Investigation on operation robustness of p-type low-temperature polycrystalline silicon thin-film transistor-based micro light-emitting diode pixel circuit using pulse width modulation under component fluctuation

Jongsu Oh\textsuperscript{a,b}, Jin-Ho Kim\textsuperscript{b}, Eun Kyo Jung\textsuperscript{a}, Jongsul Min\textsuperscript{b}, Hwarim Im\textsuperscript{a} and Yong-Sang Kim\textsuperscript{a}

\textsuperscript{a}Department of Electrical and Computer Engineering, Sungkyunkwan University, Suwon, Korea; \textsuperscript{b}Visual Display Business, Samsung Electronics Co., Ltd., Suwon, Korea

\section*{ABSTRACT}
In this study, we have investigated the operation robustness of a p-type low-temperature polycrystalline silicon (LTPS) thin-film transistor (TFT)-based micro light-emitting diode (µLED) pixel circuit adopting pulse width modulation (PWM) under circuit component fluctuations. The wavelength shift of µLEDs, depending on the current density, was suppressed by implementing PWM. The PWM pixel circuit controlled the emission time with constant µLED current in the simulated and measured results. In addition, the wavelength shift was suppressed below 0.48% within the 10-bit grayscale range. Furthermore, the component tolerance of the pixel circuit was investigated by simulating the error rate of µLED emission time with varying threshold voltage, mobility, subthreshold swing, and capacitance. The pixel circuit exhibited a robust operation with a maximum error rate of 4.0% under a component fluctuation of \(\pm 10\%\). Consequently, the µLED pixel circuit adopting PWM suppressed the wavelength shift of µLEDs and demonstrated robust circuit operation under component fluctuation.

\section*{1. Introduction}
Recently, micro light-emitting diode (µLED) displays have attracted significant attention as promising alternatives to next-generation displays [1–4]. The µLED displays have several advantages, such as long lifespan, excellent efficiency, and high brightness without burn-in. However, the problems related to µLED displays should be resolved in order to achieve high-quality images. In contrast to organic light-emitting diodes (OLEDs), µLEDs exhibit wavelength shift depending on the current density [5–7]. Therefore, color shift can occur when a grayscale is modulated by using pulse amplitude modulation (PAM), which has been widely used in conventional OLED displays. Pulse width modulation (PWM) is a method used to suppress the color shift of µLEDs [8]. Figure 1 illustrates the operation of PAM and PWM. In PAM, the grayscale is modulated by the current density. Conversely, in PWM, the grayscale is modulated by controlling the emission time of µLEDs with a constant current density. Consequently, a 10-bit grayscale can be stably expressed by applying PWM to a µLED display [8,9]. The other problem is the image distortion caused by the uniformity and degradation of thin-film transistors (TFTs) [10–13]. In particular, circuit malfunction occurs when the threshold voltage (\(V_{th}\)) of driving transistors is varied. Therefore, \(V_{th}\) should be compensated in order to improve the image quality. Internal \(V_{th}\) compensation, such as a diode-connection structure, has been widely used in active-matrix (AM) OLEDs or gate driver circuits [14–16]. \(V_{th}\) can also be compensated by using external IC modules for sensing the electrical characteristics of TFTs. Low-temperature polycrystalline silicon (LTPS) TFTs have been regarded as suitable devices for the backplane of µLED displays, owing to their excellent carrier mobility and stability [17–21]. In particular, LTPS TFTs are suitable for controlling the dozens of µA currents because of their superior electrical performance compared to that of a-Si:H and oxide TFTs. In a previous study, we proposed a p-type LTPS TFT-based µLED pixel circuit by using PWM and internal \(V_{th}\) compensation [8]. The proposed pixel circuit demonstrated an excellent grayscale expression capability and suppressed the wavelength shift. However, the µLED pixel circuit with PWM can be vulnerable to circuit component fluctuations because it used the analog input signal and capacitive coupling effect for PWM operation.
Therefore, the detailed operation and component tolerance of the μLED pixel circuit using PWM should be investigated in order to improve the circuit characteristics. In this study, we investigated the operation robustness of the LTPS-TFT-based μLED pixel circuit adopting the PWM method and internal $V_{\text{th}}$ compensation under component fluctuations. The simulated and measured data of the μLED pixel circuit revealed that the emission time was controlled by the data signal ($V_{\text{data}}$) with a constant μLED current density, and the wavelength shift was suppressed below 0.48%. The μLED pixel circuit using PWM exhibited a maximum emission-time error rate of 3.7% with varying component properties, including $V_{\text{th}}$, field-effect mobility ($\mu_{\text{FE}}$), subthreshold swing ($SS$), and capacitance. This result confirms that the μLED pixel circuit using PWM can exhibit a robust operation in the presence of deviations in the properties of the components.

