

Foldable AMOLED Display Utilizing Novel COE Structure

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Abstract

A 5.46inch WQHD foldable AMOLED display having thin thickness, wide color gamut, high brightness and low reflectivity was obtained. These properties, which outperform those of a conventional RGB OLED and circular polarizer system, were achieved with a novel structure of RGB emitter, thin film encapsulation and low temperature color filter directly patterned on TFE.

Author Keywords

AMOLED; foldable display; C-Pol free; COE;

1. Introduction

Over the last few years, active-matrix organic light emitting diode (AMOLED) displays have attracted great attention due to its typical properties including high display quality, light weight. Its flexible property prompts the application of display from rigid and flat shape to a fixed curve, bendable, and even foldable. Fixed curve shape has been widely applied in mobile-phone and watches [1-11]. However, the mechanical reliability of panels with bendable or foldable features is a major impediment to the mass production of such products. Continuous mechanical distortion would induce performance degradation or accelerate the breakdown of such devices. Therefore, improving device durability is a crucial task for the commercialization of foldable products.

In order to eliminate the strong ambient light reflection from the metal electrodes in top-emitting AMOLED panels, circle polarizer (C-Pol) is introduced. However, because of the absorb property, C-Pol reduce more than 55% of the panel lightness. At the same time, panel flexibility (bending radius) is compromised due to current limitation of its fragility and thickness (more than 100um). C-Pol is an important factor which prevents the panel from becoming a truly flexible display.

Mitsuhiro, K. et, al.[12-14] reported color filter can be used to reduce reflectivity of micro-cavity OLED Panel because the transmittance spectrum wave crest of the color filter and the reflectivity spectrum wave trough of micro-cavity OLED are adjacent at each emitting color. Lee, M. T. et, al. [15-18] reported symmetric panel stacking (color filter film attached to a AMOLED film) can significantly improve panel performance, flexibility and reliability compared to a C-Pol AMOLED panel.

According to the foregoing report, we introduced the novel COE (CF on Encapsulation) structure with RGB emitter, thin film encapsulation (TFE) and low temperature color filter array directly patterned on TFE to maintain the thinness of the flexible display and ensure its flexibility and reliability.

2. Experimental Result and Discussion

Figure 1 shows a cross-sectional view of the 5.46inch WQHD foldable AMOLED display. It consists of low temperature poly silicon (LTPS) thin film transistor (TFT) back plane deposited on a high temperature resistant PI substrate, RGB OLED micro-cavity protected by a inorganic/organic/inorganic 3-stack TFE structure, color filter array, and two function films (a bottom

support film with a PSA and a cover film attached by a OCA). The color filter array which includes 5 layers (black matrix/red/green/blue/over-coat) is patterned directly over the TFE layer at a temperature as low as 85°C. The function films are introduced to protect the panel from scratch and to ensure that the neutral axis of the stress could be placed around the most fragile layers of the flexible panel (the TFT, OLED, TFE), thereby avoiding damage during bending or folding. Finally, some COE structure panels were folded for 100,000 times at a radius of 3mm, and the brightness of the panels were almost unchanged.

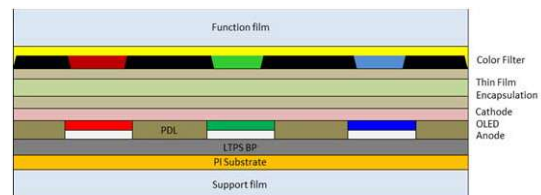


Figure 1. Side view of the 5.46inch WQHD foldable AMOLED display.

2.1 Novel COE structure to reduce reflectivity

Contrast is a key factor to display quality. Reflection of top emission of R/G/B OLED is up to 60% because it's filled with metal trace, semi-transparent cathode and reflective anode. The brighter of ambient light, the contrast of panel is lower. In order to reduce the panel reflection and improve the contrast, a C-Pol is usually applied on display panel. However, this also reduces the panel efficiency since part of internal generated light is blocked by the polarizer. Therefore, it would be an ultimate goal to dispose of polarizer film on OLED display panel and still maintain high contrast ratio.

