitaxy wafer and is ideal for small-size display applications such as micro-displays or digital watches. Moreover, the color downconverter such as quantum dot (QD) has narrow photo-luminescent emission spectrum, which helps to achieve a wide color gamut [8-10]. However, the QD can be excited not only by the light from the micro-LED, but also by the short-wavelength component of the ambient light, which will degrade the ambient contrast ratio of the displays. In addition, how to analyze the ambient excitation of QDs quantitatively needs to be explored.

In this paper, we built a simulation model to analyze the ambient light excitation of QD-based micro-LED displays. The calculated results are validated by simulated ones based on a commercial simulation tool. In order to reduce the ambient excitation and reflection, a top layer of color filter plays an important role. In addition, the impact of QD area ratio on the ambient contrast ratio is discussed.

2. Theory and Modeling

Figure 1 illustrates the device structure of blue micro-LED array with red and green QD conversion layer. When the ambient light illuminates on the device, the ambient contrast ratio may degrade due to the QD excitation. For simplicity, we divide the ambient excitation of QDs into following three parts. 1) The first-time excitation. When the ambient light first hits the QDs, some of the incident light is absorbed and converted according to the QD's absorption and emission spectra, and then emits back to air. 2) The second-time excitation. This part refers to the unabsorbed ambient light when first passing through the QDs but is absorbed and converted after being reflected by the bottom micro-LEDs and traversing through the QD at the second time. 3) Reflection. This is the reflected ambient light by the micro-LED layer without being absorbed or converted by the QDs.

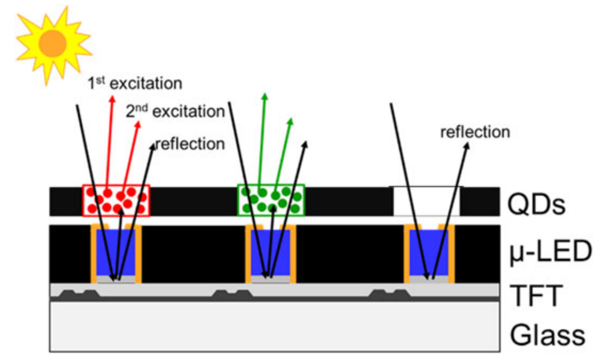

Figure 1. Device configuration of blue micro-LED array with red and green quantum dots as color conversion layer.

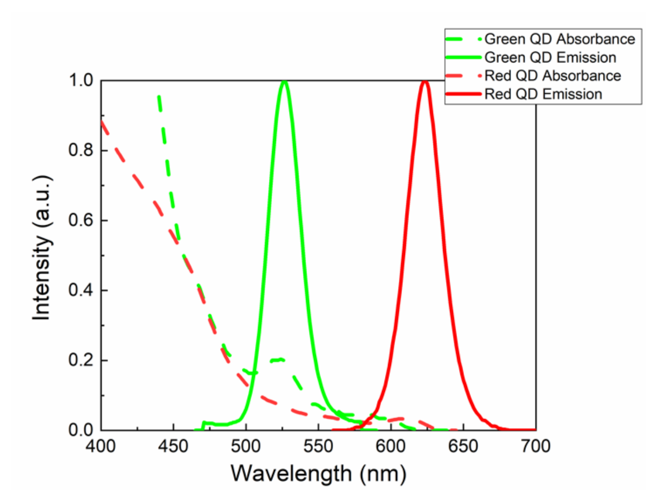

Figure 2. Absorbance and emission spectra of the employed green and red thick-shell quantum dots [11].

In order to calculate the ambient excitation of QDs, we use white light D65 as the ambient light source. The absorption and emission spectra of green and red QDs [11] are plotted in Figure 2. They are thick-shell QDs with film photoluminescence quantum yield (PLQY) as high as~70%. The absorbed number of photons (N_{abs}) by the QDs can be calculated by using Eqs. (1) and (2):

$$N_{abs}(\lambda)\cdot h\nu = I_{D65}(\lambda)\cdot A_{QD}(\lambda), \tag{1}$$

$$N_{abs} = \int I_{D65}(\lambda)\cdot A_{QD}(\lambda)\cdot \frac{\lambda}{hc} d\lambda, \tag{2}$$

