Received 7 October 2022; revised 7 December 2022; accepted 13 February 2023. Date of publication 1 March 2023; date of current version 13 March 2023.
The review of this article was arranged by Editor A. Nathan.

Digital Object Identifier 10.1109/JEDS.2023.3250605

Bit Depth of Drivers for Micro-LED Displays Adopting Low-Temperature Polysilicon Oxide Thin-Film Transistors

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ABSTRACT In this paper, the minimum bit depth of drivers for active-matrix light emitting diode (AMLED) displays has been specified to overcome luminance nonuniformity of LEDs for the first time. The pixel circuit comprises seven transistors and one capacitor (7T1C) based on low-temperature polysilicon oxide (LTPO) process. For the experiments, thirty green and blue LEDs were used. When the same data voltage was applied, there was luminance nonuniformity of up to 19% and 41% for green and blue LEDs compared to the reference LEDs. Data voltages were measured to get the same luminance as the target one. It was found that the maximum voltage intervals of 0.9 mV and 1.1 mV were necessary to overcome the luminance nonuniformity for green and blue LEDs, respectively. 1.62 V and 2.80 V were the data voltage ranges of green and blue LEDs, respectively. The bit dept of 11-bit (2,048) is the minimum one because 1.62 V / 0.9 mV for green LEDs is smaller than 2,047. In this way, at least 12-bit is necessary for the bit depth of drivers for blue LEDs.

INDEX TERMS Micro-light emitting diode (micro-LED) display, active matrix (AM), low-temperature polysilicon oxide (LTPO), luminance nonuniformity, mura, bit depth.

I. INTRODUCTION

A micro-light emitting diode (micro-LED) display is expected as a next generation display due to its high luminance, outstanding color reproduction, fast response time, long lifetime, and so on [1], [2], [3]. The micro-LED displays are manufactured on a printed circuit board (PCB) with passive-matrix (PM) drivers. Some micro-LED displays on silicon wafer with integrated complementary metal-oxide semiconductor (CMOS) drivers have been presented. It is difficult to implement active-matrix (AM) LED displays on the PCB [4], [5]. In addition, it is difficult to manufacture a large-area LED display on a silicon wafer [6], [7]. Thus, studies on AMLED displays adopting thin-film transistors (TFTs) are increasing these days. AMLED displays feature low process cost, flexibility, and large area. The micro-LED's light efficiency can be enhanced by using the AM driving method. Therefore, high-density display production is possible because the pixel size can be reduced. However, it will cause a large luminance nonuniformity when the micro-LED display is driven by the AM driving technology adopting TFTs. The luminance nonuniformity is affected by the characteristic deviations of both TFTs and LEDs. Luminance nonuniformity is observed as a mura. Currently, research on luminance nonuniformity of micro-LED display with TFT backplane is in initial stages. Thus, it is necessary to investigate image quality issues.

In this paper, the luminance nonuniformity among LEDs is investigated. Each micro-LED is driven by a pixel circuit comprising seven transistors and one capacitor (7T1C) based on low-temperature polysilicon oxide (LTPO) process. The analog voltage range and digital bit depth are investigated for the LEDs to emit the uniform luminance. The optimum data voltage range and bit depth of drivers for AMLED displays overcoming luminance nonuniformity are presented.

II. EXPERIMENT CONDITIONS AND PROCEDURE

The TFT pixel circuit and timing diagram used in the experiment are shown in Fig. 1. As shown in Fig. 1, the 7T1C compensation pixel circuit comprises LTPO TFTs. The n-type transistors such as M3, M4, M5, and M7 are oxide TFTs. The other transistors are low-temperature polycrystalline silicon (LTPS) TFTs. We modified the original LTPS 7T1C pixel circuit [8], [9], [10], [11] to the LTPO counterpart as shown in Fig. 1(a). Its microscope image is shown in Fig. 2. A data voltage is determined to express gray as follows:

$$I_{LED} = \frac{1}{2}\mu C_{ox}\frac{W}{L}(VDD - VDATA)^2 \qquad (1)$$

In Equation (1), I_{LED}, VDD, and $VDATA$ are the LED current, power supply voltage, a data voltage applied to source of M1, respectively. μ, C_{ox}, W, and L are the carrier mobility, the gate insulator capacitance per unit area, the channel width, and the channel length of M1, respectively [12], [13]. The operation of the pixel circuit is divided into three parts: initialization, sampling, and emission. During initialization period, the gate node of the driving transistor (M1) is initialized. During sampling period, the data voltage, VDATA, is applied to the source of M1. VDATA – |Vth| (the absolute value of the threshold voltage of M1) is sampled at the gate of M1. During emission period, the LED emits lights depending on the current given in Equation (1). VDD, VSS, and VINI were set to 4.0 V, −3.0 V, and −5.0 V, respectively.