Top emission of R/G/B OLED micro-cavity is applied to enhance emission peak thus achieve highly luminous efficiency to reduce power consumption, wide color gamut, and wide viewing angle. Meanwhile, the reflectivity around emission peak is diminished.

At the same time, color filter can only transmits a small range of light around emission peak while absorbing all the others. Thus for an ambient light, if the external light is not around the cavity emission peak, then it would be absorbed by the color filter. In the other case, if the light wavelength is around the micro-cavity emission peak, it would pass the color filter but most of it would be trapped in the micro-cavity, resulting in low reflection for outside observer. The reflectivity of OLED red, green, blue micro-cavity and the transmittance of the red, green, blue color filter are shown in Figure 2. The black matrix (BM) on color filter is used to shield the reflection of metal trace at non-cavity area. Thus we can obtain an overall low reflection without the assistance of circular polarizer over visible light wavelength range by combing micro-cavity structure and color filter with black matrix.

2.2 The influence factors of reflectivity

In a sub-pixel, at non-aperture area (BM shielding area), the reflection includes surface reflection (R1) and reflection of BM (R2) and the reflection of metal trace below BM (R3). The reflectivity of aperture area of none BM (R4) is equal to reflectivity of micro-cavity multiply by square of CF transmittance. The composition of panel reflection are shown in Figure 3.

The surface reflection R1 is related to refractive index of air (n_1 , 1) and surface (n_2 , 1.5), and according to Fresnel Formula, $R1 = [(n_1 - n_2) / (n_1 + n_2)]^2 \approx 0.04$. If optical density (OD) of BM is bigger than 3.0/um, R3 is equal to 0 approximately. For a fixed micro-cavity, and reflection of micro-cavity is fixed. Thus the reflection of panel is influenced by aperture ratio (AR) and transmittance of CF R/G/B.

AR of top emission OLED is concerned with the dimension of pixel define layer (PDL). But as for a COE structure, AR is related to BM size. For color filter, different transmittance of CF R/G/B means different color gamut. Thus we can say panel reflection is affected by the difference between BM size and PDL dimension and CF color gamut. Based on a 7T1C 5.5inch FHD top emission AMOLED, through simulated and practical tests by experiment, we found the relationship between panel reflection and CF color gamut and the difference between BM size and PDL dimension, which is shown in Figure 4.

From the actual results, we can see panel reflection decrease with CF color gamut and AR. When CF color gamut is larger than 80%, BM hole size is 2.7um smaller than PDL(RGB average AR are 21.3%), the panel reflectivity can be reduced to less than 6%.

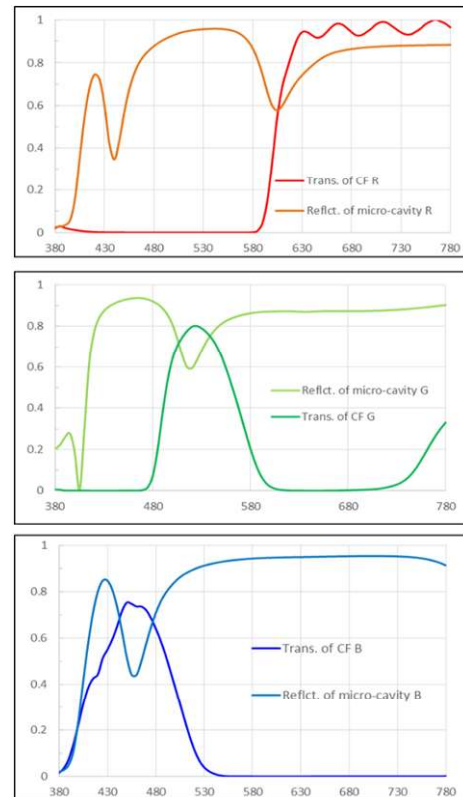


Figure 2. The reflectivity of OLED R/G/B micro-cavity and the transmittance of color filter R/G/B.

