Driving Methods for Improving Image Quality in LTPS and LTPO-based AMOLED Displays

Won Kyung Min, Hyung Tae Kim, Hyunji Son, Seok Gyu Hong, Se Hwan Na, Li Jin Kim, Jung Chul Kim, and Hyun Jae Kim*

*hjk3@yonsei.ac.kr
Department of Electrical and Electronic Engineering, Yonsei University, Seoul 03722, Korea
Keywords: Active-matrix organic light-emitting diode (AMOLED); Driving method; Ultra-low luminance; Variable‐refresh‐rate (VRR); Image quality enhancement;

ABSTRACT

In AMOLED displays, image quality degradation due to imprecise gray scale control in ultra-low luminance and difficult compensation of switching and driving transistors in variable-refresh-rate becomes a severe issue. In this work, we investigated the primary causes of the image deterioration and proposed various methodological solutions and driving schemes.

1 Introduction

The active-matrix organic light-emitting diode (AMOLED) display is an advanced market-leading technology that dominates other flat panel display technologies and is utilized in a variety of fields, including large-size display applications such as TVs and signages and small-size display applications such as smartphones. Especially, as we move toward a society in which people can access important information from anywhere, mobile AMOLED displays (small- and medium-sized displays) are anticipated to provide even higher quality and functionality [1].

As the usage environment for such mobile displays (particularly smartphones) has become increasingly diverse, two representative new demands for improving the display's performance have evolved. First, due to recent smartphone trends involving an increase in the usage time in the low-brightness mode and a rapid improvement in the camera shooting performance of the ambient low light environment, the expression accuracy and image quality of the display at the extremely low luminance have become important display performance evaluation criteria [2]. Secondly, to run social networking services (SNS), games, videos, and so on, smartphones have been designed for intimate and continuous interaction with users. Thus, the demand for high refresh rate (HRR) driving to realize seamless images is gradually increasing. On the other hand, since HRR driving leads to significant power consumption, which is sensitive to mobile devices, smartphones have adopted pixel circuits for low refresh rate (LRR) driving together with HRR driving to reduce power consumption. This technology is called as a variable refresh rate (VRR) that can be operated at high or low frame rates to achieve both fast-motion images and low-power standby scenarios. The fast-motion images in gaming and display scrolling require a high-frame rate up to 120 Hz, whereas a low-frame rate down to 1 Hz is appropriate in the low-power standby state, which has been applicated to the always-on display (AOD) and text mode [3].

However, as the required display environment becomes more sophisticated, such as extremely lower luminance and larger frame rate differences, the degradation of image quality in AMOLEDs (e.g., mura or flicker phenomenon) is frequently observed. In this study, the specific causes of the aforementioned image quality degradation were identified and analyzed via measurements using actual display panels and their simulation/experiment results. Further, to resolve these problems, various methodological solutions have been proposed from the perspective of the driving methods. The driving methods suggested in this research are based on low-temperature polycrystalline silicon (LTPS) TFTs, which are currently standard for mobile AMOLED pixel circuits, along with low-temperature polycrystalline silicon and oxide (LTPO) TFTs which have become the next-generation backplane technologies for smartphones and smartwatches.

2 Degradation of image quality in low luminance and the enhancement methodologies

At low luminance levels, it is difficult for the AMOLED panel to support the precise luminance expression and control the gray scale for implementing the superior image quality. Generally, the required current in the high-resolution range from full high-definition (FHD) to quadruple high-definition (QHD) is only tens of nano-amperes at 500 nit. Moreover, the required current is below the pico-ampere (pA) scale when the maximum brightness is 2 nit. Considering that the current for expressing low-luminance level is too low, it is challenging to accurately manage the driving current of OLEDs [4,5]. Consequently, deteriorated image quality problems with the failure phenomenon (**Fig. 1**) typically appear in the panel at extremely low luminance (2 nit) necessitating the development of new solutions to address this issue.

