LTPS TFT-Based Micro Light-Emitting Diode Pixel Circuit with Fast Falling Time

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Abstract

We proposed a p-type low-temperature polycrystalline silicon thin-film transistor(TFT)-based micro light-emitting diode (μLED) pixel circuit using pulse width modulation driving method. The circuit achieved fast falling times of 1.8 μs by increasing the source voltage of the driving TFT when μLED turns off.

Author Keywords

Micro light-emitting diode pixel circuit; pulse width modulation; low-temperature polycrystalline silicon thin-film transistors; falling time

1. Introduction

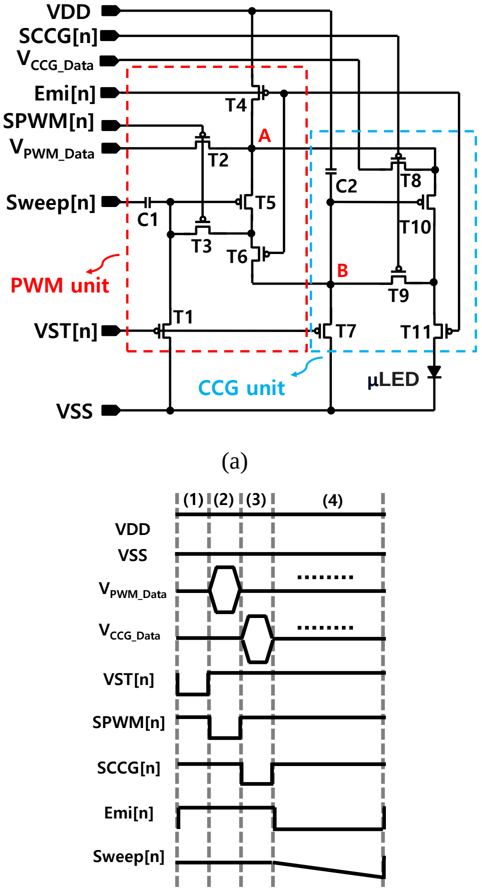
Micro light-emitting diode (μLED) displays are expected to be the next-generation display technology, due to their excellent image quality, high contrast ratio, high luminance, and high efficiency [1]. However, designing pixel circuits for μLEDs requires careful consideration of their characteristics. One issue is the wavelength shift caused by variations in current density [2]. Therefore, μLED pixel circuits widely employ pulse width modulation (PWM) driving method [3], [4], [5]. The PWM driving method modulates the emission time while maintaining a constant current, effectively preventing wavelength shifts and preserving color accuracy [3], [4].

However, despite these advantages, there is an issue with long falling time of the μLED current caused by ramping Sweep signal. This issue can be a limitation in expressing low gray levels. Therefore, several μLED pixel circuits have been developed to improve falling time [5], [6]. Previous works reported that pixel circuits include inverters which consisted of p-type low-temperature polycrystalline silicon (LTPS) thin-film transistors (TFTs) and n-type metal-oxide compound semiconductor TFT. And this hybrid backplane technology is called low-temperature polycrystalline silicon and oxide (LTPO). However, LTPO TFT fabrication processes are more complicated than conventional LTPS TFT fabrication process [7]. Thus, LTPS TFTs-based μLED pixel circuits with fast falling time can be notable advantage in the development of μLED display pixel circuits.

In this paper, we proposed a μLED pixel circuit using only p-type LTPS TFTs without an inverter structure. The proposed pixel circuit achieves fast falling times by voltage variance at the source node of PWM unit and constant current generation (CCG) unit driving TFTs. Additionally, the proposed pixel circuit includes a compensation structure for the threshold voltage (V_{TH}) shifts of the driving TFTs. We investigated the operation of the proposed μLED pixel circuit and successfully expressed 256 gray levels despite V_{TH} variation. The proposed circuit improved low gray level expression by fast μLED current falling time.