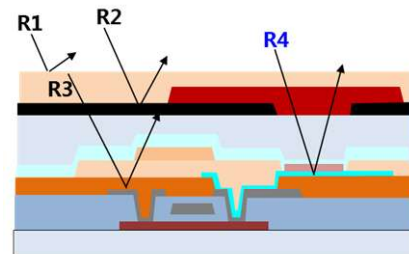


Figure 3. The composition of panel reflection.

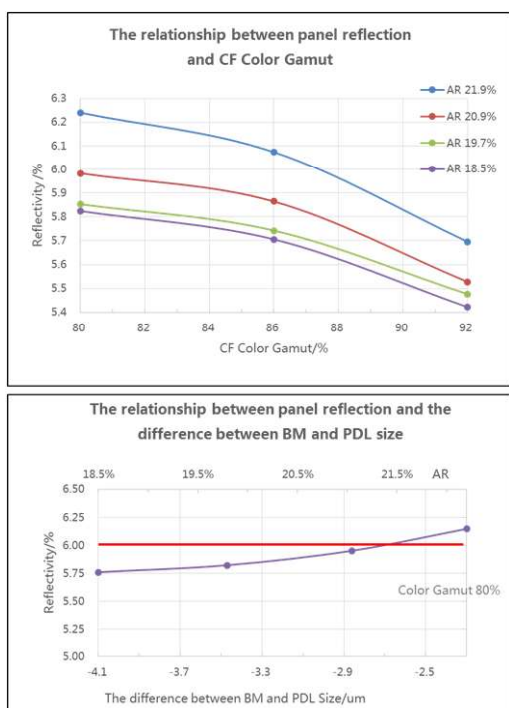


Figure 4. The relationship between panel reflection and CF color gamut and the difference between BM size and PDL dimension on 5.5inch FHD.

2.3 Prototype Flexible Display

Base on the results above, a 5.46inch WQHD flexible panel with COE structure (COE Panel) was fabricated. Meanwhile, a panel with C-Pol (C-Pol panel) was fabricated under identical TFT array, OLED deposition and TFE processes. The specification and performance of these panels are summarized in Table 1.

Table 1. The specification and performance of COE Panel

Structure	OLED + C-Pol	OLED + COE
Inch	5.46	
Resolution	2560*1440	
PPI	538	
Reflectivity	5.0 %	5.4%
Thickness	360 μ m	250 μ m
Brightness	350 nit	430 nit
NTSC Gamut	99%	112%

COE structure incorporating micro-cavity RGB OLED and CF has many advantages over traditional C-Pol approach. The COE panel and C-Pol panel had almost the same reflectivity. While the COE Panel with the color filter had a higher level of color saturation and a wider color gamut than the C-Pol panel (112.2% NTSC for the COE panel vs. 98.9% NTSC for the C-Pol panel). When both panels were measured under the same voltage and same load conditions at the same white point (CIE_{xy} coordinate of 0.31, 0.32), the COE panel have a 430 nits screen brightness compared to 350nits for C-Pol panel. The COE panel would have lower reflectivity and longer lifetime

than the C-Pol panel at the identical panel brightness. The COE panel is 150 μ m thinner than the C-Pol panel, which means it have better flexibility. Figure 5 is the photographs of the 5.46 WQHD AMOLED COE Panel on SID 2017 in Los Angeles.



Figure 5. The 5.46 WQHD AMOLED COE Panel on SID 2017.