2. Experiment

The electrical characteristics of LTPS TFTs were investigated in order to design the pixel circuit. Figure 2 depicts the measured and simulated transfer characteristics of LTPS TFTs. The LTPS TFTs exhibited a $V_{\text{th}}$ of $-1.1$ V and $\mu_{\text{FE}}$ of $78.5 \text{ cm}^2/\text{V} \cdot \text{s}$. Furthermore, the gate-induced drain leakage (GIDL) was rarely observed by using a lightly doped drain (LDD) structure. As shown in Figure 2, the simulated transfer characteristics corresponded well with the measured data, and these were used in the circuit simulation (SmartSpice, Silvaco). The operation robustness of the PWM pixel circuit was simulated by varying the parameters of the TFT model. In particular, the zero-bias threshold voltage ($V_{\text{TH0}}$), high-field mobility ($\mu_{\text{H}}$), and subthreshold ideality factor ($\eta$) were varied in order to simulate a deviation in $V_{\text{th}}$, $\mu_{\text{FE}}$, and $SS$, respectively.
3. Operation principle of PWM pixel circuit

Figure 3 illustrates the circuit schematic and the timing diagram of the μLED pixel circuit with PWM. We simplified the previously reported PWM circuit by removing the μLED discharging TFT in order to intensively analyze operation robustness. The simplified pixel circuit is composed of 12 TFTs and 2 capacitors. As mentioned previously, it is required to modulate the grayscale of μLED displays by the emission time under a constant current density. Therefore, pixel circuit can be divided into PWM and constant current generation (CCG) parts, as shown in Figure 3(a). The PWM part controls the emission time of each grayscale, whereas the CCG part enables the flow of constant current through μLEDs. The dimensions of the devices used in the circuit simulation are listed in Table 1. The low (VGL) and high (VGH) levels of signals were −5 and 15 V, respectively. The voltage of VDD1, VDD2, and VSS were 11, 12.4, and 0 V, respectively. The circuit operation can be divided into four periods, as shown in Figure 3(b).

3.1. Initialization

At the beginning of each frame, the initialization TFTs (T6, T12) are turned on by the $V_{ST}$ signal. Consequently, nodes A and C, which are the control nodes of the PWM and CCG parts, respectively, are initialized as VGL during the initialization period. The initialization voltage, VGL, is stored in the capacitor of each part. After the initialization period, $V_{INI}$ signal, as well as $V_{ST}$, is VGH to reduce bias stress on T6 and T12.

3.2. Data writing and $V_{th}$ compensation of PWM part

Subsequently, the PWM data ($V_{data,PWM}$) are written and the $V_{th}$ of T1 ($V_{th,T1}$) is compensated. The PWM switching TFTs (T2, T3) are turned on by SPWM[n], which is the output signal of the gate driver. The voltage of node A increases at $V_{data,PWM} + V_{th,T1}$ because T1 and T3 form a diode-connection structure. Consequently, the $V_{th,T1}$-compensated $V_{data,PWM}$ is stored at node A (C1). This process is repeated in all horizontal lines during this period.

3.3. Data writing and $V_{th}$ compensation of CCG part

During this period, the CCG switching TFTs (T8, T9) are in the on-state. Subsequently, T7 and T9 form a diode-connection structure. Consequently, the CCG data ($V_{data,CCG}$) with the compensated $V_{th}$ of T7 ($V_{th,T7}$) are stored in C2. Unlike the PWM data, all the CCG data can be written simultaneously because the same current flows through all the μLEDs of the PWM pixel circuit.

