Optimization of Capping Layer Thickness in OLED Panel for Film Color Filter Application

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Abstract

In this study, we conducted experiments to investigate the effects of varying thicknesses of capping layer (CPL) on OLED cathode with the aim of reducing power consumption by lowering reflectance and improving white efficiency. The optimal CPL thickness for improving white efficiency is found to be 40 nm, balancing both reflectance reduction and white efficiency improvement.

Author Keywords

Capping Layer (CPL); Reflection; Efficiency; Film Color Filter

1. Introduction

The OLED market has been experiencing rapid growth as its application scope expands and demand increases [1]. To further expand this market, reducing power consumption by enhancing panel luminous efficiency is crucial. The overall efficiency of an OLED panel comprises both internal luminous efficiency, which refers to the light generation within the device, and external luminous efficiency, which pertains to the light emitted outside the panel. External luminous efficiency measures how effectively light generated within the OLED device passes through the cathode and exits the panel. Various strategies have been proposed to improve this efficiency, including the use of micro-lens arrays in the optical path after light passes through the cathode [2,3].

In addition to improving luminous efficiency, OLED panels must maintain a high contrast ratio despite exposure to external light sources [4]. However, front lighting using the micro-resonance effect can reduce the contrast ratio due to the high reflectivity of the cathode and anode metal electrodes. To mitigate this issue, attaching a polarizer on top of the panel can reduce internal reflections caused by the metal electrodes, thereby enhancing the contrast ratio. However, since a polarizer maintains transmittance below 50% in the visible spectrum, it significantly reduces the amount of light passing through the panel's encapsulation glass, leading to lower luminous efficiency and increased power consumption.

To address this limitation, one approach is to increase the transmittance of the polarizer to over 50% in the red, green, and blue emission wavelength regions of the visible spectrum, thereby improving luminous efficiency. Additionally, applying a film color filter can reduce transmittance in other regions to minimize power consumption. The outgoing optical path and transmittance spectra of the polarizer and film color filter in a top-emission OLED panel are illustrated in Figure 1.

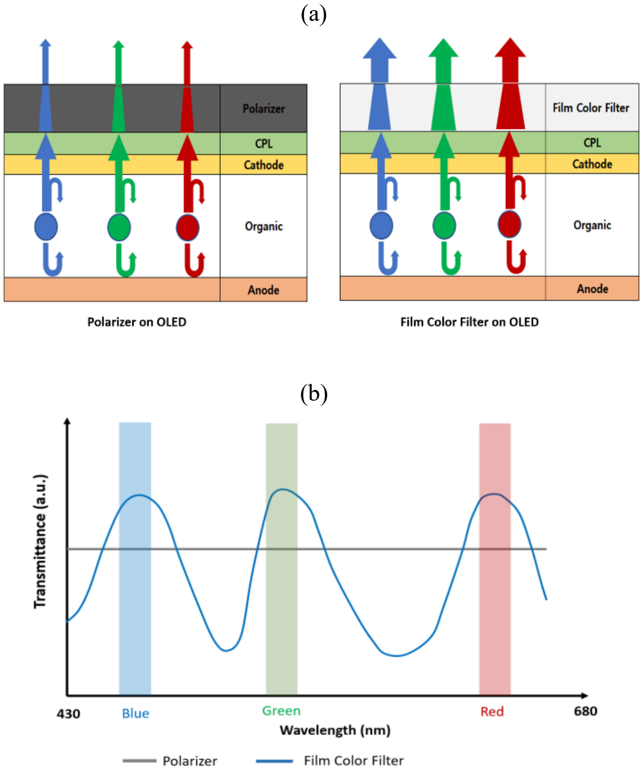

Fig. 1 (a) Light exit path for the polarizer and film color filter (b) transmittance spectrum of the polarizer and film color filter

The polarizer has the disadvantage of low transmittance. However, when an external light source with a random polarization direction passes through the polarizer, it becomes linearly polarized due to the polarization phenomenon. This linearly polarized light then passes through a retarder beneath the polarizer, converting into circularly polarized light before entering the OLED panel. Upon reflection from the metal electrode within the OLED panel, the circularly polarized light undergoes a 180-degree phase shift. When this reflected light exits the OLED panel and reaches the polarizer again, its linear polarization direction is rotated by 180 degrees, thereby extinguishing most of the reflected light and reducing external reflections.

However, applying a film color filter increases panel reflectance due to the interaction between the OLED RGB emitting regions in the visible spectrum and the transmittance in non-emission wavelength regions [5]. In this paper, we investigate the impact of varying the thickness of the capping layer (CPL) formed on the cathode electrode on panel specular component included (SCI) reflectance, specular component excluded (SCE) color coordinates, and white efficiency.