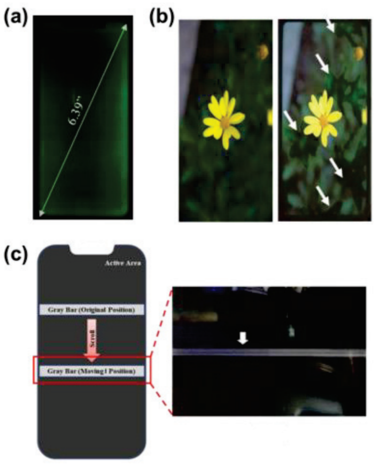

Fig. 1. 3 types of failure phenomenon appeared at the ultra-low luminance: (a) low gray mura: brighter edge area than center, (b) contour image: color crush which looks like contour, and (c) bluish motion blur: gray bar color change during moving [2].

To find a solution to these deteriorated image quality problems, we should first comprehend why the low current for expressing low luminance is problematic. As shown in **Fig. 2(a)**, 3 sequences are to be executed for the turning-on and light emission of OLEDs. In period I, the charges are accumulated to the OLED capacitance (C_{OLED}) and the anode voltage begins to rise from its initial voltage (V_{init}). In period II, the voltage charged to the C_{OLED} increases to the OLED turn-on voltage (V_{to}), and the current begins to flow through it. Also, during period II, the anode voltage is increased to the saturation voltage (V_{sat}, the forward voltage of the OLED for emitting the gray current) in order to achieve the gray brightness described in **Fig. 2(b)** and **(c)**. Then, during period III, the anode reaches the corresponding voltage and emits light while flowing a constant current during the light-emission period.

However, in the case of low gray scale, the required luminance for the actual emission is almost close to black and it should be implemented with a low pA-level current. It indicates that an extremely small current is used to charge the C_{OLED} and raise the anode voltage in order to emit the light. Consequently, when the deviation appears during charging from the initial voltage (V_{init}) to the V_{to} and V_{sat}, the OLED emitting time in a frame time is altered. As a result, the amount of luminance and performance of each pixel varies. In other words, due to the low current applied to implement an extremely low brightness, the OLED could be turned-on in different characteristics to reach the V_{sat}, which is directly induced by a difference in brightness. So, it could be explained that the charging delay caused by the low current becomes the primary cause of the stain and other phenomena.

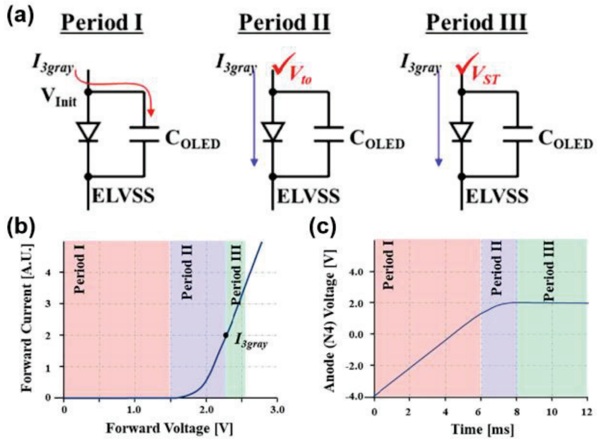

Fig. 2. Schematics of OLED operation sequences based on a specific period. (a) Change of the conduction in equivalent circuit by 3 period, (b) OLED I-V curve by the operating period, and (c) anode voltage transition sequence [2].

To reduce the negative effect generated by the low current, various methods have been proposed to improve image quality even at low luminance, as shown in **Table 1.** Among these methods, lowering the ELVSS is an effective way to reduce the charging delay that occurs before the OLED emits light. This is because it is possible to reduce the delay deviation required for charging by decreasing the saturation time through reducing V_{sat}. By optimization of C_{OLED} charging delay, it was possible to significantly enhance the picture quality as shown in **Fig. 3**. This charging delay is a major factor of deviation occurring on the operation of the pixel, decreasing electrical potential applied to the OLED can be expected that shorten the saturation time to improve the picture quality. Therefore, the minimizing electric potential of anode help the panel improved for high picture quality at ultra-low luminance condition.