2. Proposed Pixel Circuit

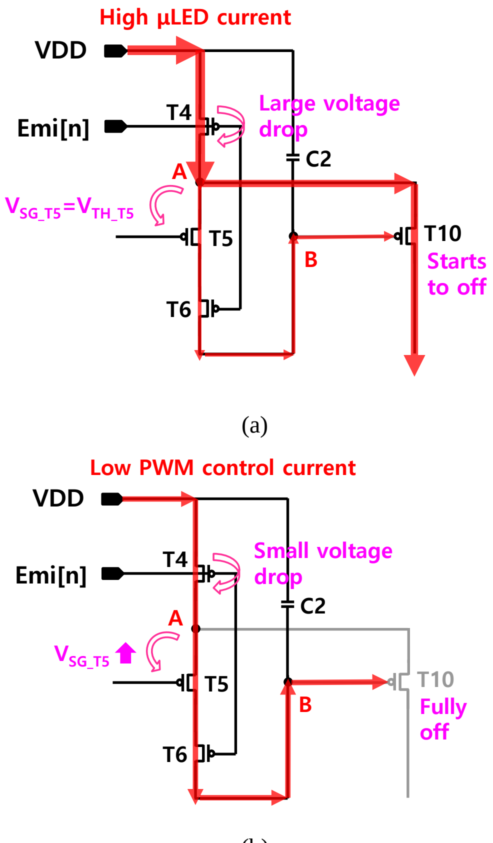
Figure 1 (a) and (b) respectively show, the circuit schematic and timing diagram of the proposed μLED pixel circuit, which consists of eleven TFTs and two capacitors (11T2C). The circuit is divided into two units: the PWM unit and the CCG unit. These units share the source node (node A) of their respective driving TFTs (T5, T10), which is connected to the VDD power source via a switching TFT (T4). The PWM unit compensates for the V_{TH} of the PWM driving TFT (V_{TH_T5}) and controls the μLED emission time by using PWM data voltage (V_{PWM_Data}) and the Sweep[n] signal. The CCG unit also compensates for the V_{TH} of the CCG driving TFT (V_{TH_T10}) and ensures a constant μLED current flow with CCG data voltage (V_{CCG_Data}).



(a)

(b)

Figure 1. (a) Circuit schematic and (b) timing diagram of the proposed μLED pixel circuit.



(a)

(b)

Figure 2. (a) Proposed circuit operation in emission period when µLED starts to turn off and (b) µLED turns fully off.

The proposed µLED pixel circuit operation can be divided into four periods: (1) initialization, (2) V_{PWM_Data} writing and V_{TH_T5} compensation, (3) V_{CCG_Data} writing and V_{TH_T10} compensation, and (4) µLED emission period.

In the initialization period, VST[n] signal becomes the low-level voltage of -5 V, turning on T1 and T7, and initializing the gate node of T5 and node B to the VSS voltage level.

In the V_{PWM_Data} writing and V_{TH} compensation period, SPWM[n] signal becomes the low-level voltage of -5 V, turning on T2 and T3. Through the diode connection structure (T2, T3, and T5), V_{TH_T5} compensation occurs. Then gate node voltage of T5 becomes $V_{PWM\_Data}+V_{TH\_T5}$ and stored in C1.

In the V_{CCG_Data} writing and V_{TH} compensation period, SCCG[n] signal becomes the low-level voltage of -5 V, turning on T8 and T9. Through the diode connection structure (T8, T9, and T10), V_{TH_T10} compensation occurs. Then gate node of T10, which is node B, becomes $V_{CCG\_Data}+V_{TH\_T10}$ and stored in C2.

In the emission period, Emi[n] signal becomes the low-level voltage of -5 V, turning on T4, T6, and T11. First, T5 is in the off state, while T10 remains on, as shown in Figure 2(a). The µLED current flows from VDD through T4, which has a larger TFT channel length than width, causing a voltage drop at node A. This current is determined by the source-gate voltage of T10 (V_{SG_T10}), which drives the µLED to emit light.

Table 1. Design parameters of the proposed circuit

Parameter Values of Proposed Pixel Circuit			
L of all TFT except T4	4 µm	VDD	12 V
L of T4	12 µm	VSS	0 V
W of T1-T4, T7-T9	4 µm	V_{PWM_Data}	7.2 to 12.5 V
W of T5-T6, T10	8 µm	V_{CCG_Data}	4.7 V
W of T11	12 µm	VST[n]	-5 to 15 V
C1	300 fF	SPWM[n]	
C2	500 fF	SCCG[n]	
Sweep[n]	0 to 5 V	Emi[n]	
L = TFT channel length, W = TFT channel width			

