P-Type LTPS TFT-based Micro Light-Emitting Diode Pixel Circuit using Quaternary Digital Driving

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ABSTRACT

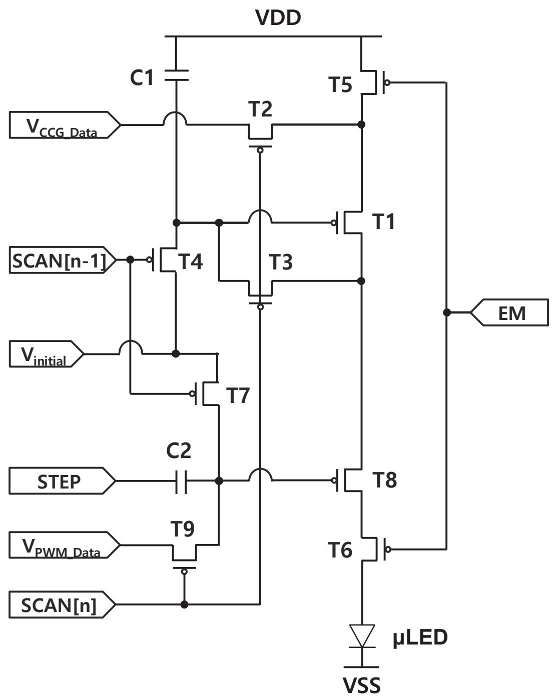
We proposed a micro light-emitting diode (μLED) pixel circuit using quaternary digital driving. The proposed circuit used a stepwise signal to control the emission time. The proposed circuit exhibited a low delay time below 500 ns and an error rate below 3% with a threshold voltage shift of ±0.5 V.

1 Introduction

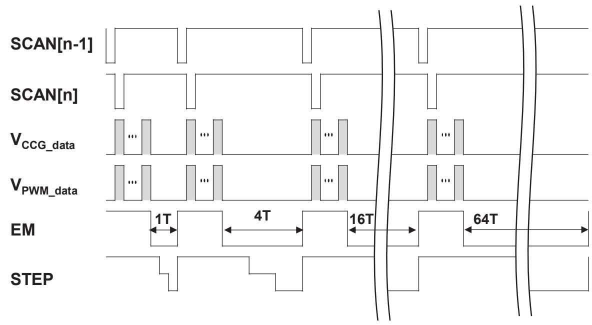
Micro light-emitting diodes (μLEDs) have been extensively studied as a promising candidate for a next-generation display technology [1]. Although commercial μLED displays are based on a printed circuit board (PCB) until now, μLED pixel circuits based on thin-film transistors (TFTs) have been studied to reduce production costs [2-3]. Although pulse amplitude modulation (PAM) has been widely used for organic light-emitting diodes (OLEDs), it is hard to be used for μLED due to the wavelength shift of μLED as current density variations. Therefore, the grayscale of μLED displays should be expressed with the constant μLED current to avoid image distortion due to color shift. In the previous reports, pulse width modulation (PWM) and digital driving method were applied to TFT-based μLED pixel circuits to modulate grayscale with the fixed μLED current [2-3].

The PWM μLED pixel circuit modulates the emission time using the gradually decreased signal [2]. Although the PWM μLED pixel circuit can express the grayscale with the fixed μLED current, it has some issues, such as considerable falling time and circuit complexity. The reported digital driving μLED pixel circuit expresses the grayscales using eight subframes with different emission times [3]. The digital driving pixel circuit conducts the data signal writing and the compensates for threshold voltage (V_{TH}) before each subframe. Therefore, the digital driving circuit needs a high-speed data driver and considerable compensation time.

Herein, we proposed a new μLED pixel circuit based on p-type low-temperature polycrystalline silicon (LTPS) TFTs using the quaternary digital driving method. The proposed circuit successfully expressed 256 gray levels based on digital driving with four subframes. Furthermore, although the internal compensation circuit was not implemented in the PWM unit, the proposed circuit exhibited a sufficiently low error rate of luminance below 3.0% with V_{TH} variations of ±0.5 V.



(a)



(b)

Fig. 1 Proposed μLED pixel circuit (a) schematic and (b) timing diagram.