2. Experimental Design

2.1 Fabrication Process

The panel manufacturing process can be broadly categorized into three stages: backplane formation on the lower glass substrate, OLED device fabrication and encapsulation, and the film attachment stage. The backplane fabrication involves the creation of a thin-film transistor (TFT), an anode electrode, and a pixel definition layer (PDL). Subsequently, the RGB light-emitting section is formed through organic material deposition, followed by the deposition of a cathode electrode and a CPL layer. The panel is then completed through the encapsulation process. Finally, a film color filter may be attached to finalize the manufacturing sequence, as illustrated in Figure 2. Film color filters employ various dyes for their absorption peak wavelengths. These absorption wavelengths are located outside the R, G, and B emission regions, and their transmittance is set lower than that of the emission regions.

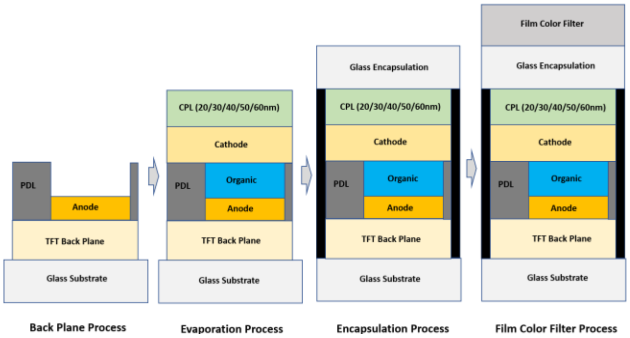

Fig. 2 Process Flowchart of an OLED Panel with an Attached Film Color Filter (Backplane, Evaporation, Encapsulation, and Film Color Filter Process)

2.2. Computer Simulation

A computer simulation was conducted to evaluate whether adjusting the CPL thickness could reduce panel reflectance. The simulation considered both the emitting and non-emitting regions of the R, G, and B pixels, which significantly influence panel reflection. For the emitting region, the structure consisted of a stack comprising CPL, cathode, electron transport layer (ETL), emissive layer (EML), hole transport layer (HTL), and anode. For the non-emitting region, the structure included CPL, cathode, ETL, HTL, and the pixel definition layer (PDL). The simulation setup is illustrated in Figure 3. The inputs to the simulation included the refractive index, extinction coefficient, and thickness of each layer within the panel stack. A D65 light source was used to illuminate the panel from above the CPL. The CPL thickness was adjusted to 60 nm, 40 nm, and 20 nm to examine its effect on reflectance.

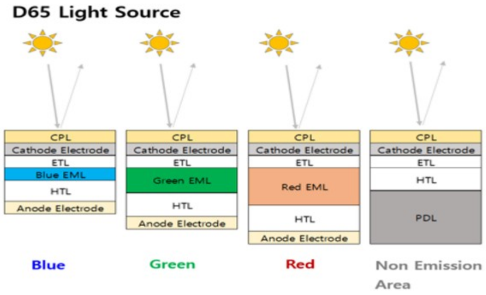

Fig. 3 Stack-up Structure for Simulation of OLED Subpixels (B, G, R Emitting and Non-Emitting Areas)

The simulation results indicated a significant reduction in reflectance within the 480 nm to 580 nm wavelength range for the non-emitting area when the CPL thickness was set to 40 nm. This decrease is expected, as this wavelength range has a substantial impact on overall panel reflectance.

For the RGB emitting regions, reflection occurs not only at the cathode semi-transparent electrode but also at the anode metal electrode. As a result, variations in CPL thickness have a smaller effect compared to the non-emitting area. However, with a CPL thickness of 40 nm, a notable reduction in reflectance was observed across the wavelength range of 430 nm to 630 nm for R, G, and B emissions. This effect is illustrated in Figure 4.

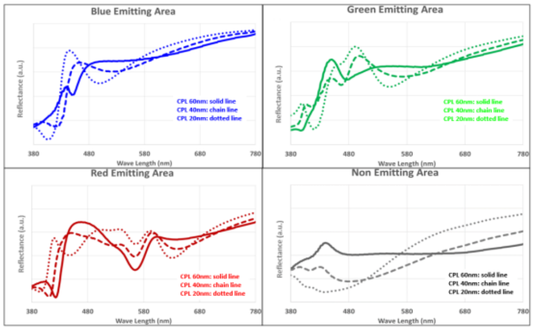

Fig. 4 Simulation Result of Reflectance Spectra of R, G, B Emitting and Non-Emitting Area

To evaluate the impact of varying CPL thickness on reducing reflectance in non-emissive areas, we simulated reflectance by multiplying the reflection spectrum with the luminous efficiency function. As shown in Figure 5, the lowest reflectance was observed at a CPL thickness of 40 nm, suggesting that adjusting the CPL thickness can effectively reduce internal panel reflectance.