The system for the experiment was set up as shown in Fig. 3. The LTPO pixel circuit manufactured on glass was placed in the probe station. The power and driving signals were applied to PADs on the glass through a power supply and waveform generator, respectively. The LTPO pixel circuit and micro-LED were connected. The luminance of LED was measured by spectroradiometer PR670 with a focus lens.

The target values of luminance and color coordinates were set as those of a commercially available mobile phone. It is assumed that the RGB luminance ratio of the micro-LED display is the same as that of the commercially available mobile phones. Thus, the target white luminance of the micro-LED display became 1,000 cd/m2. As shown in Table 1, maximum luminance values of red, green, and blue were given to reflect the RGB ratio of the commercially available mobile phone.

The width and length of an LED were 75 μm and 200 μm, respectively. Fig. 4 shows the measured luminance of green, blue LEDs depending on the LED current.

We assumed the aperture ratio of 10% that is defined as the ratio of the light-emitting area to the total area of one pixel. Thus, the luminance of LEDs must be 10 times higher than those shown in Table 1. Thirty green and blue LEDs were prepared for the experiment. Red LEDs were not prepared. We defined the target luminance of red LED as 2,080 cd/m2 which requires higher current than 30 μA. We fabricated switching TFTs M2 and M6 with W/L = 4 μm/6 μm. However, we found that W/L = 4 μm/6 μm was too small to endure the LED current through M2 and M6. This is the reason why the data for red LEDs were not prepared. Each LED was numbered and measured as follows:

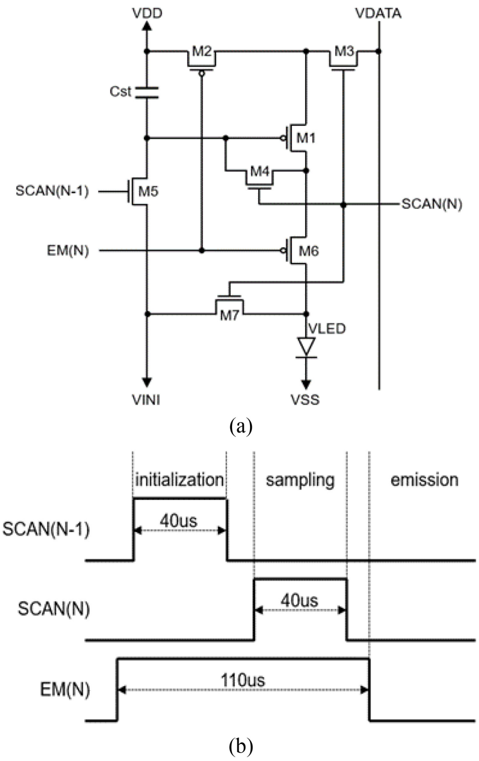

FIGURE 1. (a) LTPO 7T1C pixel circuit and (b) its timing diagram.

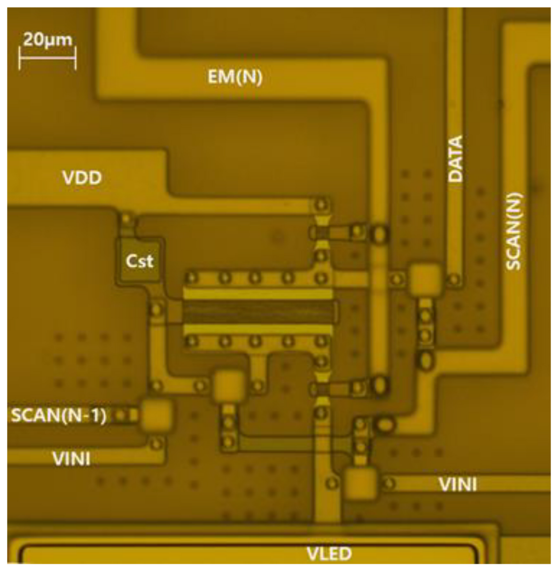

FIGURE 2. Micrograph of the fabricated 7T1C pixel circuit.