where I_{D65} is the intensity of ambient light, A_{QD} is the absorbance of QDs, λ is the wavelength, h is the Planck constant, and c is the speed of light in vacuum. Then the emitted number of photons (N_{emit}) can be obtained according to the PLQY and light extraction efficiency (LEE) of the QD layer as:

$$N_{emit} = LEE\cdot PLQY\cdot N_{abs}. \tag{3}$$

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Therefore, the emitted light intensity from the QD layer can be calculated from following equation:

$$I_{emit} = I_{PL}(\lambda)\cdot\frac{LEE\cdot PLQY\cdot\int I_{D65}(\lambda)\cdot A_{QD}(\lambda)\cdot\frac{\lambda}{hc}d\lambda}{\int I_{PL}(\lambda)\cdot\frac{\lambda}{hc}d\lambda}. \quad (4)$$

In Eq. (4), I_{PL} is the emission spectra of QD materials.

In order to verify above calculation model with Matlab code, we also built a simulation model using commercial ray-tracing software LightTools [12]. Because of the nano-size QD, its photo-luminescence is simulated using the mean free path, which is defined as the average distance a ray travels inside the QD film before striking a QD nanoparticle [13, 14]. The value of mean free path is adjusted to let all of the blue light from micro-LEDs be absorbed. The absorption spectrum, PLQY (70%), and emission spectrum are all taken into account during simulations (Figure 2). The refractive index of QDs is set to be 1.5 at all wavelengths. Simulation process starts with the emission of ambient light source D65. When the light encountering QD particles, the ambient light is partially absorbed by the QD particles. The absorbed light will be converted to red or green light with isotropic radiation, while the unabsorbed light will continue to travel without changing its path [13].

3. Results and Discussions

3.1 Micro-LED with QD

Figure 3 depicts the calculated and simulated ambient light excitation spectra and they agree very well. These results show that the blue component of ambient light is nearly absorbed and converted to red and green counterparts. Especially for red component, the ambient excitation even exceeds 100%.

In order to further understand the ambient excitation of QDs, we plot the emitted light for RGB subpixels in Figure 4. The area ratio of each subpixel to a whole pixel is assumed to be 1/3. For the red and green subpixels, the blue component of the ambient light is absorbed and converted by the QDs through first-time and second-time excitations, and other light is reflected by the bottom micro-LEDs. While for blue subpixel, only reflection needs to be considered because there is no QD presented.

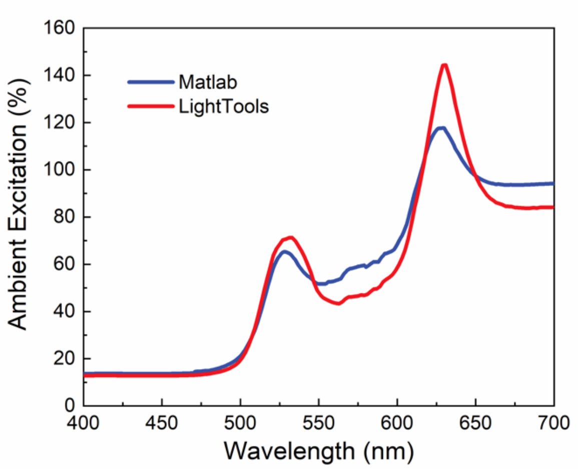

Figure 3. Calculated and simulated ambient light excitation spectra in quantum dot-converted micro-LED displays based on Matlab and LightTools.

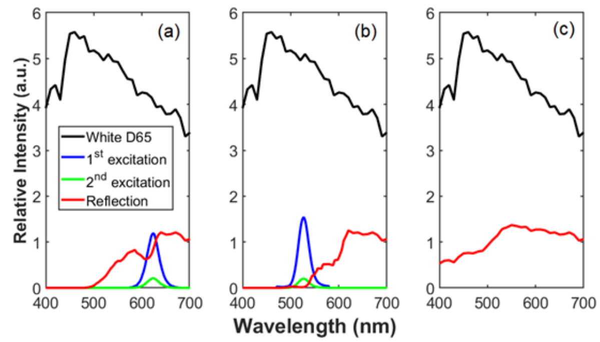

Figure 4. Calculated ambient light excitation and reflection for (a) red, (b) green and (c) blue subpixel in QD-converted full color micro-LED displays.

