High Ambient Contrast Ratio OLED and Quantum-dot LED without a Circular Polarizer

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Abstract

A high ambient contrast ratio display device using a transparent OLED or transparent Quantum-dot LED (QLED) with embedded multilayered structure and absorber is proposed. With the help of the multilayered structure, the device structure allows almost all ambient light to get through the display and be absorbed by the absorber. Because the reflected ambient light is greatly reduced, the ambient contrast ratio of the display system is improved significantly. Meanwhile, the multilayered structure helps lower the effective refractive index, which in turn improves the outcoupling efficiency of the display system. Potential applications for sunlight readable flexible and rollable displays are emphasized.

Author Keywords

Sunlight readability, organic light emitting device, quantum dot LED, flexible displays.

1. Introduction

Thin-film-transistor liquid crystal display (LCD) and organic light emitting diode (OLED) are now two major display technologies. LCDs have been widely used in smartphones, tablets, televisions and other display devices, with advantages of low cost, long lifetime, relatively high ambient contrast ratio (ACR), and wide color gamut with a quantum dot (QD) backlight [1]. While OLEDs exhibit advantages in true black state, vivid colors, flexibility, and fast response time [2-4]. In spite of all these advantages, sunlight readability of OLEDs is still quite limited because of the strong reflection from the metallic electrodes. In order to improve ACR, circular polarizer (CP) has been commonly used in OLED display systems to suppress ambient light reflection [5]. Although CP helps to eliminate the reflection of OLEDs (4-6%), it causes some drawbacks [6], such as 50% absorption loss of OLED output efficiency, decreased flexibility, and increased cost. That's why several other prior approaches have also been proposed to reduce the reflectance and increase the ACR of an OLED device [7], for instances, black cathode [8-10], absorbing transport layer [11-12], and black matrix [13]. However, most of these methods either fail to get low enough luminous reflectance to replace CP or result in a big sacrifice in optical efficiency. And some of these approaches need to insert additional layers to the electrical active region, which would undesirably affect OLED's electrical properties and lifetime.

In this paper, we propose a new high ACR display device, which consists of a transparent light emitting diode, for instance OLED or QLED, with embedded multilayered structure and an absorber. The transparent OLED (or QLED) is comprised of two transparent electrodes. The multilayered structure is embedded in the transparent OLED or QLED, and then an absorber is arranged to the opposite side of the multilayer. The thicknesses and materials of the multilayer can be well optimized to reach the destructive interference for the whole structure. And then, with the help of the multilayered structure, the whole device works as an anti-reflection structure and allows all ambient light to get through the display and be absorbed by the absorber, instead of being reflected by the metallic electrode. As a result, the reflected ambient light is greatly reduced, and the ACR of the display system is improved significantly. Meanwhile, the optimized multilayered structure also helps to lower the effective refractive index, which in turn distributes more energy to the substrate mode and direct emission. So the multilayered structure also improves the outcoupling efficiency of the display system. This new high contrast display device shows several advantages in comparison with prior arts: (1) quite low luminous reflectance (~1%), (2) high efficiency for direct emission and substrate mode when combined with a high index substrate, (3) no effect on the electrical properties of OLED or QLED because the structure is integrated outside of the electrical active region, (4) low color shift, and (5) thin and flexible because no CP is used.

2. Device Structure

The cross-sectional view of proposed high ACR display device is shown in Fig. 1(a). The multilayered structure, is deposited on the transparent OLED or QLED, and an absorber (e.g. carbon black) is laminated unto the multilayered structure. The material used in the multilayer can be two or more dielectric mediums with different refractive indices, for example, SiO_2 and TiO_2. And the thickness of each layer needs to be optimized in order to obtain low reflectance and to enhance the optical efficiency.

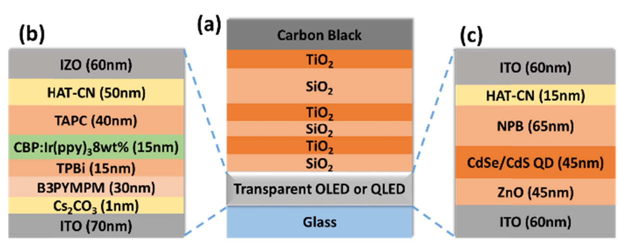

Figure 1. (a) Proposed high ACR device structure, (b) transparent OLED stack, and (c) the proposed transparent QLED stack.

