

Analysis of Viewing Angle Properties on TEOLEDs Adopting Curved Anode Structure

Ji-Sub Park*, ***Byeonggon Kim****, ***Kyung-Mi Kim****, ***Kyu-Il Han*****,
Ji-Ho Baek**, ***Soo-Young Yoon*****

*LG Display Co., Ltd, Gumi, Gyeongsangbuk-do 39394, Korea

**LG Display Co., Ltd, LG Science Park, Seoul 07795, Korea

Abstract

We present the TEOLED device adopting curved anode structure to improve viewing angle properties. To obtain the improved viewing angle properties, we investigated the optimized curved deflection angle of anode structure for each color by simulation process. Compared to conventional TEOLEDs, the luminance at viewing angle and color coordinate shift are improved. We expect that this method will be useful for obtaining TEOLEDs with various viewing angle properties.

Author Keywords

Organic light-emitting diodes; Viewing angle; White color coordinate shift; Curved anode structure.

1. Introduction

Organic light-emitting diodes (OLEDs) have attracted much attention in the display industry owing to their advantages such as low power consumption, fast response, and superior color purity [1, 2]. In addition, they are also attractive for next generation display devices such as foldable and flexible display device because of their flexibility and thin film properties.

Efficiency is one of the important factors in OLEDs because customers demand display devices with better battery lifetime. Therefore, many studies were proceeded to achieve high-efficiency OLEDs in the past few years [3-5]. To obtain high-efficiency in OLEDs, top-emitting OLEDs (TEOLEDs) are widely used because they can provide a high resolution and aperture ratio in active-matrix OLEDs [4,5]. TEOLEDs consist of organic layers and two metal layers as anode and semi-transparent cathode. Therefore, TEOLEDs inevitably have a cavity effect due to the high reflection properties of the cathode and anode. In this case, efficiency can be improved, but the viewing angle properties are deteriorated due to the Purcell effect [6]. To improve the viewing angle properties in TEOLEDs, the addition of a scatter layer on the top of cathode to generate randomly extracted emission light, and applying semi-transparent silver mirror for the cathode were suggested [7, 8]. However, these techniques were difficult to optimize for each color condition because they were only controlled by the viewing angle properties for white color condition.

Recently, the luminance at viewing angle has attracted much attention for mobile display applications, thus OLEDs with upward color coordinate conditions has been suggested to achieve high luminance at viewing angle. However, this method has disadvantage such as color gamut reduction by applying upward color coordinate condition. Therefore, a new method is required to improve the viewing angle properties by optimizing for each color condition without color gamut reduction.

In this study, we presented TEOLEDs adopting the curved anode structure to improve viewing angle properties. By simulation process, the correlation between the curved deflection angle condition and the viewing angle properties was

analyzed for each color. In addition, the optimized curved deflection angle conditions of each color were proposed for the case with the max luminance at viewing angle, and the case with the optimized luminance at viewing angle and white color coordinate shift.

2. Method

For the simulation process, TEOLEDs were fabricated on the flat anode structure. First, organic layers such as emitting layers and transport layers were evaporated on a cleaned anode surface. Then, a semi-transparent metal layer for cathode was evaporated on the organic layers. Finally, to passivate the fabricated TEOLEDs, an encapsulation layer was formed. We measured the color coordinates and viewing angle properties by a spectrometer (CAS-140) and viewing angle measurement instrument (ELDIM EZContrast), respectively. The color coordinates (CIE x , y) of fabricated TEOLEDs for red, green, and blue are (0.691, 0.308), (0.250, 0.715), and (0.138, 0.046), respectively. We confirmed that this color coordinate condition can achieve DCI-P3 100% coverage. Based on the measurement result of viewing angle properties for fabricated TEOLEDs, we projected the viewing angle properties according to the curved deflection angle of anode structure. Here, viewing angle properties were considered only for a specific azimuthal angle condition. First, we calculated the length of the arc for each condition and divided the arc into specific intervals. Then, the viewing angle properties of each area were projected and combined. This process was conducted for each color and curved deflection angle condition. In the case of viewing angle properties for white color, it was calculated by the projected results of red, green and blue color condition.