The luminous ambient reflectance of the device is defined as:

$$R_L = \frac{\int I_{emit}(\lambda)\cdot V(\lambda)d\lambda}{\int I_{D65}(\lambda)\cdot V(\lambda)d\lambda}, \quad (5)$$

where $V(\lambda)$ is the photopic human eye sensitivity function. The calculated and simulated luminous ambient reflectance for RGB subpixels are listed in Table 1. Due to the reflectance of micro-LED, the luminous ambient reflectance from blue subpixel is dominant.

Table 1. Luminous ambient reflectance for RGB subpixels.

Pixels	Red	Green	Blue	RGB	
				Cal.	Sim.
R_L	15.2%	17.0%	26.4%	58.6%	55.0%

3.2 Micro-LED with QD and Color Filter

In order to improve the display performance and reduce the ambient light excitation from QDs, we add a layer of pixelated color filter on top of the QD as shown in Figure 5. The transmission spectra of the color filter are taken from [7]. The calculated and simulated ambient light excitation spectra are plotted in Figure 6. Compared to the results without color filter, the ambient excitation of QDs is greatly suppressed.

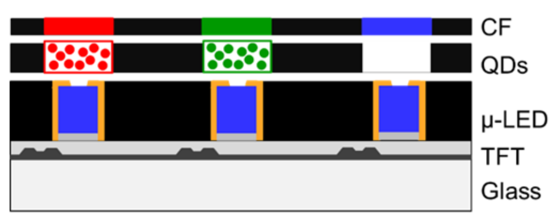

Figure 5. Schematic diagram for configuration of QD-converted micro-LED with top color filter.

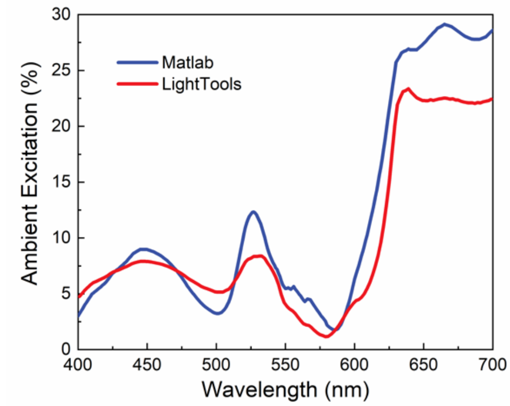

Figure 6. Calculated and simulated ambient light excitation spectra in QD-converted micro-LED displays with a top pixelated color filter based on Matlab and LightTools.

Figure 7(a) shows the calculated results for red subpixel, although the reflected red light is still strong, the first-time and second-time excitations are greatly reduced. This is because with the color filter, only red component in the ambient light can transmit through and enter the QD layer and it can hardly be absorbed according to the absorption spectra in Figure 2. While for green subpixel, because the green QDs can still absorb the green light, the first-time excitation still exists. For the blue subpixel, the blue light is simply reflected by the micro-LEDs and other light is absorbed by the color filter. Table 2 lists the luminous ambient reflectance for RGB subpixels. Compared to the results listed in Table 1, the reflectance is reduced by ~87% with color filter. Besides, the reflectance from green subpixel is dominant because of human eye sensitivity.

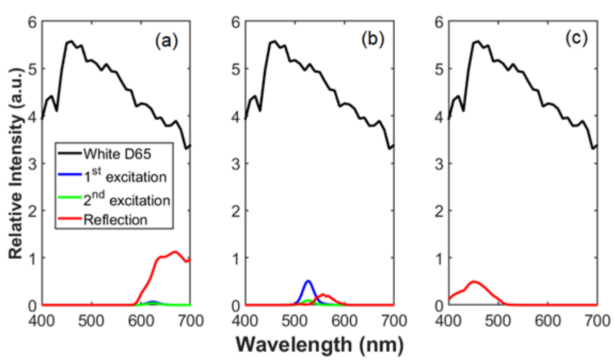

Figure 7. Calculated ambient light excitation and reflection for (a) red, (b) green and (c) blue subpixel in quantum dot-converted full color micro-LED displays with top color filter.

Table 2. Luminous ambient reflectance for RGB subpixels with top color filter.