Table 1. Recommendation of the enhancement methodologies for low luminance stain [2].

Classification I	Classification II	Detail Methodology
OLED	Current sensitivity reduction	OLED efficiency decrease
	Capacitance reduction	Aperture area decrease
		OLED thickness increase
Design/process	Charging delay enhancement	Anode/cathode resistance reduction
		OLED V_{to} reduction
Driving	Electric potential optimization	V_{init} increase, ELVSS decease
	Unit pixel current increase	Applying PWM Driving

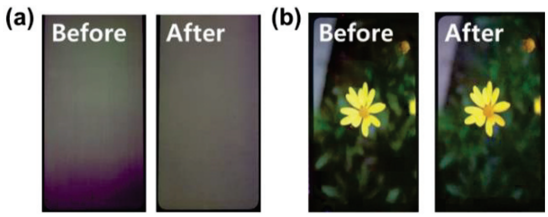

Fig. 3. Improved result by minimizing of electric potential difference of anode: (a) low gray color uniformity and (b) low gray color crush [2].

3 The impact of VRR technologies on image quality and how to compensate the image degradation

The frame rate variations by VRR technologies could induce image quality deterioration in AMOLED displays [6.7]. At the high frame rate, the scan time of one row is shortened; the compensation time is too insufficient to reduce the threshold voltage (V_{th}) variation, and compensation performance degrades, leading to luminance deviations at different frequencies. Meanwhile, at the low frame rate, flicker is crucial; the lower the frame rate, the longer the time required to hold data on the storage capacitor. So, the limitations of driving devices such as the leakage current of switching TFT and hysteresis of driving TFT have detrimental effects on image quality degradation in low-frame rate-driven displays [8,9].

First, a new driving method with variable V_{init} was introduced to prevent deterioration that occurs on HRR driving. At high frequency, the change in luminance occurs because the threshold voltage compensation and the OLED charging time are shortened. We measured these luminance deviations at various frequencies by using a 6.76'' AMOLED display with 7T1C compensation pixel structures of LTPS TFTs backplane. In **Fig. 4(a)**, the right axis represents the absolute luminance difference between frequencies of 60Hz and 120Hz, while the left axis represents the difference rate expressed in percentage. Meanwhile, the absolute difference is significant for high luminance, the difference rate grew as the luminance decreased. Actually, as human vision regarding luminance has non-linear characteristics, the perception of luminance is more sensitive to the luminance difference rate rather than to the absolute difference [10].

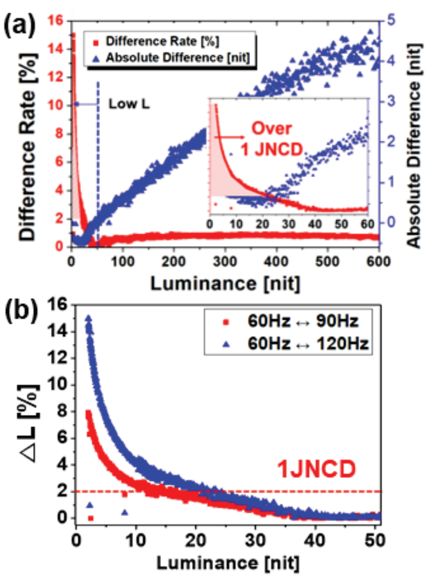

Fig. 4. (a) Differences in luminance between frequencies of 60 Hz and 120 Hz. (b) At low gray levels, differences in luminance under a frequency change from 60 to 90 Hz and 60 Hz to 120 Hz (without V_{init} compensation) [3].

Therefore, as shown in **Fig. 4(a)** inset, it was confirmed that the value of just noticeable color difference (JNCD)-measurements for evaluating the color accuracy of a display [11,12]-exceeded 1 under a luminance of 20 nit and increased even further as the luminance diminished. As shown in **Fig. 4(b)**, the luminance differences between the two frequencies increase resulting in the shorter emission and data programming time at high frequency. In addition, as described above, since the current is insufficient in the low luminance region, the decrease in the charging rate of the OLED is further accelerated.