2 Proposed μLED Pixel Circuit

Fig. 1 shows the proposed μLED pixel circuit schematic and timing. The proposed pixel circuit is composed of 9 TFTs and two capacitors (9T2C) and consists of PWM and constant current generation (CCG) units, as shown in Fig. 1(a). The PWM unit modulates the emission time for each subframe, and the CCG unit flows the constant μLED current. The STEP signal modulates the emission time of each subframe. The proposed pixel circuit can reduce the number of subframes by using the STEP signal.

The proposed circuit operation for each subframe is divided into three periods: initialization, PWM and CCG data writing, and μLED emission. The subframe is repeated four times with different emission times during one frame.

In the initialization period, the switching TFTs for initializing are turned on, and the control nodes of PWM and CCG units are initialized as an initial voltage level.

The PWM and CCG data are simultaneously stored in the following period. In this period, the V_{th}-compensated CCG data is stored in C1 using the diode-connection structure, while the PWM data is stored in C2 without Vth compensation.

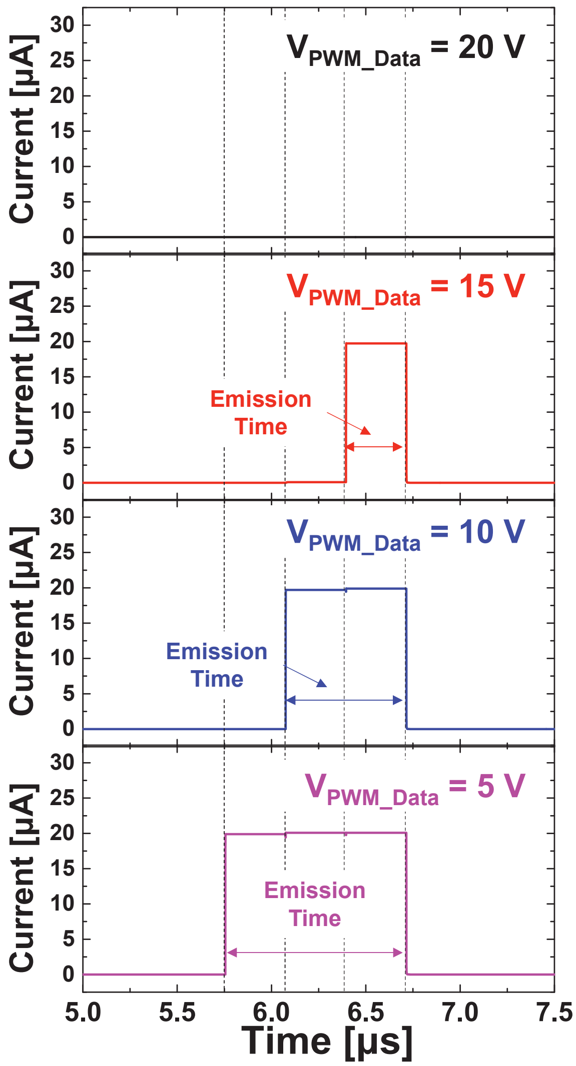


Fig. 2 μLED current waveforms varying V_{PWM_Data} from 5 to 20 V.

In the emission period, the emission TFTs are turned on, and the PWM driving TFT (T8) gate node voltage is changed by a STEP signal using a capacitive coupling effect. The STEP signal is a stepwise signal having three voltage levels in the emission period. When the PWM driving TFT is turned on, as the gate node voltage of T8 decreases, the current flows through the PWM driving TFT. As a result, the μLEDs start to emit light.

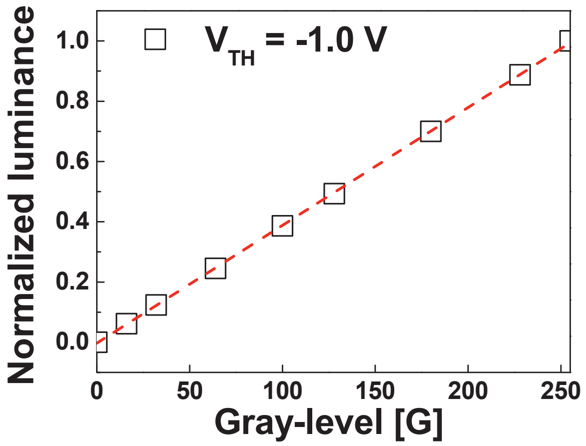
3 Results and Discussion

We investigated the proposed circuit operation using the circuit simulation (SmartSpice, Silvaco). The low and high voltage levels of SCAN and EM signals are -5 and 20 V, respectively. The initial V_{TH} of all TFTs used in the circuit simulation was set to -1.0 V.