Pixels	Red	Green	Blue	RGB	
				Cal.	Sim.
R_L	2.8%	4.4%	0.52%	7.68%	5.8%

3.3 QD Area Ratio

In the above ambient light excitation calculation, we assume the area ratio of each subpixel to one pixel is 1/3, which is not practical for real display applications because the black matrix is always needed to reduce the color crosstalk. Therefore, we need to investigate the luminous ambient reflectance as a function of the QD area ratio, which is defined as the QD area to one subpixel area. Besides, the surface reflectance of 1.5% with commercial antireflection coating is applied. Results are plotted in Figure 8. As the QD area ratio increases, the luminous ambient reflectance increases linearly. In addition, the luminous ambient reflectance is greatly suppressed with the top color filter.

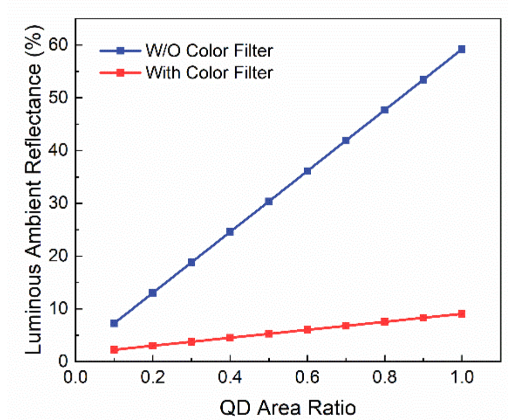

Figure 8. Calculated luminous ambient reflectance as a function of QD area ratio. The surface reflectance is 1.5%.

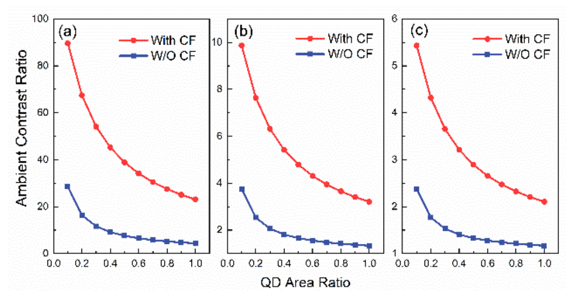

Figure 9. Calculated ambient contrast as a function of QD area ratio at ambient light of (a) 500 lux, (b) 5,000 lux and (c) 10,000 lux. The surface reflectance is 1.5%.

In order to reduce the ambient reflectance, ambient contrast ratio (ACR) is calculated using the following equation [15, 16]:

$$ACR = \frac{L_{on} + L_{ambient} \cdot R_L}{L_{off} + L_{ambient} \cdot R_L}. \qquad (6)$$

In Eq. (6), L_{on} (L_{off}) represents the on-state (off-state) luminance value of a display, $L_{ambient}$ is the ambient luminance. Figure 9 plots the calculated results at different ambient conditions: office lighting (500 lux), overcast sky (5,000 lux) and full daylight (10,000 lux) [17]. The L_{on} and L_{off} are assumed to be 1000 nits and 0 nits, respectively. The results show that the ACR decreases as the QD area increases because of increased ambient reflectance. Under the office lighting condition, the device without color filter looks great when QD area ratio is smaller than 0.3 because the ACR is larger than 10:1. As the QD area ratio increases to 0.8, the device is still adequately readable (ACR > 5:1). While with the color filter, the ACR becomes much larger than 10:1 even with QD area ratio equal to 1. Under a stronger ambient lighting condition such as overcast sky as shown in Figure 9(b), the display is barely readable without color filter (ACR ≤ 5:1). But if the QD area is reduced to 0.4, with the help of color filter, the ACR keeps larger than 5:1. However, if it is under full daylight, the QD area ratio needs to be further reduced to 0.1 in order to make the display to be adequately readable. The trade-off will be decreased optical efficiency. To address this issue, the AR coating can be optimized to reduce the surface reflectance to 0.2% so that the QD area ratio can be kept to 0.3 [18].

4. Conclusion

We have analyzed the ambient light excitation of QD-converted micro-LED displays and the calculated results agree well with the simulated ones based on LightTools. In order to improve the ambient contrast ratio, a top layer of color filter is employed to absorb the ambient light. Besides, by reducing the area ratio of QD to one subpixel to 0.1, the ambient contrast ratio can be improved to 5:1 under the full daylight, which is adequately readable.

5. Acknowledgements

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