To address this issue, we matched the charging characteristics to the target voltage at each frequency by applying a variable V_{init} value. **Fig. 5(a)** shows the simulation-based mechanism validation and improvement. Considering the simulation results, it can be seen the variations of OLED charging voltages when the same V_{init} was applied under 90 Hz HRR and 60 Hz normal refresh rate (NRR) conditions. Due to the charging delay, the OLED current is significantly reduced in HRR conditions. In contrast, when the V_{init} is raised from -2.8 to -2.6 V under the 90 Hz condition, it is clarified that in 1 frame the current amounts under 90 Hz are comparable to those under 60 Hz. Based on the simulation results, it was confirmed that the OLED current variation during frequency changes could be compensated by V_{init} control securing the anode voltage charge. **Fig. 5(b)** shows the measurement results when different V_{init} was used for different frequencies: -2.8 V for 60 Hz, -2.6 V for 90 Hz, and -2.4 V for 120 Hz. After applying voltage compensations, both luminance and color fluctuations decrease to less than 1 JNCD. As a result of applying the variable V_{init}, there has been no corruption in the image quality regardless of whether the frame rate is 60 Hz or 120 Hz.

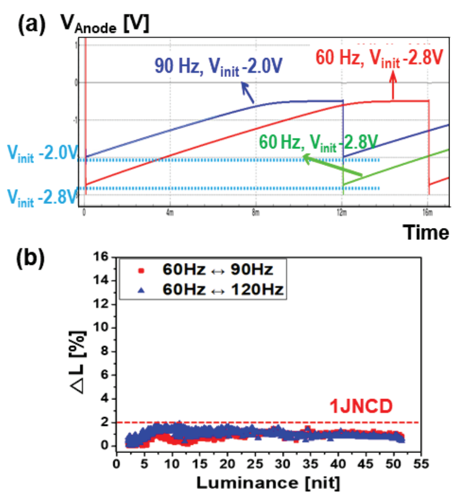

Fig. 5. (a) Simulation results for OLED anode voltage in various V_{init} at 60 and 90 Hz Conditions. (b) The differences in luminance under variable frequency changes with V_{init} compensation [3].

Therefore, as our strategy could prevent image quality distortion by utilizing an existing compensation pixel structure without the need for additional compensation steps or modification of the pixel structure, it would be a promising technique for enhancing the picture qualities in AMOLED displays. Additionally, regarding LTPO technology, we introduce the driving scheme that extends compensation time during the refresh frame and applies a high negative bias to the driving TFT during the skip frame. The method of extending compensation time can secure sufficient time to sense the V_{th} of the driving voltage by overlapping the compensation stage of multiple rows. In the case of the method for applying the high negative bias to the driving TFT, it shifts the transfer curve of the driving TFT toward the opposite direction of the shift during the programming and V_{th} sampling stages. Consequently, the proposed driving scheme made sufficient V_{th} compensation and recovery of V_{th} shift in the transfer curve of driving TFT resulting in the reduction of the OLED current fluctuation in both high and low frame rates.

4 Conclusion

In this paper, we presented several methodological strategies to address the issues of image quality degradation that arise when driving an AMOLED display in low luminance or VRR operation. When the brightness and gray scale are extremely low, it is challenging to control the precise pico-ampere-level currents for driving the current of the OLED. This is due to the charging delay being increased by the high electrical potential applied to the anode of the OLED. To reduce the applied electrical potential, lowering ELVSS technology was introduced, and the improved image quality including low gray color uniformity and gray color crush is shown from the AMOLED panel. Additionally, the color and brightness quality on the AMOLED panel utilizing VRR are degraded due to insufficient current charging capacity which results in severe image distortion especially in low luminance. The following issues can be resolved by using optimized V_{init} depending on frequency. Therefore, we demonstrated that the proposed strategies improved the image quality degradation by endowing high expression accuracy and image quality to resolve the emerging issues including mura, color crush, and color fluctuation in mobile AMOLED panel.