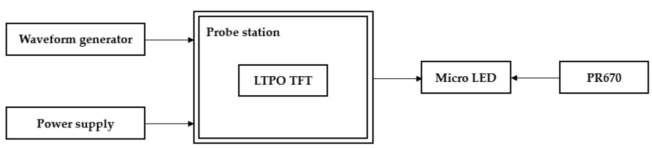

FIGURE 3. The schematic diagram of our experimental setup.

TABLE 1. Target luminance values of white, red, green, and blue.

Luminance [cd/m²]			
White	Red	Green	Blue
1,000	208	714.5	77.5

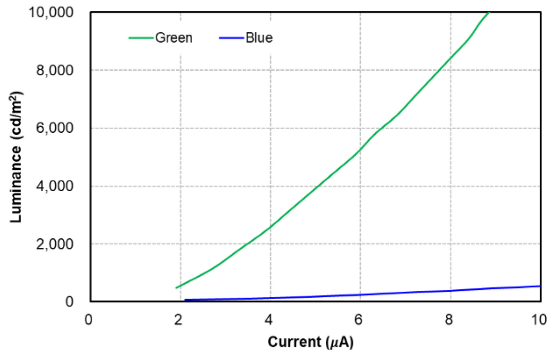

FIGURE 4. LED luminance measured by the spectroradiometer PR670.

Step 1. To measure the VDATA that allows the first green LED (reference green LED) to emits 7,145 cd/m^2, the target luminance.

Step 2. To apply the VDATA obtained in step 1 to the second green LED and measure its luminance.

Step 3. To find VDATA that causes the LED to emit 7,145 cd/m^2.

Step 4. To repeat Steps 2 and 3 with other LEDs.

Step 5. To repeat from step 1 to step 4 for blue LEDs with the target luminance of 775 cd/m^2.

III. RESULTS AND DISCUSSION

Thirty green LEDs and thirty blue LEDs were measured. Table 2 shows the measurement results of them.

VDATA of 2.45 V was applied to the reference green LED to emit the target luminance value of 7,145 cd/m^2. When 2.45 V was applied to the second green LED, its luminance was 7,542 cd/m^2. When 2.51 V was applied to this LED, its luminance becomes 7,145 cd/m^2.

The VDATA of 1.44 V was applied to the reference blue LED to emit the target luminance value of 775 cd/m^2. When 1.44 V was applied to the second blue LED, its luminance was 967 cd/m^2. When 1.88 V was applied, its luminance becomes 775 cd/m^2.

Fig. 5 shows the normalized luminance distribution of the green and blue LEDs when VDATAs of the reference LEDs were applied. Each LED luminance was normalized the target luminance. The luminance of thirty green LEDs ranged from 95% to 119%. The maximum luminance deviation for green LEDs was 19%. The luminance of thirty blue LEDs ranged from 91% to 141%. The maximum luminance deviation for blue LEDs was 41%. Fig. 6 shows VDATA distribution of green and blue LEDs to emit their target luminance. Green LEDs had the maximum VDATA deviation of 0.24 V, while blue LEDs had the maximum deviation of 0.83 V.

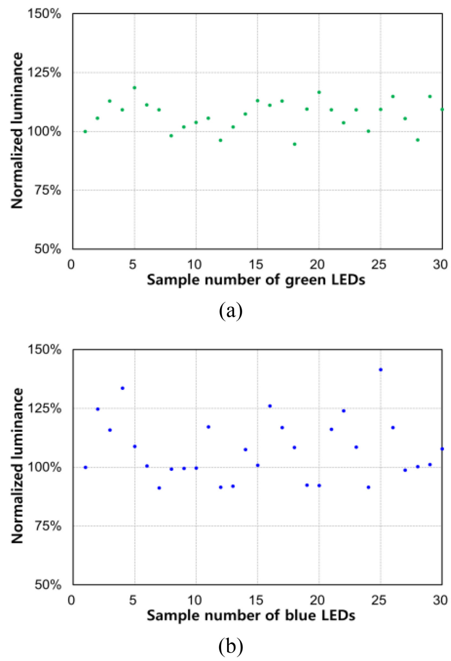

FIGURE 5. Normalized luminance distribution when VDATA of the reference LED was applied to (a) green LEDs and (b) blue LEDs.