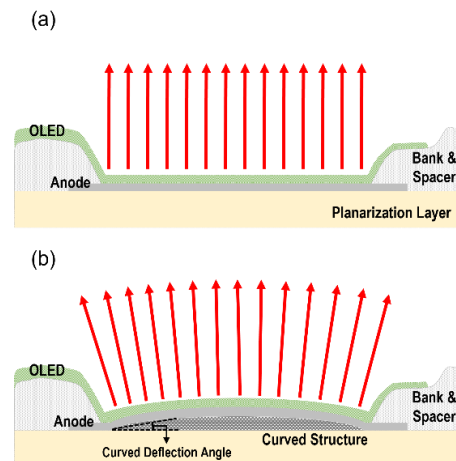


Figure 1. Schematic of emission property for TEOLEDs on (a) the flat (Conventional) and (b) curved anode structure.

3. Result

Figure 1 shows a schematic of the emission property for TEOLEDs with different anode structure conditions. In the case of conventional TEOLEDs, the flat anode and cathode layer are formed. Therefore, the optical axes are strongly formed in the frontal direction due to the cavity effect between the two metal layers (Figure 1(a)) [6]. By this phenomenon, the TEOLED efficiency can be improved, while the viewing angle properties are deteriorated because of the increasing luminance in the frontal direction for devices. As shown in Figure 1(b), the TEOLEDs on a curved anode structure have different emission properties. In this case, TEOLED layer also has a curved structure according to the anode curvature. Due to these structural characteristics, a broad distribution on the axes of the cavity effect can be obtained. Therefore, the luminance according to the viewing angle is relatively higher than of conventional TEOLEDs.

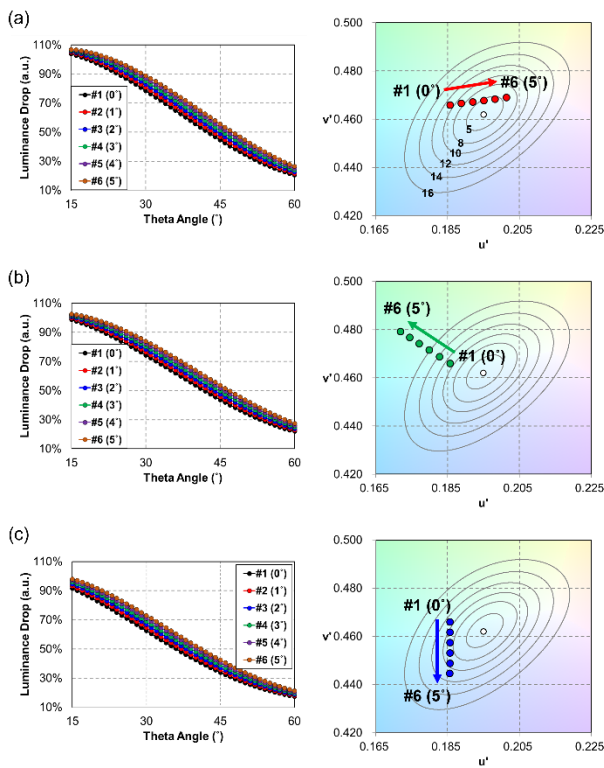


Figure 2. Luminance according to the viewing angle, and the white color coordinates of CIE1976 (u' , v') at a 45° viewing angle depending on the curved deflection angle condition of anode structure for each color: (a) red, (b) green, and (c) blue.