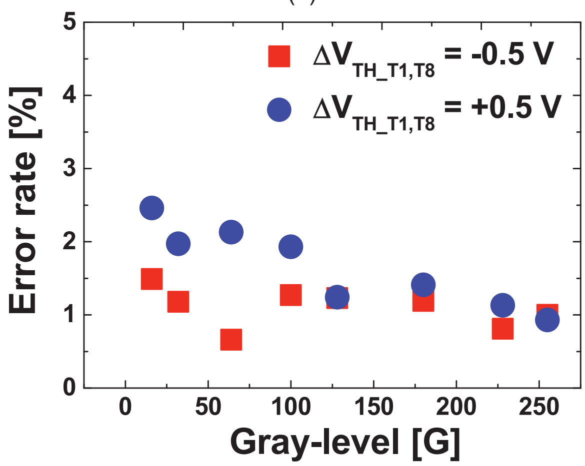
Fig. 2 shows the μLED current waveforms of the last subframe with different PWM data values. As mentioned earlier, the μLED emission starts when the PWM driving TFT is turned on in the proposed pixel circuit. Because the gate node voltage of the PWM driving TFT decreased with the STEP signal, the μLED emission time increased as the PWM data decreased. Furthermore, the μLED current sharply increased and dropped at the beginning and end of the emission, respectively. The rising and falling time of the proposed pixel circuit were below 500 ns. These low delay times were attributed to the STEP signal. The PWM driving TFT's current-driving capability increased quickly because the STEP signal's voltage level changed rapidly.

We investigated the luminance controllability of the proposed pixel circuit as the PWM data of each subframe varied. The emission time of each subframe was controlled by the same method. As mentioned earlier, the proposed pixel circuit operated one frame time dividing four subframes, and each subframe can have four different emission times. As a result, the proposed μLED pixel circuit can express 256 gray levels. Fig. 3(a) shows the normalized luminance according to the gray levels. The proposed circuit successfully controlled the brightness of the gray levels.

Fig. 3(b) shows the luminance error rate of the proposed pixel circuit under V_{TH} shift (ΔV_{TH}) of ±0.5 V. the V_{TH} of the PWM driving TFT is not compensated in the proposed pixel circuit. However, the proposed pixel circuit exhibited a low error rate below 3% under ΔV_{TH} of ±0.5 V. The μLED emission starts when the gate node voltage of the PWM driving TFT is sufficiently low to flow the μLED current. The gate node voltage of T8 is changed as the voltage-level change of the STEP signal. Because the STEP signal rapidly changed, the V_{TH} variations of the PWM driving TFT had a negligible effect on the LED emission time with the sufficient voltage-level change of the STEP signal.



(a)



(b)

Fig. 3 (a) Normalized luminance as gray-level varied. (b) The luminance error rate of the proposed μLED pixel circuit with ΔV_{TH} of $\pm$0.5 V.

4 Conclusions

We proposed a p-type LTPS TFT-based μLED pixel circuit using a quaternary digital driving method. The proposed pixel circuit modulated the emission time with the constant μLED current to avoid the color shift and used the stepwise signal to control the emission time of each subframe. We simulated the circuit operation and reliability. The proposed circuit controlled the emission time of each subframe by varying the PWM data and successfully modulated the luminance according to gray levels. The proposed circuit exhibited low rising and falling time below 500 nm. Furthermore, the proposed pixel circuit exhibited a low luminance error rate below 3%, although the V_{TH} of the PWM driving TFT was not compensated. These results are attributed to the rapidly changed STEP signal. Consequently, the proposed μLED pixel circuit using a quaternary digital driving exhibited a reliable operation and an excellent grayscale-expression capability.

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