Reality vs. Simulation in Black Matrixless Solution of Color Filter on Encapsulation Technology

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Abstract

We develop a black matrix less OLED using a color filter overlap method, which boasts excellent optical performance. Through extensive optical simulations, we identify the optimal overlap method. Actual samples have been used to refine the simulation model and determine the minimal thickness of the upper color filter. The synergy between reality and simulation plays a crucial role in the design of the product.

Keywords

COE; BM less; color filter overlap, reflectivity; hue

1. Introduction

Conventional OLED (Organic Light-Emitting Diode) displays reduce reflectivity by using circular polarizers, which will result in more than 55% loss in brightness. To achieve lower power consumption, Mitsuhiro K. et al.[1-3] proposed that color filters can reduce micro cavity reflectivity and increase light transmission efficiency of the device, thereby realizing OLED displays with low power consumption, high brightness, and wide color gamut. In recent years, various types of COE (Color Filter On Encapsulation) OLED displays have gradually entered mass production.

The conventional structure of COE, from top to bottom, consists of RGB OLED emitting devices, thin-film encapsulation (TFE), touch layers, and RGB low-temperature color filter patterns. Fabricating the COE functional layers requires five masks: BM (Black Matrix), R color filter, G color filter, B color filter, and OC (overcoat) which is the planarization layer. A new scheme is now proposed to reduce the BM mask. As two or three different color filters can overlap to reduce transmittance, it can be used to replace BM. Besides reducing one mask, this method can also simplify the process flow, improve production efficiency, and simultaneously enhance yield and reduce costs.

Now, we introduce a BM less scheme in COE technology, where two or three overlapped color filters serve the role of BM. This structure is designed to reduce reflectivity of metal traces in touch layers as well as the cathode layer. Given that there are multiple ways to achieve color filter overlap, we need to conduct simulations to select the optimal solution: the method of overlap and the thickness limitations of different color filters.

2. Simulation principles and background

First, we introduce the structure used in the simulation. Figure 1 shows the cross-sectional structure of a normal COE display [4]. Figure 2 presents the cross-sectional structure and corresponding reflectivity zones of COE technology with BM less scheme. In this scheme, overlapped color filters are used to replace BM, simplifying the structure and improving performance. The stack-up, from bottom to top, includes:

- TFT (Thin-Film Transistor) backplane
- RGB OLED light-emitting devices (with pixel definition layers made of BPDL material)
- Thin-film encapsulation (TFE) layers
- Touch layers
- CF (Color Filter) array layers
- Module materials

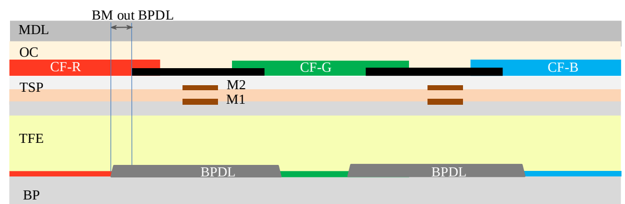

Figure 1. COE Cross-Sectional Structure

This novel COE structure consists of four layers: RGB color filters and an OC planarization layer. Obviously the total number of layers of COE is reduced from five to four in BM less scheme. To improve viewing angle performance and reduce brightness degradation, the design typically features that BM aperture should be larger than BPDL aperture. This ensures better light management and visual quality from different angles.

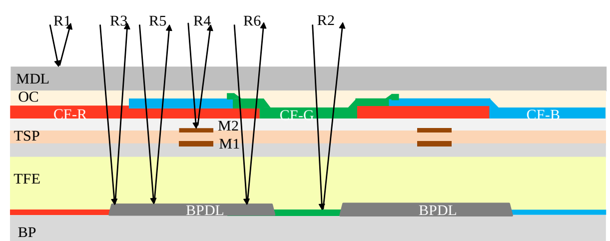

Figure 2. Cross-Sectional Structure and Reflectivity Zones of BM Less Scheme

Reflectivity in a BM Less COE display comes from two main sources: surface reflectivity (R1 in figure 2) which is from the surface of module materials and internal reflectivity which includes several components:

- Reflectivity from Pixel Opening Area (R2): it occurs in the pixel opening area and is calculated as the micro cavity reflectivity multiplied by the square of the color filter transmittance.
- Reflectivity from BM out PDL Area (R3): it is from BM aperture area where PDL exists.
- Reflectivity from Color Filter Overlap Area (R4 and R5/R6): it comes from touch metal traces and cathode. Specifically:
  - R4: Reflectivity from touch metal traces. This is minimized by the overlapped color filters.