Acknowledgments

This work was supported by the Technology Innovation Program (20017208, Development of 6th Generation Ion Implantation Equipment for Display) funded by the Ministry of Trade, Industry & Energy (MOTIE, Korea).

References

[1] S. Hong, C. Jeon, S. Song, J. Kim, J. Lee, and D. Kim, “25.4: Invited Paper: Development of Commercial Flexible AMOLEDs,” SID Symp. Dig. Tech. Pap., Vol. 45, pp. 334–337 (2014).

[2] S. H. Na, W. K. Min, D. H. Kim, H. W. Hwang, Y. M. Ha, and H. J. Kim, “Enhancement of picture quality on ultra-low brightness by optimizing the electrical potential required for OLED charging in the AMOLED displays,” J. Inf. Disp., Vol. 22, No. 4, pp. 275–284 (2021).

[3] L. J. Kim, S. Jung, H. J. Kim, B. H. Kim, K. J. Kwon, Y. M. Ha, and H. J. Kim, “Image quality enhancement in variable-refresh-rate AMOLED displays using a variable initial voltage compensation scheme,” Sci. Rep., Vol. 12, No. 1, pp. 1–7 (2022).

[4] D. Ji, J. Jang, J. H. Park, D. Kim, Y. S. Rim, D. K. Hwang, and Y. Y. Noh, “Recent progress in the development of backplane thin film transistors for information displays,” J. Inf. Disp., Vol. 22, No. 1, pp.1–11 (2021).

[5] K. Oh, S.-K. Hong, and O.-K. Kwon, “A luminance compensation method using optical sensors with optimized memory size for high image quality AMOLED displays,” J. Opt. Soc. Korea, Vol. 20, No. 5, pp. 586–592 (2016).

[6] T. K. Chang, C. W. Lin, and S. Chang, " 39‐3: invited paper: LTPO TFT technology for AMOLEDs," SID Symp. Dig. Tech. Pap., Vol. 50, No. 1, pp. 545–548 (2019).

[7] J. Kim, H. J. Chung, and S. W. Lee, "A low-power pixel circuit comprising low-temperature poly-silicon and oxide TFTs for liquid crystal displays with panel self-refresh technology,” IEEE Electron. Dev., Vol. 41, No. 6, pp. 868–871 (2020).

[8] U. J. Chung, S. C. Choi, S. Y. Noh, K. T. Kim, K. J. Moon, J. H. Kim, K. S. Park, H.-C. Choi, and I. B. Kang, "15-1: Invited Paper: Manufacturing Technology of LTPO TFT," SID Symp. Dig. Tech. Pap., Vol. 51, No. 1, pp. 192–195 (2020).

[9] J. C. Kim, S. H. Hong, S. J. Jung, M. H. Shin, J. S. Yoo, H. W. Hwang, Y. M. Ha, and H. J. Kim, "A novel OLED Pixel circuit with controllable threshold voltage compensation time," Proc. IDW ’19, pp. 505-506 (2019).

[10] T. Acharya and A. K. Ray., " Image Processing: Principles and Applications," John Wiley & Sons, Inc., pp. 37-39 (2005).

[11] C. H. Yang, P. Yin, J. H. Tao, J. C. Hsiao, M. T. Lee, H. H. Lu, Y. H. Lin, "Novel thin film encapsulation structure for wearable plastic AMOLED display," SID Symp. Dig. Tech. Pap., Vol 47, pp. 841-843 (2016).

[12] J. S. Steckel, J. Ho, C. Hamilton, J. Xi, C. Breen, W. Liu, P. Allen, S. Coe-Sullivan, "The ultimate down-conversion material for LCD displays," J. Soc. Inf. Disp., Vol 23, pp. 294-305 (2015).