Figures 1(b) and 1(c) show the structures of transparent OLED and QLED, respectively. The transparent OLED in Fig. 1(b) has been demonstrated experimentally [14]. It has an inverted structure with two transparent electrodes: ITO and IZO. The green light emitting layer material is 8 wt% $Ir(ppy)_3$ [fac-tris(2-phenylpyridine) iridium] doped CBP [4,4'-N,N'-dicarbazolebiphenyl], whose PL spectrum is shown in Fig. 2(a). Figure 1(c) shows the device structure of the proposed transparent QLED. Such structure is similar to that proposed in [15-16]. The only difference is that the top Al electrode in original structure has been replaced by ITO to make it transparent to visible light. A cadmium selenide-cadmium sulfide (core-shell) quantum dot layer is used as the emitting layer (EML). The PL spectrum of the QD emitting layer is shown in Fig. 3(a).

Here we use dipole model [17] to evaluate the outcoupling efficiency and angular dependence of the OLED and QLED structures. Our main purpose is to analyze the optical outcoupling efficiency of OLEDs and QLEDs. Without losing generality, let us assume internal quantum efficiency is unity. The simulation results of energy mode distribution of two transparent structures are shown in Figs. 2(b) and 3(b).

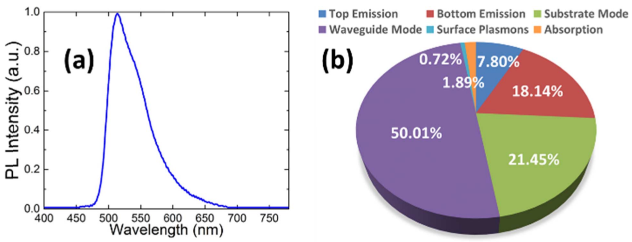

Figure 2. Transparent OLED: (a) PL spectrum of 8 wt% $Ir(ppy)_3$ doped CBP taken from [14], and (b) simulation result of amount of power coupled to different optical channels.

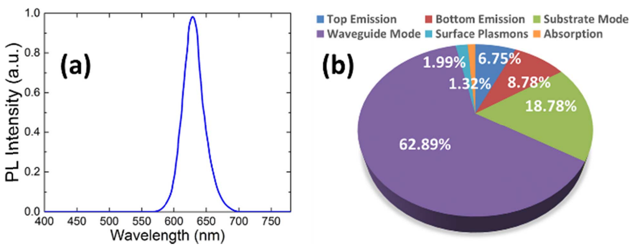

Figure 3. Transparent QLED: (a) PL spectrum of CdSe/CdS QDs taken from [16], and (b) simulation result of amount of power coupled to different optical channels.

3. Low Reflectance

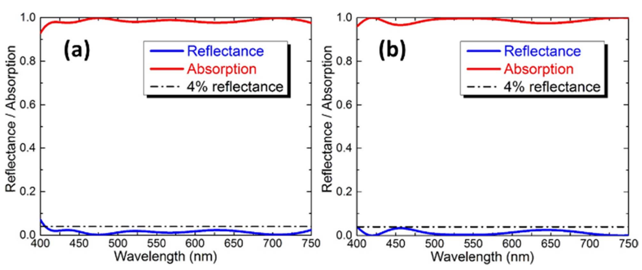

Figure 4. Simulated reflectance and absorption of the proposed high ACR device in the visible spectra region: (a) high contrast OLED and (b) high contrast QLED.

First, we optimize the multilayers of the proposed devices with glass BK7 (refractive index ~1.5) as substrate and carbon black as absorber. The optimized high contrast OLED structure is BK7/TOLED/SiO_2(5nm)/TiO_2(48nm)/SiO_2(18nm)/TiO_2(17nm)/SiO_2(152nm)/TiO_2(10nm)/Carbon Black. And similarly, after optimization, the high ambient contrast QLED structure is BK7/TQLED/SiO_2(38nm)/TiO_2(10nm)/SiO_2(63nm)/TiO_2(3nm)/SiO_2 (145nm)/TiO_2(15nm)/Carbon Black. Both structures show quite low reflectance, less than 4% reflectance over the whole visible spectrum 400nm~750nm [Fig. 4]. In our reflectance calculation, we neglect the surface reflection between the glass substrate and the air interface, by assuming a 100% transmittance surface anti-reflection coating.

We also calculate the luminous reflectance which is defined as:

$$R_L = \frac{\int_{\lambda_1}^{\lambda_2} V(\lambda)R(\lambda)S(\lambda)d\lambda}{\int_{\lambda_1}^{\lambda_2} V(\lambda)S(\lambda)d\lambda} \quad (1)$$

where V(λ) is the spectral eye sensitivity, R(λ) is the reflectance of the device, and S(λ) is the spectrum of ambient light. The calculated luminous reflectance, 1.52% for high contrast OLED and 0.85% for high contrast QLED, are both low enough to displace circular polarizer. But at the same time, the efficiency should also be considered. For the proposed OLED, the direct emission is 9.70% and substrate mode is 18.42%, while for QLED the direct emission is 7.29% and substrate mode is 13.71%. Considering more than 50% loss of circular polarizer, our high contrast OLED and QLED can reach about the same efficiency as conventional OLED and QLED but with greater flexibility.