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- R5: Reflectivity from cathode. This is also reduced by the overlapped color filters R and B.
- R6: Additional reflectivity from the cathode, is similarly managed by the overlapped color filters R and G.

Figure 2 is a schematic diagram of one representative color filter overlap. The above content has described the principles of reflectivity simulation, and we will provide more specific simulation design information below:

- PDL aperture ratio is 18.27%, with an R:G:B ratio of 1:1.7:1.4.
- BM out value is 4μm.
- The BM less area uses color filter overlap, including two-color filter overlap and three-color filter overlap.

3. Reality versus simulations

3.1 Initial Simulation

Reflectivity is an important performance indicator for COE products. The sources of reflectivity are shown in Figure 2. In BM less scheme of COE technology, the role of color filter overlap is to reduce the reflection from the touch layer metal traces and the cathode above BPDL. In the BM less scheme, the color filter overlap can be either two-layers or three-layers. The color filter thickness in normal COE is typically designed to be 3μm. Due to lack of actual output at the beginning, the thickness of the first color filter is designed to be 3μm and the thickness of the upper color filter in the overlapping area during the design phase is an estimated value ranging from 1μm to 3μm as is shown in Figure 3.

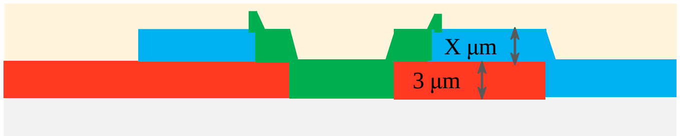

Figure 3. Diagram of Two-Color Filter Overlap

3.1.1 Simulation Conditions and Results of Two-Color Filter Overlap

When using two-color filter overlap, we generally name the overlap type based on the larger component of the upper color filter. We will take Figure 3 as an example, as the lower layer is R color filter with thickness of 3um and B takes a larger part in the upper layer, the structure is named as R3+BX where X represents the thickness of B color filter. We have simulated all conditions and compared them to find the optimal experimental conditions.

Considering the arrangement of the color filter overlaps and the thickness range of upper color filter, there are 18 combinations for two-color filter overlaps as is listed in Table 1.

Table 1. Simulation Conditions for Two-CF Overlap

Conditions	*The first CF*		*The upper CF*			
	Material	*Thickness(μm)*	*material*	*Thickness (μm)*		
R3+GX	R CF	3	G CF	1	2	3
R3+BX	R CF	3	B CF	1	2	3
G3+RX	G CF	3	R CF	1	2	3
G3+BX	G CF	3	B CF	1	2	3
B3+RX	B CF	3	R CF	1	2	3
B3+GX	B CF	3	G CF	1	2	3

Through comparative analysis, it is clear that the optimal condition is R3+BX, which has the lowest and most stable reflectivity. As shown in Figure 4, the numbers 1, 2, and 3 in the bar chart represent the thickness of the upper color filter. For the solution of R3+BX, the thickness variation of the upper color filter has almost no impact on reflectivity, while other schemes do not offer such good stability.

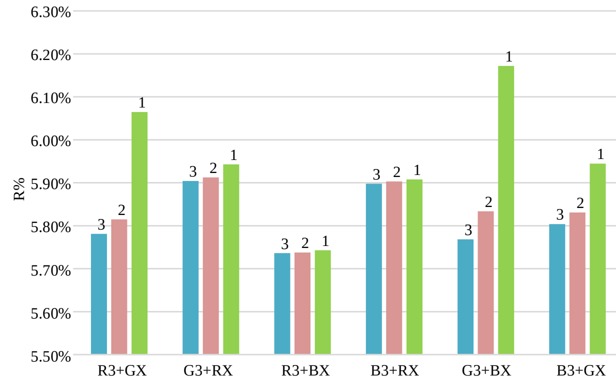

Figure 4. Conditions of Two-Color Filter Overlap and the Impact of Upper Color Filter Thickness on Reflectivity