3. Conclusion

We have successfully developed a foldable AMOLED display with high resolution and optimal image quality that could achieve 112% coverage of NTSC color space at CIE. 1931. The design of our innovative AMOLED panel utilizing low temperature CF patterned on TFE is aiming for the truly flexible product application in the near future. This novel COE structure (top emission OLED / thin film encapsulation / LT. CF) can also be used in high resolution products such as AR/VR.

References

- [1] R. Kataishi, T. Sasaki, K. Toyotaka, H. Miyake, Y. Yanagisawa, H. Ikeda, H. Nakashima, N. Osawa, S. Eguchi, S. Seo, Y. Hirakata, S. Yamazaki, C. Bower, D. Cotton, A. Matthews, P. Andrew, C. Gheorghiu, J. Bergquist, "Development of side-roll and top-roll panels for an RGBW high-resolution flexible display using a white OLED with microcavity structure", SID Digest **45**, 187-190 (2014).
- [2] L. Y. Lin, C. C. Cheng, C. Y. Liu, M. F. Chiang, P. H. Wu, M. T. Lee, C. Y. Chen, C. C. Chan, C. C. Lin, C. H. Chang, "A 4-in. QVGA flexible AMOLED driven by solution-processed metal-oxide TFTs", SID Digest **45**, 252-255 (2014).
- [3] Y. Jimbo, T. Aoyama, N. Ohno, S. Eguchi, S. Kawashima, H. Ikeda, Y. Hirakata, S. Yamazaki, M. Nakada, M. Sato, S. Yasumoto, C. Bower, D. Cotton, A. Matthews, P. Andrew, C. Gheorghiu, and J. Bergquist, "Tri-Fold flexible AMOLED with high barrier passivation layers", SID Digest **45**, 322-325 (2014).
- [4] R. Komatsu, R. Nakazato, T. Sasaki, A. Suzuki, N. Senda, T. Kawata, H. Ikeda, S. Eguchi, Y. Hirakata, S. Yamazaki, T. Shiraishi, S. Yasumoto, C. Bower, D. Cotton, A. Matthews, P. Andrew, C. Gheorghiu, J. Bergquist, "Repeatedly foldable book-type AMOLED Display", SID Digest **45**, 326-329 (2014).
- [5] C. C. Lee, J. C. Ho, G. Chen, M. H. Yeh, J. Chen, "Flexibility improvement of foldable AMOLED with touch panel", SID Digest **46**, 238-241 (2015).