The viewing angle properties in our study are highly dependent on the curved deflection angle of anode structure. To investigate the correlation between condition of curved deflection angle and viewing angle properties, we simulated the luminance according to the viewing angle for each condition of curved deflection angle. As shown in Figure 2, the luminance at viewing angle is improved by increasing the curved deflection angle in all color conditions. Compared to the luminance according to the viewing angle between #1 (curved deflection angle: 0°) and #6 (curved

deflection angle: 5°; max condition in our study), color coordinates for each color are not changed and the luminance at a 45° viewing angle of red, green and blue increases by 11.1%, 9.9% and 8.6%, respectively. This result means that that our approach can achieve an improvement in the luminance at viewing angle without color gamut reduction. In addition, it also means that a broad ray distribution can be obtained by adopting the curved anode structure because the axes of the cavity effect depend on the anode-cathode formation. Figure 2 also shows the white color coordinate shift characteristics depending on the curved deflection angle of anode structure. To obtain the effect of each color condition, we simulated one color condition by applying the curved anode structure and the other color conditions by applying the flat anode structure. In the case of applying the curved anode structure for the red color (Figure 2(a)), the white color coordinate is shifted towards the red color compared to conventional TEOLEDs, and the level of shift increases as the curved deflection angle increases. This trend is also confirmed for the green and blue color. As shown in Figure 2(b) and (c), by adopting the curved anode structure for green and blue color, the white color coordinate is shifted towards the green and blue color compared to conventional TEOLEDs, respectively. These results indicate that not only the luminance at viewing angle, but also the white color coordinate shift is affected by the curved anode conditions. In addition, it also means that the white color coordinate shift characteristics can be optimized by adopting the curve deflection angle with proper condition for each color.

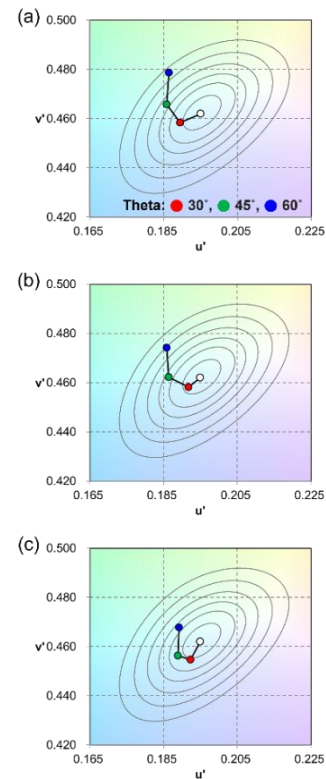


Figure 3. The trajectory of white color coordinate shift for each case: (a) Conventional OLEDs, (b) max luminance condition (Case #1), and (c) optimized luminance and color shift condition (Case #2), respectively.

Based on the simulation results for each color, we investigated the optimized curved deflection conditions for improving the luminance at viewing angle and the white color coordinate shift characteristics. Figure 3 and Table 1 show the viewing angle properties for each case. First, we investigated the condition of the optimized curved deflection angle for each color to meet the max luminance at viewing angle (Case #1). In this study, we simulated up to 5° curved deflection angle condition to obtain the viewing angle properties of TEOLEDs on the curved anode structure. Therefore, we confirmed the viewing angle properties of TEOLEDs on the curved anode structure with curved deflection angle of 5° for all color conditions because the luminance at viewing angle increases as the curved deflection angle of anode structure increases. As shown in Figure 3(b), the white color coordinate shift is slightly downshifted compared to the conventional TEOLEDs (Figure 3(a)). In addition, as shown in Table 1, the luminance at a 45° viewing angle was found to increase by approximately 10% compared to the conventional TEOLEDs. This is the same phenomenon as the previous result in Figure 2, which means that the luminance at viewing angle can be improved by adopting the curved deflection angle while having similar white color coordinate shift characteristics.

Table 1. The viewing angle properties of each case.