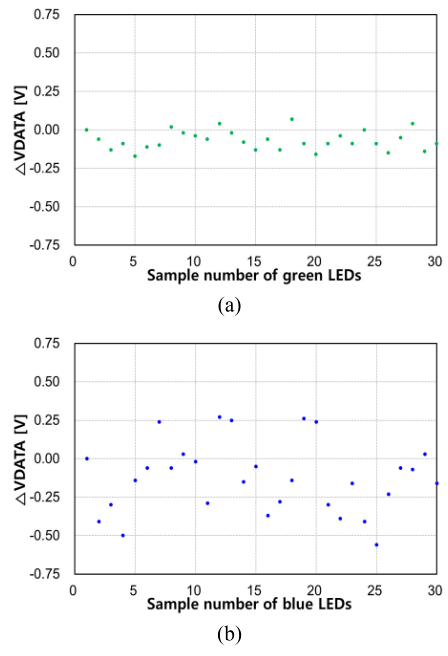

FIGURE 6. The distribution of VDATA for the target luminance of (a) green LEDs and (b) blue LEDs.

Although the same VDATA was applied to micro-LEDs driven by the 7T1C circuit compensating for the threshold voltage variation, luminance nonuniformity among LEDs was inevitable as shown in Fig. 5. Table 3 shows measured luminance values of the brightest, reference, and darkest LEDs when the reference VDATA was applied.

The bit depth of drivers was calculated to express grayscale of displays with luminance nonuniformity [14], [15]. We assumed that digital-to-analog

TABLE 2. LED measurement result.

		Target luminance [cd/m²]	VDATA applied to the samples		VDATA for target luminance	
			Luminance [cd/m²]	VDATA [V]	Luminance [cd/m²]	VDATA [V]
Green	First (Reference)	7,145	7,145	2.45	7,145	2.45
	Second	7,145	7,542	2.45	7,145	2.51
Blue	First (Reference)	775	775	1.44	775	1.44
	Second	775	967	1.44	775	1.88

TABLE 3. Measured luminance of green and blue LEDs when the reference VDATA was applied.

	The brightest LED	Reference LED	The darkest LED
Green LED Luminance [cd/m²] (VDATA = 2.45 V)	8,469	7,145	6,757
Blue LED Luminance [cd/m²] (VDATA = 1.44 V)	1,096	775	709

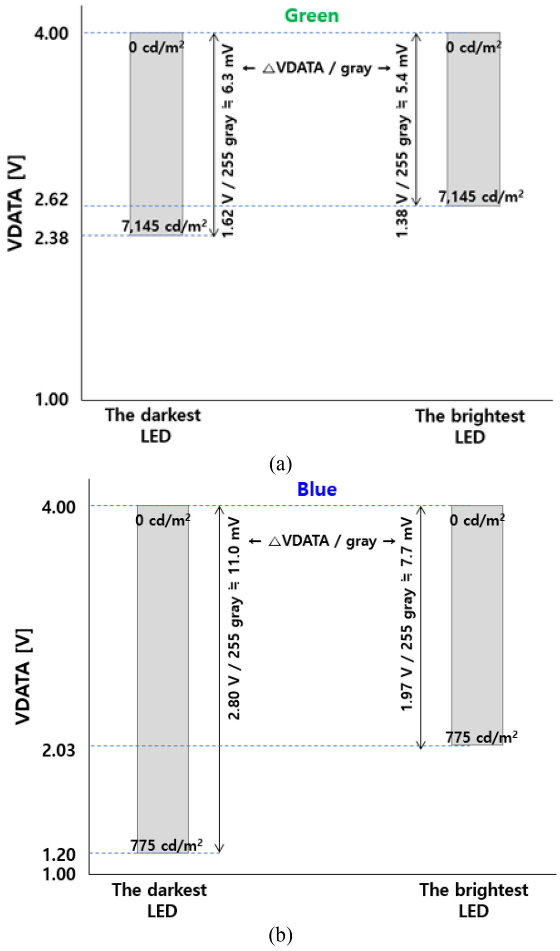

FIGURE 7. VDATA range, ΔVDATA/gray of (a) green LEDs and (b) blue LEDs.