- [6] K. Watanabe, Y. Iwaki, Y. Uchida, D. Nakamura, H. Ikeda, H. Miyake, Y. Hirakata, S. Yamazaki, M. Katayama, T. Cho, "An 8.67-in. foldable OLED display with an in-cell touch sensor", *SID Digest* **46**, 246-249 (2015).
- [7] M. T. Lee, C. L. Wang, C. S. Chan, C. C. Fu, C. C. Chen, K. H. Lin, W. C. Huang, C. H. Tsai, Z. X. Weng, C. C. Chan, Y. L. Lin, T. Y. Huang, P. Y. Lin, H. H. Lu, Y. H. Lin, "A symmetric panel stacking design for achieving a 3mm rolling radius in plastic-based AMOLED displays", *SID Digest* **46**, 958-961 (2015).
- [8] J. Yoon, H. Kwon, M. Lee, Y. Y. Yu, N. Cheong, S. Min, J. Choi, H. Im, K. Lee, J. Jo, H. Kim, H. Choi, Y. Lee, C. Yoo, S. Kuk, M. Cho, S. Kwon, W. Park, S. Yoon, I. Kang, S. Yeo, "World's first large-sized 18-in. flexible OLED display and the key technologies", *SID Digest* **46**, 962-965 (2015).
- [9] M. T. Lee, C. L. Wang, C. S. Chan, C. C. Fu, C. C. Chen, K. H. Lin, W. C. Huang, Y. H. Chen, W. J. Su, C. H. Chang, C. H. Tu, P. H. Lu, C. H. Tsai, Z. X. Weng, J. H. Tao, H. H. Lu, Y. H. Lin, "Ultra Durable Foldable AMOLED Display Capable of Withstanding One Million Folding Cycles", *SID Digest* **47**, 305-307 (2016).
- [10] C. H. Tu, C. C. Chang, J. F. Chen, M. C. Hsu, W. J. Hsieh, W. T. Wang, C. H. Chang, Y. H. Lai, W. T. Wang, C. M. Hsu, H. S. Lin, K. L. Hwu, Y. H. Lin, "Flexible AMOLED display with bending interactive interface", *SID Digest* **47**, 1049-1051 (2016).
- [11] T. Nagata, S. Hirasa, Y. Dozen, Y. Jimbo, K. Yokoyama, Y. Hirakata, S. Yamazaki, R. Sato, C. Fujiwara, T. Shiraishi, "A 2.78-in. 1058-ppi ultra-high-resolution flexible OLED display using CAAC-IGZO FETs", *SID Digest* **47**, 1052-1055 (2016).
- [12] M. Kashiwabara, K. Hanawa, R. Asaki, I. Kobori, R. Matsuura, H. Yamada, T. Yamamoto, A. Ozawa, Y. Sato, S. Terada, J. Yamada, T. Sasaoka, S. Tamura, T. Urabe, "Advanced AM-OLED Display Based on White Emitter with Microcavity Structure", *SID Digest* **35**, 1017-1019 (2004).
- [13] S. Kim, H. Shim, H. J. Kwon, S. Lee, Y. T. Chun, J. H. Kwack, D. Han, M. Song, J. Kim, I. Kee, S. Kim, S. Y. Lee, "Low Temperature Color Filter on Thin Film Encapsulation Active Matrix OLED(AMOLED) for Flexible Display", *IDW*, 1119-1122 (2010).
- [14] C. C. Chen, T. Y. Cho, J. J. Fu, H. Y. Hsiao, Z. X. Weng, C. H. Tsai, C. H. Chung, K. C. Lo, W. H. Lo, T. C. Chang, Y. Lin, *SID Digest* **44**, 416-418 (2013).
- [15] M. T. Lee, S. M. Shen, Z. X. Weng, J. J. Fu, C. L. Chen, C. S. Chuang, Y. Lin, *SID Digest* **45**, 573-575 (2014).
- [16] M. T. Lee, C. L. Wang, C. S. Chan, C. C. Fu, C. C. Chen, K. H. Lin, W. C. Huang, C. H. Tsai, Z. X. Weng, C. C. Chan, Y. L. Lin, T. Y. Huang, P. Y. Lin, H. H. Lu, Y. H. Lin, "Symmetric Panel Stacking Design for Achieving 3mm Rolling Radius in Plastic-based AMOLED Display", *SID Digest* **46**, 958-961 (2015).
- [17] M. T. Lee, C. L. Wang, C. S. Chan, C. C. Fu, C. C. Chen, K. H. Lin, W. C. Huang, Y. H. Chen, W. J. Su, C. H. Chang, C. H. Tu, P. H. Lu, C. H. Tsai, Z. X. Weng, J. H. Tao, H. H. Lu, Y. H. Lin, "Ultra Durable and Foldable AMOLED Display Capable of Withstanding One Million Folding Cycles", *SID Digest* **47**, 305-307 (2016).
- [18] M. T. Lee, C. L. Wang, C. S. Chan, C. C. Fu, C. Y. Shih, C. C. Chen, K. H. Lin, Y. H. Chen, W. J. Su, C. H. Liu, C. M. Ko, Z. X. Weng, J. H. Lin, Y. H. Chin, C. Y. Chen, Y. C. Chang, A. T. Huang, H. H. Lu, Y. H. Lin, "Achieving a Foldable & Durable OLED Display with BT.2020 Color Space using Innovative Color Filter Structure", *SID Digest* **48**, 334-337(2017).