The closer the hue at 1 μm film thickness is to the hue at 3 μm, the smaller the hue difference is caused by film thickness variation. We use Δa*b* ($\Delta a*b* = \sqrt{(\Delta a*)^2 + (\Delta b*)^2}$) to represent this difference, and obviously a smaller Δa*b* is better. From Figure 5 we can see that the optimal condition is also R3+BX which has the smallest Δa*b* of 0.12. The thickness variation of the upper color filter has the least impact on hue, providing a sufficiently large margin for manufacturing process.

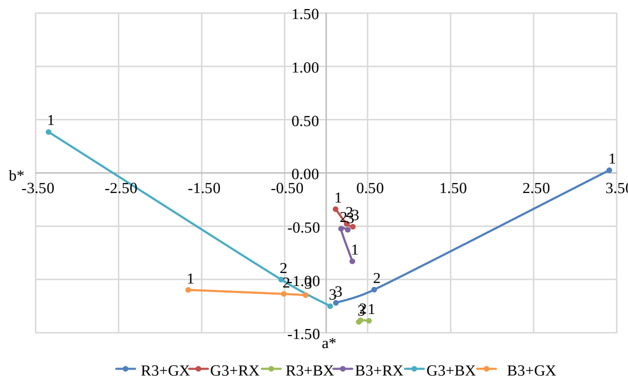

Figure 5. Conditions of Two-Color Filter Overlap and the Impact of Upper Color Filter Thickness on hue

3.1.2 Conditions and Simulation Results of Three-Color Filter Overlap

Table 2. Simulation Conditions for Three-CF Overlap

Conditions	*The first CF*		*The second CF+The third CF*	
	Material	*Thickness (μm)*	*Material*	*Thickness (μm)*
R3+GX+BX	R CF	3	G CF+B CF	1/2/3
R3+BX+GX	R CF	3	B CF+G CF	1/2/3
G3+RX+BX	G CF	3	R CF+B CF	1/2/3
G3+BX+RX	G CF	3	B CF+R CF	1/2/3
B3+RX+GX	B CF	3	R CF+G CF	1/2/3
B3+GX+RX	B CF	3	G CF+R CF	1/2/3

Considering the arrangement of the color filter overlaps and the thickness range of upper color filters, there are 18 combinations of three-color filter overlaps. Table 2 shows all conditions and simulation results:

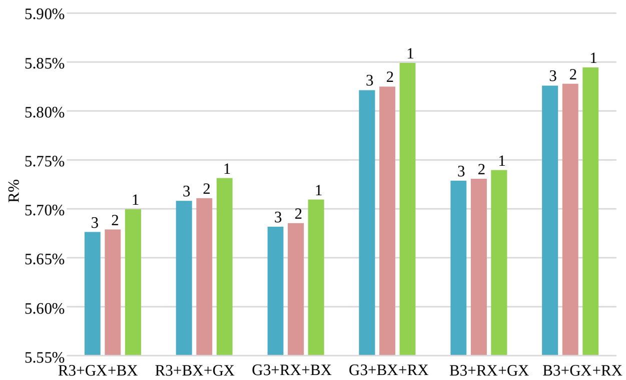

Figure 6. Conditions of Three-Color Filter Overlap and the Impact of Upper Color Filter Thickness on Reflectivity

By analyzing the simulation results, the scheme with the lowest reflectivity is R3+GX+BX, with a corresponding Δa*b* of 0.28, and the scheme with the smallest Δ a*b* 0.13 is B3+RX+GX, however, the corresponding reflectivity is 5.77%. Figures 6 and 7 show the impact of upper color filter thickness variations on reflectivity and hue, respectively.