Parameter		Refer.	Case #1	Case #2
JND _{max} (0°~60°)		16	14	10
Luminance at viewing angle (@White)	30°	74.5%	84.4%	81.3%
	45°	43.2%	53.3%	50.0%
	60°	21.3%	26.7%	24.7%

As mentioned above, in the case of the condition of optimized curved deflection angle for each color to meet the max luminance at viewing angle (Case #1), the luminance at viewing angle is improved, but the white color coordinate shift is similar compared to the conventional TEOLEDs. Therefore, we investigated another case that improves not only the luminance at viewing angle but also the white color coordinate shift characteristic (Case #2). The viewing angle properties were investigated under the white color coordinate condition by combining the simulation results for each curved deflection angle of each color. Herein, we checked whether the white color coordinate shift characteristic of case #2 was improved by the just-noticeable difference (JND) [9]. As shown in Figure 3(c), the white color coordinate shift is improved compared to the conventional TEOLEDs by adopting the curved deflection angle of 4°, 3°, and 5° for red, green, and blue color, respectively. In this case, we can confirm that JND_{max} (the maximum JND value between 0°~60° of viewing angle) is improved from 16 (conventional TEOLEDs) to 10 (Case #2). Moreover, the luminance at a 45° viewing angle was found to increase by 6.8% compared to the conventional TEOLEDs, because the curved deflection angle was applied to green, which is the most dominant in the luminance at viewing angle. This result means that we can obtain the conditions that can improve not only the luminance at viewing angle but also and color coordinate shift by adopting proper curved anode structure for each color without color gamut reduction.

4. Conclusion

We demonstrated the simple and controllable approach to improve the viewing angle properties of TEOLEDs by adopting curved anode structure. The correlation between curved deflection angle of anode structure and viewing angle properties was investigated by simulation process. In addition, we also obtained that optimized condition of curved deflection angle for each color to improve the viewing angle properties of TEOLEDs without color gamut reduction. Our simulation study on the method would be very useful to obtain structure condition for enhancing the viewing angle performance in TEOLEDs.

5. References

- Zhang Q, Li B, Huang S, Nomura H, Tanaka H, Adachi C. Efficient blue organic light-emitting diodes employing thermally activated delayed fluorescence Nat. Photonics 2014;8:326-331.
- Cho SH, Pyo SW, Suh MC. Efficient blue organic light-emitting diodes employing thermally activated delayed fluorescence Synth. Metals 2012;162:402-405.
- Lee JY. Mixed-host-emitting layer for high-efficiency organic light-emitting diodes J. Info. Disp. 2014;15:139-144.
- Lee CJ, Podo R B, Han JI, Moon DG. Green top-emitting organic light emitting device with transparent Ba/Ag bilayer cathode Appl. Phys. Lett 2006;89:123501-123503.
- Huang Q, Walzer K, Pfeiffer M, Lyssenko V, He G, Leo K. Highly efficient top emitting organic light-emitting diodes with organic outcoupling enhancement layers Appl. Phys. Lett 2006;88:113515-113517.
- Juang F-S, Lai H-L, Lin C-J, Hsu Y-J. Angular Dependence of the Sharply Directed Emission in Organic Light Emitting Diodes with a Microcavity Structure Jap. J. Appl. Phys. 2002;41:2787-2789.
- Lidzey D G, Pate M A, Whittaker D M, Bradley D D C, Weaver M S, Fisher T A, Skolnick M S. Control of photoluminescence emission from a conjugated polymer using an optimised microactivity structure Chem. Phys. Lett. 1996;263:655-660.
- Neyts K, Visschere P D, Fork D K, Anderson G B. Semitransparent metal or distributed Bragg reflector for wide-viewing-angle organic light-emitting-diode microcavities J. Opt. Soc. Amer. B 2000;17:114-119.
- Sharma G, Wu W, Dalal E N. The CIEDE2000 color-difference formula: Implementation notes, supplementary test data, and mathematical observations Inc. Col Res Appl, 2005;30:21-30.