Second, as the Sweep[n] signal decreases, the gate voltage of T5 decreases due to the coupling effect of C1. When source-gate voltage of T5 (V_{SG_T5}) exceeds V_{TH_T5}, T5 turns on. This causes node B to rise toward VDD slowly because at this moment, V_{SG_T5} remains small. Third, as node B voltage increases, T10 begins to turn off, reducing the current flows through T4. This decreased current reduces the voltage drop across T4, raising node A voltage toward VDD. This increases V_{SG_T5}, allowing T5 to conduct more current, accelerating the rise of node B. With node B rising rapidly, T10 fully turns off, as shown in Figure 2(b). Therefore fast falling time of the µLED current has been achieved.

3. Results and Discussion

We investigated the proposed circuit through simulation (Smartspice, Silvaco). We assumed a modular panel with 470 horizontal gate lines, a 120Hz frame rate, and progressive emission with one horizontal time (H) of 18 µs. The emission period was set to 90 µs times and could be repeated using a multicycle operation to achieve the desired luminance. Table. 1 shows the specifications of the proposed PWM pixel circuit design using p-type LTPS TFTs.

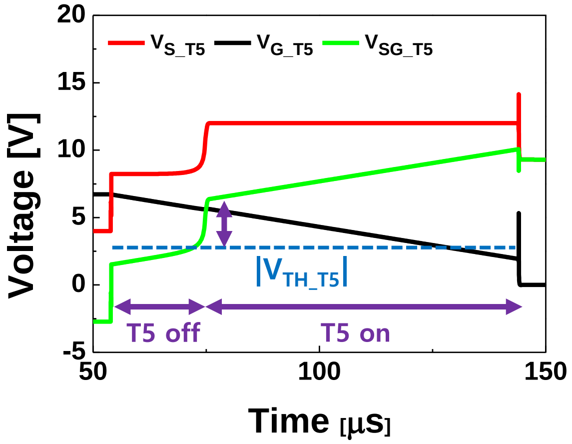
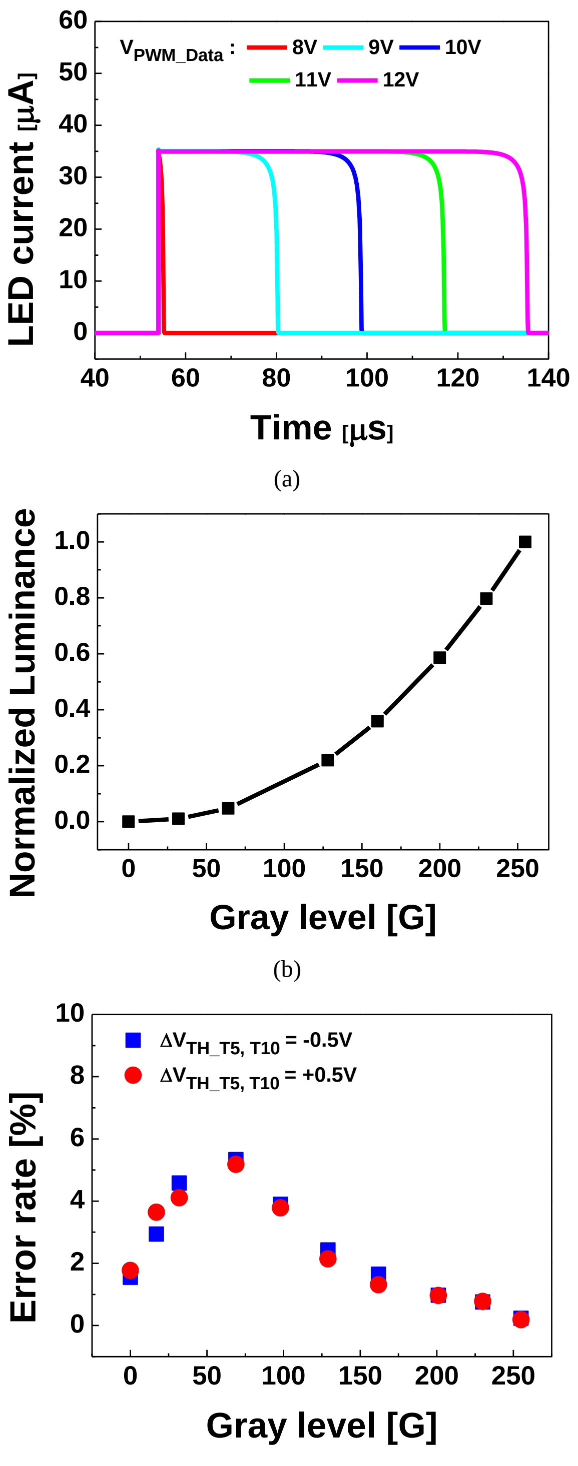


Figure 3. Source and gate node voltage of T5 during emission period.