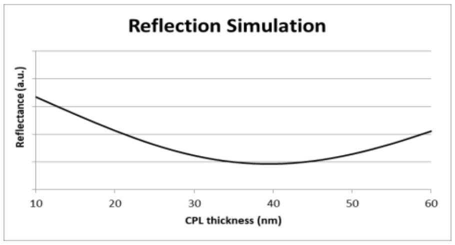

Fig. 5 Reflection Simulation Results of Non-Emitting Areas According to CPL Thickness

3. Result & Discussion

3.1 SCI Reflectance

A rigid OLED panel with varying CPL thicknesses was fabricated, and a film color filter was attached instead of a polarizer. SCI reflectance was measured using a spectrophotometer. As shown in Figure 6, the measured SCI reflectance closely aligns with the simulation results. At a CPL thickness of 30 nm, the minimum reflectance was 5.9%, which is 19% lower than the 7.3% reflectance observed at a CPL thickness of 60 nm. For a CPL thickness of 40 nm, the reflectance was 6.1%, representing a 16% reduction compared to that of 60 nm. The SCI reflectance increased again at a CPL thickness of 20 nm, consistent with the simulation results. This trend occurs because variations in CPL thickness alter the phase difference between reflected light waves, significantly reducing the reflectance of non-emitting regions at a wavelength of 550 nm, which has a substantial impact on the SCI reflection spectrum.

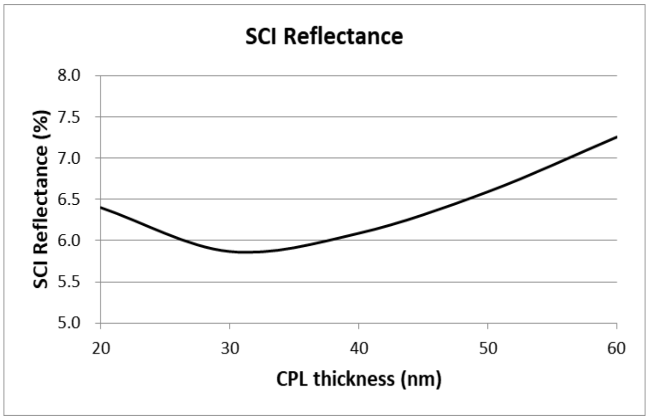

Fig. 6 SCI Reflectance Measurement Results of the OLED Panel According to CPL Thickness

3.2 SCE Color Coordinates

Figure 7 illustrates the SCE color coordinates as a function of CPL thickness. In this context, the +a* direction represents a pinkish hue, while the -a* direction corresponds to a greenish hue. Similarly, the +b* direction indicates a yellowish hue, whereas the -b* direction signifies a bluish hue. As the values approach zero, the reflected color becomes less noticeable.

For a 60 nm CPL with a film color filter, the b* value is negative, indicating higher reflectance at shorter wavelengths near 450 nm. This suggests that as CPL thickness decreases, the b* value increases, meaning reflectance in the 450 nm region continues to decline. Additionally, the a* value also increases due to reduced reflectance at longer wavelengths around 620 nm and relatively higher reflectance near 530 nm. Consequently, as CPL thickness decreases, a* shifts further from zero, while b* moves closer to it.

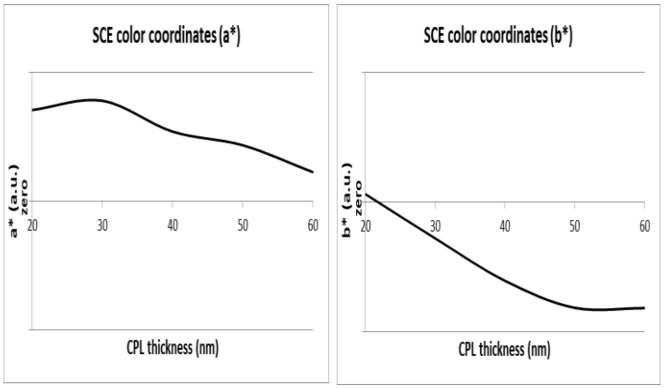

Fig. 7 Measurement Results of SCE Color Coordinates a* and b* According to CPL Thickness