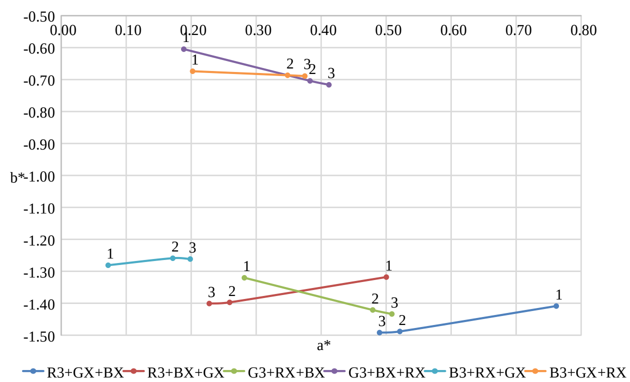

Figure 7. Conditions of Three-Color Filter Overlap and the Impact of Upper Color Filter Thickness on Hue

3.1.3 Comparison of Simulation Results and Selection of Optimal Conditions

Firstly, as shown in the simulation results, the best reflectivity solution for two-color filter overlap is R3+BX, with a corresponding reflectivity of 5.74%. For three-color filter overlap, the best reflectivity solution was R3+GX+BX. However, the reflectivity of R3+GX+BX is only 0.01% lower than that of R3+BX. Secondly, the simulated hues of R3+GX+BX and R3+BX are similar. They could be adjusted by changing the color filter thickness, so it is not a critical criterion for judgment. Thirdly, the Δa*b* of R3+BX is the smallest, which is better than R3+GX+BX.

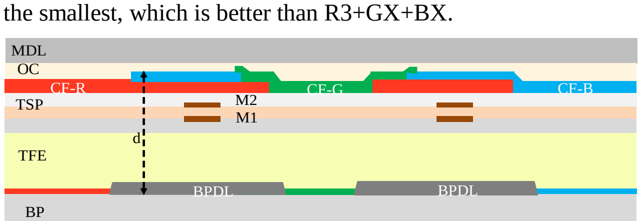

Figure 8. The d Value affecting Bright-state Optics

An increase in the d value leads to a great decay in viewing angle brightness, as shown in Figure 8. The overlap of three color filters increases the d value and leads to a loss in bright-state optical performance. Additionally, three-color filter overlap will also increase process complexity. Simultaneously, from a theoretical perspective, as shown in Figure 9, the transmittance of R3+BX is sufficiently low, and its match with the color matching function spectrum is poor. Additionally, the interface reflectance between B color filter and OC is the lowest among all three color filters. To sum up, the reflectance of R3+BX is low, and its impact on hue is minimal. Therefore, the best solution is the two-color filter overlap R3+BX.

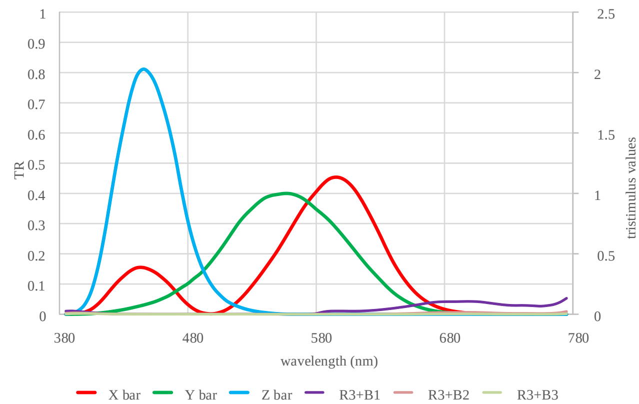

Figure 9. Transmittance of R3+BX and Tristimulus Values

In addition to the BM less scheme simulation, we have also conducted a simulation for normal COE. The corresponding reflectivity and hue for normal COE are 5.9% and (-0.13, -1.3).

3.2 Experimental results

We have successfully developed actual samples of BM less. Table 3 shows the measured reflectivity and hue results for BM less (R3+BX) and normal COE products. From the data, it can be concluded that the reflectivity of BM less products is better than that of normal COE products.

Table 3. The Reflectivity and Hue Results for BM Less and Normal COE

	Normal COE	**BM Less**
R%	5.87%	5.71%
*a**	0.8	1.18
*b**	-1.88	-2.21

Another key off-state optical characteristic of COE products is color breakup. The diffraction photos taken under point light sources for BM less and normal COE products are shown in Figure 10. The diffraction levels were comparable, indicating that BM less scheme does not degrade diffraction performance. The a* value of BM less (1.18) is more positive than that of Normal COE (0.8), and the reddish visual feeling is due to the shift of a*, which can be optimized through hue adjustment.