(a)

(b)

(c)

Figure 4. (a) μLED current waveforms (b) normalized luminance at 2.2-gamma correction (c) Error rate of luminance with the shift of $V_{TH\_T5,\ T10}$.

Figure 3 shows the variation of V_{SG_T5} during the emission period. First, the μLED emits light and a high μLED current of 35 μA flows through T4 and T10. This current causes a voltage drop across T4, setting the source voltage of T5 (V_{S_T5}) to 8.2 V, reduced from the VDD of 12 V. As gate voltage of T5 (V_{G_T5}) decreases from V_{PWM_Data}+ V_{TH_T5} of 7.0 V due to the coupling of the Sweep[n] signal, T5 turns on when V_{SG_T5} exceeds V_{TH_T5}. Once T5 turns on, node B voltage rises to VDD, turning off T10. This transition reduces the μLED current to a low PWM control current of 8.8 μA, which flows through T4 and T5. This current is smaller compared to μLED current, so the voltage drop across T4 reduces, causing V_{S_T5} to rise toward VDD. As a result, V_{SG_T5} increases rapidly, accelerating the rise of node B's voltage and further speeding up the turn off process of T10. Consequently, the μLED current can achieve fast falling time. The falling time is calculated as the time between the 90% point and the 10% point of the peak current and is extracted 1.8 μs, and can express 43G without reduction of peak current. This result is improved than previous LTPS-based μLED pixel circuit [3], which can express 93G with PWM driving method, and therefore proposed circuit achieved improved low gray level expression in LTPS-based μLED pixel circuit.

Figure 4(a) illustrates the μLED current waveforms for various V_{PWM_Data} voltages from 8 V to 12 V, demonstrating PWM operation with a constant peak current of 35 μA during the emission period. Therefore, these results confirm the ability to express gray levels through PWM by adjusting V_{PWM_Data}.

Figure 4(b) shows normalized luminance based on a 2.2-gamma corrected 256 gray levels for the proposed pixel circuit. Luminance was estimated by integrating the μLED current over the emission time. The proposed pixel circuit successfully achieved 256 gray levels with 2.2-gamma correction.

The performance of the proposed pixel circuit under V_{TH} variations (ΔV_{TH}) was also investigated. Figure 4(c) shows the luminance error rate for $\Delta V_{TH\_T5,\ T10}$ of ±0.5 V. The proposed circuit compensates for the V_{TH} of the PWM driving TFT and CCG driving TFT by using a diode connection structure. The proposed μLED pixel circuit effectively compensates for the V_{TH} shifts of both the PWM driving TFT and the CCG driving TFT. The luminance error rate was below 5.3% under Δ $V_{TH\_T5,\ T10}$ of ±0.5 V. These results confirm circuit's stable operation under the V_{TH} variations.

4. Conclusion

We proposed an LTPS TFT-based μLED pixel circuit employing a PWM driving method to address the wavelength shift issue and expressed the gray levels successfully by setting a constant current density. By sharing the source node of T5 and T10, we achieved a fast falling time of μLED current. Simulation results verified that the proposed circuit successfully expressed 256 gray levels with a 2.2-gamma correction using the PWM driving method. The proposed pixel circuit could express low gray levels, including 43G due to the fast falling time of 1.8 μs. Additionally, the proposed circuit compensates for V_{TH} variations in the PWM and CCG driving TFTs through a diode connection compensation structure, ensuring stable μLED current even under V_{TH} variations. The maximum error rate of the luminance was only 5.3% under ΔV_{TH} of ±0.5 V. In conclusion, the proposed μLED pixel circuit demonstrated effective PWM operation, achieved precise gray level expression, and operated stably despite the variations in the V_{TH} of the driving TFTs, using only p-type TFTs.

5. Acknowledgements

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