converters (DACs) in drivers are linear. VDATA for black image was set to 4.0 V. As shown in Fig. 7(a), VDATA range for the darkest green LED was 1.62 V. The VDATA ranges of the darkest and brightest LEDs must contain 256 levels to express 8-bit grayscale. The incremental VDATA (ΔVDATA) corresponding to one gray level (ΔVDATA/gray) can be obtained by dividing the VDATA range by 255. ΔVDATA/gray of 6.3 mV/gray and 5.4 mV/gray were obtained for the darkest and brightest green LEDs, respectively. The greatest common divisor of 6.3 and 5.4 is 0.9. The bit depth of DAC in drivers must be higher than 8-bit that is bit depth of the digital image data. To drive the darkest and brightest LEDs by the same driver, ΔVDATA per one least-significant bit (LSB) must be at most 0.9 mV/LSB. For one gray level change, the darkest LED and the brightest LED need to change VDATA of 7 and 6 LSBs, respectively. Then, the luminance nonuniformity can be resolved for both the brightest and darkest LEDs. Let's divide the VDATA range of 1.62 V of the darkest green LED by 0.9 mV. Then, we get 1,800 that is bigger than 1,024 (10-bit) and smaller than 2,048 (11-bit). The bit depth of drivers for green LEDs must be at least 11-bit. Thus, VDATA per LSB for 11-bit green LED drivers becomes 0.79 mV. As shown in Fig. 7(b), the VDATA range for blue LEDs was 2.80 V. ΔVDATA / gray of the darkest and brightest blue LEDs were 11.0 mV and 7.7 mV, respectively. The greatest common divisor of 11.0 mV and 7.7 mV is 1.1 mV. We get 2,546 when dividing 2.80 V with 1.1 mV, which is bigger than 2,048 (11-bit) and smaller than 4,096 (12-bit). The bit depth of drivers for blue LEDs must be 12-bit. Thus, VDATA per LSB for 12-bit blue LED drivers becomes 0.68 mV. Fig. 8 shows VDATA ranges, bit depth of drivers, ΔVDATA / LSB of green LEDs and blue LEDs.

We can determine 11-/12-bit digital data (D_{max}) for each green/blue LED to emit the same luminance of 7,145/775 cd/m^2. We found that D_{max}'s of the green LED #5 and the blue LED #25 were the biggest among green and blue LEDs, respectively. They have the minimum number of available digital data up to 2047 and 4095 for green and blue LEDs, respectively. Thus, they may have maximum digital error to compensate for the luminance non-uniformity. We need to evaluate the determined bit-depth by using a just noticeable

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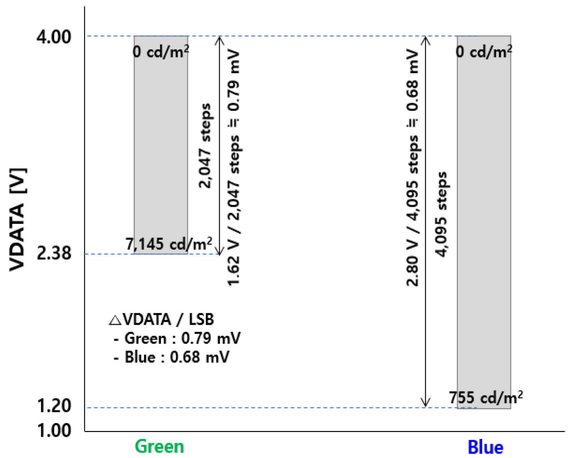

FIGURE 8. VDATA range, bit depth of drivers, ΔVDATA/LSB of green LEDs and blue LEDs.

TABLE 4. Calculated 11-/12-bit digital data and luminance error ratios (ΔL/L) for the selected green/blue LEDs.

X	Green LED #5		Blue LED #25	
	D_{11}	ΔL/L	D_{12}	ΔL/L
8/8	304	0.126 %	1214	0.076 %
7/8	522	0.144 %	1574	0.087 %
6/8	740	0.168 %	1934	0.102 %
5/8	958	0.202 %	2294	0.122 %
4/8	1175	0.252 %	2654	0.153 %
3/8	1393	0.336 %	3015	0.204 %
2/8	1611	0.505 %	3375	0.306 %
1/8	1829	1.012 %	3735	0.612 %

difference (JND). Fujine at al. claimed that JND (ΔL/L) is almost 0.01 when display luminance is higher than 0.5 cd/m^2 [14]. We assume the gamma value of the LED display is 2.2. Thus, the luminance (L) becomes as follows:

$$L = L_{max}\left(\frac{2^n - 1 - D_n}{2^n - 1 - D_{max}}\right)^{2.2} = L_{max}(X)^{2.2} \quad (2)$$