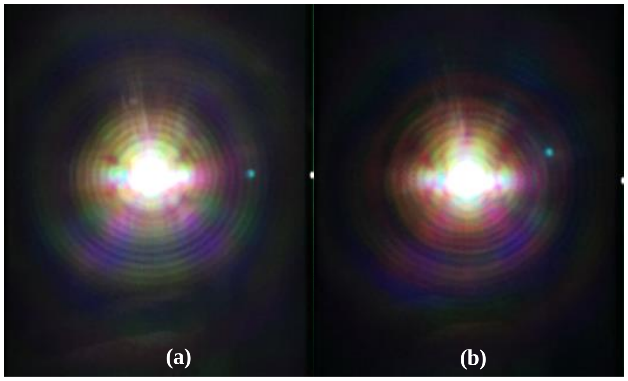

Figure 10. Diffraction Photos of Point Light Source
(a) Normal COE (b) BM Less

From the analysis of above two off-state optical characteristics, we can see that BM Less scheme is feasible and can be further studied and summarized.

3.3 Second Fine Simulation after Data Regression

After the actual samples were produced, the real model could be obtained through FIB images. In BM less scheme, the thickness of the lower R color filter is uniform, while the thickness of the upper G or B color filter gradually increases from the center of aperture area to edge. As shown in Figure 11, d2>d1 and d4>d3. The thickness of the upper color filter in the overlap area is non-uniform. According to the measured film thickness data, the thickness of the upper color filter ranges from 0.7μm to 1.3μm. Figure 11 shows the FIB image of the G/B color filters in BM less scheme.

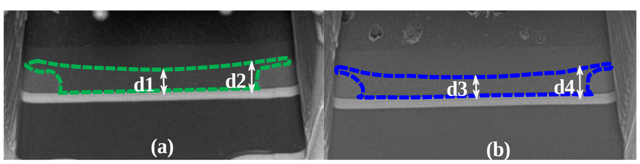

Figure 11. FIB Image of CF Thickness in BM Less
(a) G CF (b) B CF

We have input the measured values of color filter thickness into the simulation model to accurately reconstruct the model. Through second fine simulation, we have determined the final thickness of upper color filter in the BM less area. We assumed that the thickness of the upper B color filter in the BM less area is 1.0μm, and the thickness of the overlapping G color filter range from 0.8μm to 1.3μm. The detailed simulation results are shown in Table 4.

Table 4. Reflectivity and Hue for Different G CF Thicknesses

	Thickness of G CF					
	0.8	0.9	1	1.1	1.2	1.3
R%	5.68%	5.67%	5.67%	5.66%	5.66%	5.66%
*a**	0.70	0.63	0.57	0.52	0.48	0.44
*b**	-2.46	-2.49	-2.51	-2.53	-2.54	-2.56

We have also assumed that the thickness of the upper G color filter in the BM less area is 1.1μm, and the thickness of the overlapping B color filter range from 0.7μm to 1.2μm. The detailed simulation results are shown in Table 5.

Table 5. Reflectivity and Hue for Different B CF Thicknesses

	Thickness of B CF					
	0.7	0.8	0.9	1	1.1	1.2
R%	5.69%	5.67%	5.67%	5.66%	5.66%	5.66%
*a**	0.82	0.66	0.57	0.52	0.48	0.46
*b**	-2.46	-2.50	-2.52	-2.53	-2.53	-2.53

From the simulation data, we can see that the thickness of the overlapping G color filter and B color filter should be controlled to be above 1.1μm and 1.0μm, respectively, to ensure the minimum and stable reflectivity. Of course, this data cannot be directly applied to all situations, but the simulation logic can provide guidance for product design and process control.

4. Conclusion

We have successfully developed BM less samples with high-performance optics. This scheme, as a new technology for COE, can be implemented in products without degrading off-state optical performance. Through simulation, we have found out that the optimal reflectivity reduction solution is the two color filter overlap of R3+BX. During the product design process, simulation and reality are inseparable. Simulation provides guidance for design, while real-world conditions serve to validate and refine the simulation models. Simulation and reality must form a close loop which needs to be continuously improved and play a crucial role in aligning product design with real-world performance.

5. References

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