4. Efficiency Enhancement

Please note that in the optimized multilayer, the total thickness of low refractive index material SiO_2 is much larger than that of high refractive index material TiO_2. So, the effective refractive index of entire structure would be reduced by adopting the multilayer. The lower effective refractive index helps distribute more energy to the substrate mode and direct emission, if we use a high refractive index substrate.

Next, we explore how a high refractive index (n_s) substrate enhances the outcoupling of both direct emission and substrate mode. With outcoupling structures such as micro extractors, most of the substrate mode can be extracted. We increase substrate refractive index and optimize the multilayers for each n_s and then calculate the reflectance and efficiency. Figure 5 shows the fraction of power for both direct emission and substrate mode under different n_s, while keeping the luminous reflectance as low as about 1%. As Fig. 5 shows, efficiency increases and then gradually saturates as n_s increases. The combined efficiency of direct emission and substrate mode can get over 70%, which conventional CP-based OLED and QLED cannot reach because more than 50% of the emitted light is absorbed by the employed circular polarizer.

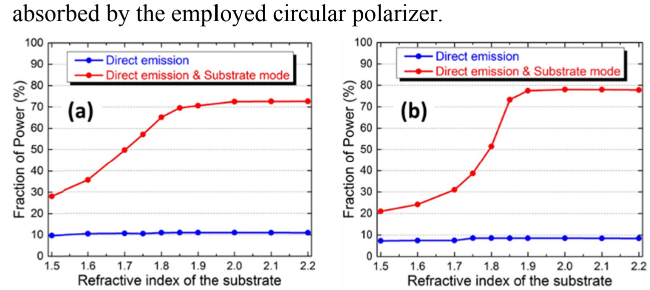

Figure 5. Optical efficiency of high contrast devices with different refractive index (n_s) of substrate: (a) high contrast OLED and (b) high contrast QLED.

From Figure 5, the efficiency starts to saturate when $n_s \geq 1.85$. Considering the high cost of high index glass, the optimal refractive index of substrate should be around 1.85. So, we choose n_s = 1.85 to investigate the angular dependence of the proposed structure. When n_s = 1.85, the luminous reflectance remains quite low, 1.13% for OLED and 0.77% for QLED.

5. Angular Dependence

As analyzed above, the reflectance keeps quite low for normally incident ambient light. But large angle incident light should be analyzed as well. Figure 6 shows the luminous reflectance for light with different incident angle in the substrate. We know that the angle inside the substrate is correlated to the angle in the air by Snell's law. For a flat surface, by simple calculation, the ambient light incident from the air will be confined within 0~32.7° in the substrate. From Fig. 6, we can see that in this angular range, the luminous reflectance still keeps less than 4%. So the proposed structures can maintain low reflectance for large angle incident light from the air.

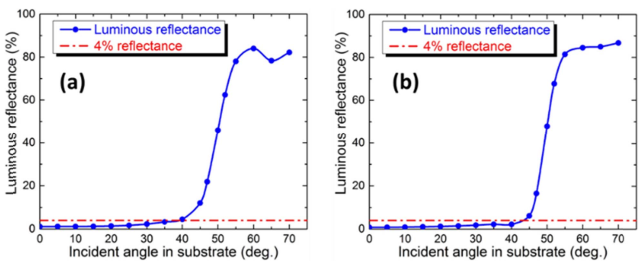

Figure 6. Luminous reflectance for ambient light with different incident angle in the substrate: (a) high contrast OLED and (b) high contrast QLED.

The color performance of a microcavity structure could vary strongly depending on the viewing angle. Here, we evaluate the color shift of our devices and results are plotted in Fig. 7. From Fig. 7, the color shift Δμ'v' is less than 0.002, which is much smaller than that of commercial OLED products. An important reason that our proposed structure shows negligible angular dependency is due to its weak cavity effect, in comparison with conventional OLED and QLED.

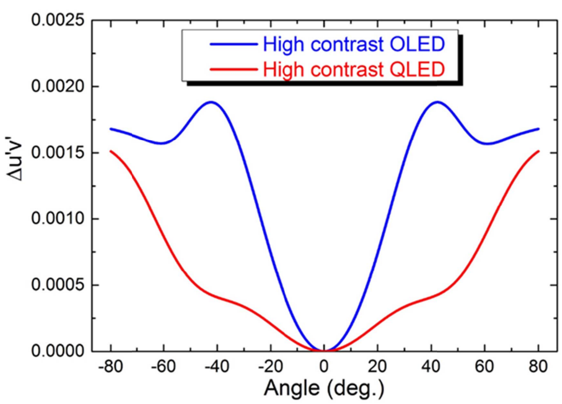

Figure 7. Calculated color shift of the proposed high contrast OLED and high contrast QLED.