3.3 White Efficiency

A film color filter was attached to the OLED panel, and white efficiency was measured. Initially, Colorimeter was used to measure panel brightness and color coordinates. The current required to achieve target brightness and color coordinates was adjusted through a dedicated driving algorithm. For measuring efficiency, the panel luminance was set about 400nit of white with x and y color coordinates at 0.305 and 0.320, respectively, based on a color temperature of 7,000K. With a fixed voltage supply to the panel, panel efficiency could be calculated through current changes. To confirm efficiency improvements, the white efficiency for a CPL thickness of 60 nm with a polarizer attached was set at 1.0, and the change in efficiency was measured by attaching a film color filter and reducing the CPL thickness. As shown in Figure 8, the white efficiency is approximately 10% higher than that of the polarizer at 60 nm, about 12% higher at 40 nm, and around 18% higher at 50 nm; however, it matches the polarizer's efficiency at 30 nm and decreases below this level for 20 nm. Therefore, from an efficiency improvement perspective, a CPL thickness of 40 nm or more is required. Considering reflectance and reflection color coordinates together, applying a CPL thickness of 40 nm is optimal.

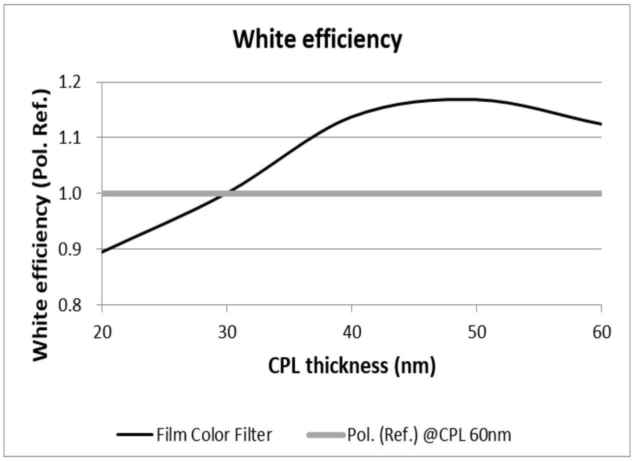

Fig. 8 White Efficiency Measurement Results According to CPL Thickness with Film Color Filter Applied (Reference Polarizer White Efficiency Based on CPL Thickness of 60nm)

Figure 9 illustrates the changes in white efficiency for red, green, and blue as CPL thickness varies. For red and green, efficiency decreases as CPL thickness decreases. However, for blue, efficiency increases until the CPL thickness reaches 40 nm, after which it sharply declines. Since OLED devices have inherently low luminous efficiency in the blue spectrum, its contribution to overall white efficiency is significantly high. Therefore, optimizing the transmittance of the film color filter for blue wavelengths while maintaining appropriate reflectance and reflection color coordinates can maximize white efficiency.

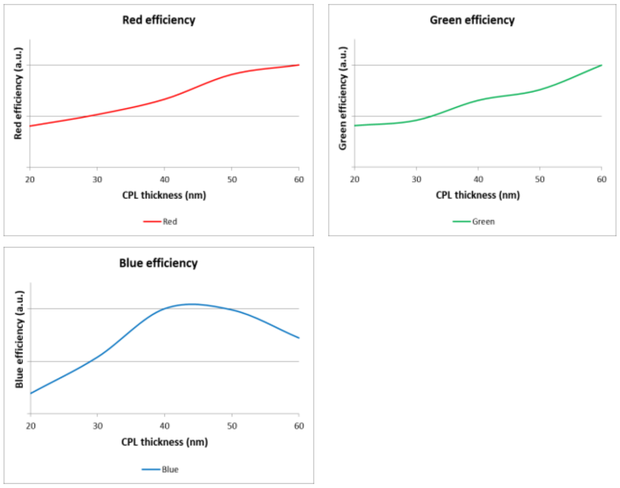

Fig. 9 Red, Green, Blue Subpixel Efficiency According to CPL Thickness

4. Conclusion

Our experimental findings demonstrate that reducing the thickness of the CPL from 60 nm to 40 nm in OLED panels significantly reduces SCI reflectance by 16% and improves SCE color coordinates. The b* value increased, indicating a decrease in short-wavelength (blue) reflectance and an increase in long-wavelength (green) reflectance.

The white efficiency of the OLED panels also showed notable improvements when the CPL thickness was reduced to 40 nm, with an approximate 12% increase compared to the original 60 nm thickness.

However, further reduction below 20 nm led to a decrease in white efficiency. For individual colors (R, G, B), red and green efficiencies decreased as the CPL thickness was reduced, while blue efficiency increased until 40 nm and then began to decrease.

These results suggest that a CPL thickness of 40 nm is optimal for achieving both lower reflectance and improved white efficiency in OLED panels with film color filters. This finding has significant implications for reducing power consumption in OLED displays without compromising on visual quality, which could lead to more energy-efficient and cost-effective OLED devices.

5. References

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