In Eq. (2), L_{max} and D_n are the maximum luminance (7,145/775 cd/m^2 for green/blue LEDs) and n-bit (11/12-bit for green/blue LEDs) input data to the linear DAC, respectively. $2^n - 1 - D_n$ is used instead of D_n because the luminance becomes lower as D_n increases. The largest digital error is just 1 LSB. Thus, we can calculate the luminance (L) and the luminance error (ΔL) depending on X given in Eq. (2). Table 4 shows the calculation results for the green LED #5 and the blue LED #25. As shown in Table 4, calculated ΔL/L values for various luminance levels were almost smaller than 1%.

Micro-LED display is composed of many LEDs. For example, there are two million RGB LEDs in an FHD display. Conventionally, digital image data were directly input to the digital to analog converters (DACs) in driver ICs, and then lights are emitted according to converted analog voltages VDATAs. To inspect the luminance nonuniformity of the LEDs, a CCD (charge coupled device) camera is used as shown in Fig. 9. By using the CCD camera, luminance

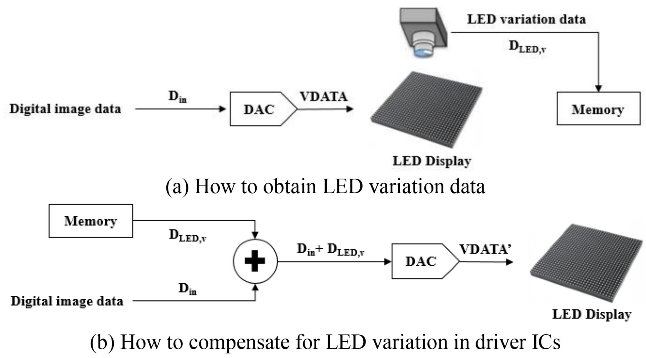

FIGURE 9. Schematic diagram on (a) how to obtain LED variation data using CCD camera and (b) how to compensate for LED variation in driver ICs.

variation data are taken from the micro-LED display with 7T1C compensation circuits when a VDATA is applied to all the red (or green or blue) subpixels. The obtained optical data are converted to LED variation data (D_{LED},v). Then, D_{LED},vs are stored in a memory in a driver as shown in Fig. 9(a). D_{LED},v read from the memory is added to digital image data (D_{in}). New analog VDATA' converted from the sum of Din and D_{LED},v compensates for the variation of LEDs. In this way, driver ICs for micro-LED displays need to integrate a memory storing LED variation data.

Currently available drivers feature the bit depth of 10-bit. Our findings revealed that at least 11-bit or 12-bit drivers are necessary. The requirement of higher bit depth seems to be caused by the abrupt current-voltage relation of LEDs and non-uniformity of them. If luminance and VDATA are measured more strictly or more accurately, the bit depth must be very high, for example 18-bit. However, it is impossible to implement 18-bit DACs in driver ICs. Our investigation is focused on the implementable specification of driver ICs for micro-LED displays. The drivers with higher bit depth for AMLED displays, however, may be unrealistic at the moment. 11-bit or 12-bit drivers may need far larger chip area, which increases the cost of drivers. To implement 11-bit or 12-bit-like drivers, we can adopt dithering or frame rate control (FRC) technologies [16], [17], [18] that have been used for display to increase grayscale expression even using drivers with lower bit depth. Thus, we believe that dithered 11-bit or 12-bit drivers (intrinsic bit depth: 9-bit or 10-bit), will work for AMLED displays. We have specified the minimum bit depth of drivers for AMLED displays for the first time.

IV. CONCLUSION

The luminance nonuniformity among LEDs with 7T1C compensation pixel circuit comprising LTPO TFTs was investigated. The normalized luminance of thirty green LEDs ranged from 95% to 119%. The luminance of thirty blue LEDs ranged from 91% to 141%. In order to emit the same luminance, green LEDs have a maximum data voltage deviation of 0.24 V, while blue LEDs have a maximum deviation of 0.83 V. Bit depth of drivers to re-solve the luminance nonuniformity of AMLED display is required at least 11-bit or 12-bit for green or blue LEDs, respectively, which is the first study in the world.

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