6. Adoption of Microstructures

As mentioned before, after employing the high index substrate, we still need microstructure to extract the enhanced substrate mode energy. In this section, we investigate the effects of adoption of microstructure on out-coupling efficiency and reflectance in detail. We just use OLED as an example to analyze the effects of microstructure. The simulation of OLEDs with microstructure as external extractor can be token in two steps: 1) emission into the substrate and 2) light propagation in the substrate [18]. The emission in the substrate can be calculated with dipole model, as clearly stated above. The propagation of light in the substrate need to be simulated by ray tracing model because its thickness is in the order of millimeter and optical interference effects play no role. We use commercial ray tracing programs LightTools to accomplish the light propagation modelling. We tried two simple microstructures, micro lens and micro pyramid array, as examples to investigate the effects of microstructure. The geometrical representation of the whole structure has been shown in Fig. 8.

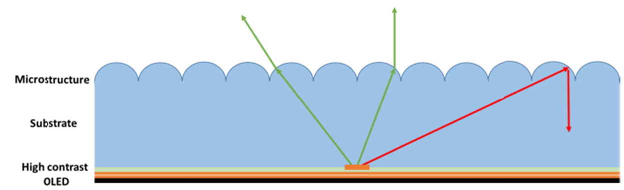

Figure 8. Geometrical representation of high contrast OLED with microstructure as out-coupling extractor.

We simulated the efficiency enhancement of OLED with micro lens and micro pyramid array and the results are listed in Table.1. The micro lenses are implemented as hemispherical caps whose radius and height both equal 0.5mm. The micro pyramid array consists of four sided pyramids with a square base measuring 1×1mm^2 and 45° slope. For both structures, the distance between two neighboring elements is 1mm.

Table 1. Efficiency enhancement with microstructures

Device Structure	EQE by Dipole Model	Enhancement ratio by LightTools	Simulated EQE
Reference	11.02%	--	11.02%
Micro lens	--	2.57	28.23%
Micro pyramid	--	1.99	21.88%
Hemisphere lens	69.60%*	6.32	69.69%

* This value is the summation of the power dissipations to air mode and substrate mode under the assumption that both modes can be extracted by the hemi-spherical lens.

From the simulated data, the micro lenses and micro pyramid can both enhance the out-coupling efficiency as expected. And we need to notice that the efficiency will earn extra ×2 enhancement, considering more than 50% loss of circular polarizer. At the same time, the employment of microstructure would also change the reflectance of the whole structure. The luminous reflectance of the whole structure has been calculated. The results are shown in Fig. 9.

We use the structure with planer surface and AR coating as reference. From the calculated luminous reflectance, the structures with both microstructures can still maintain quite low reflectance (<4%) for small angle incident light (<30°). For incident light with large angle, although the total reflectance increases, the reflected lights have wider angular distribution according to our simulation. That's the scattering caused by microstructures. The scattering can help to reduce the strong mirror reflection, just as anti-glare film does. The micro pyramid array shows lower reflectance than micro lens array, but less efficiency enhancement. The tradeoff between the low reflectance and high efficiency rises again. The microstructure can be further optimized.

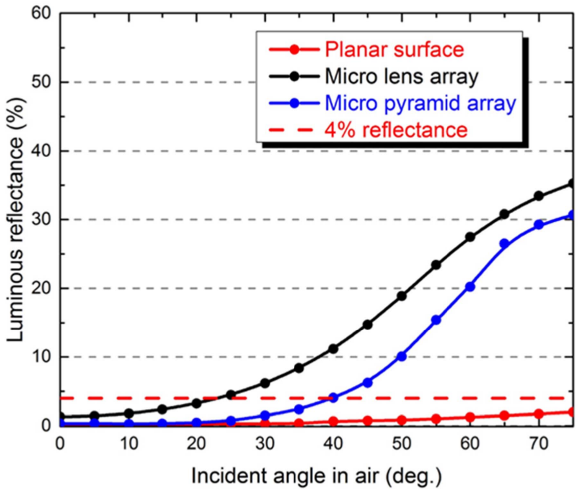

Figure 9. Luminous reflectance of high contrast OLED with microstructures for ambient light with different incident angle in air.

7. Conclusion

High ambient contrast ratio OLED and QLED are proposed. Both devices show quite low luminous reflectance (~1%), high efficiency, and negligible color shift. Our devices do not need a circular polarizer, and therefore it opens a new door for flexible and rollable display applications.

8. Acknowledgments

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9. References

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