Table 1. Design parameters of the μLED pixel circuit with PWM.

| μLED Pixel Circuit with PWM |   |
|-----------------------------|--|
| L of all TFTs except for T10 | 5 μm |
| L of T10                    | 3 μm |
| W of T4, T5, T10, and T11  | 8 μm |
| W of T2 and T3              | 5 μm |
| W of T8 and T9              | 5 μm |
| W of T6 and T12             | 5 μm |
| W of T1                     | 6 μm |
| W of T7                     | 5 μm |
| C1                          | 220 fF |
| C2                          | 300 fF |

$L = $ TFT channel length, $W = $ TFT channel width

1 frame time = 8.3 ms

Figure 3. (a) Circuit schematic and (b) timing diagram of the simulated PWM pixel circuit.
3.4. Emission

The μLEDs emission period is the final period. At the beginning of this period, the driving (T7) and emission TFTs (T10, T11) are in the on-state, resulting in the emission condition of the μLEDs. Since a gradually varying SWEEP signal is applied to C1, the state of T1 changes from the off-state to the on-state, and VDD1 is applied to node C. Subsequently, the current in the μLEDs becomes negligibly small, and the emission is terminated.

4. Results and discussions

Figure 4(a) illustrates the simulated voltage waveforms of nodes A and C for first stage for 1 frame time (120 Hz: 8.3 ms). As mentioned previously, the emission time was controlled by the voltage of node A. The voltage of node A gradually decreased, whereas that of node C exhibited a constant value. When the voltage of node A was charged by VDD1 + Vth_T1, T1 operated in the on-state, and the voltage of node C was charged by VDD1. In particular, the voltage of node C was approximately 5.3 V at the beginning of emission because we set the \( V_{\text{data}_{-}\text{CCG}} \) to 6.5 V. The voltage of node C changed from 5.3 to 11 V during the emission period, assuming a grayscale of 512. Consequently, the driving TFT of the CCG part (T7) was turned off and the μLEDs stopped emitting light. From this simulation result, we also found that the process of writing the \( V_{\text{data}_{-}\text{CCG}} \) and compensation for \( V_{\text{th}_{-}\text{T7}} \) required approximately 10 μs. Therefore, the simulated PWM pixel circuit can complete the process of data writing and compensation for the pixels within 10 μs.

Figure 4(b) depicts the simulated voltage of nodes A and C during the data writing and \( V_{\text{th}} \) compensation of the PWM part. When a \( V_{\text{data}_{-}\text{PWM}} \) of 13 V was applied to the PWM part, node A was charged by approximately 11.8 V within 3 μs, as shown

![Figure 4.](image-url)
in Figure 4(b). Since this process was sequentially repeated for each horizontal line, the minimum total time of this period could be calculated as the number of horizontal lines multiplied by 3 μs. For example, if the number of horizontal lines was 470, the minimum time required for this process would be 1,410 μs.

Figure 5 shows the simulated voltage of node A and the current of μLEDs with different $V_{data, PWM}$ to verify the PWM operation. As $V_{data, PWM}$ increased, additional time was required to charge node A by $VDD1 + V_{th,T1}$, because a higher voltage was written in C1 during the data writing and $V_{th,T1}$ compensation of the PWM part. Consequently, when the $V_{data, PWM}$ increased from 11.6 to 14.6 V, the emission time linearly increased from 810 to 3,320 μs, as shown in the inset of Figure 5(b). Conversely, the peak current exhibited a constant value, as depicted in Figure 5(b). This simulation result revealed that the PWM pixel circuit could modulate the grayscale by varying the emission time under a constant current density. Furthermore, the maximum emission time under the given panel operation conditions could be estimated based on these simulation results. For instance, when the operation frequency of μLED displays with 470 horizontal lines was 120 Hz, a sufficient duration could be set with a margin for the initialization, data writing, and $V_{th}$ compensation of the PWM part, and that of the CCG part as 50, 4,230, and 20 μs, respectively. Therefore, a maximum emission time of 4,000 μs and a μLED duty of 48.2% could be obtained (Figure 3(b)).

We confirmed that the PWM method suppressed color shift depending on grayscale by measuring the wavelength of the fabricated pixel circuit. The top gate coplanar p-type LTPS TFTs were fabricated by using the conventional process. The μLED chips with a size of 34 μm × 58 μm were implemented in the fabricated pixel circuit. Before measuring the wavelength shift, we found the PWM data for expressing 10-bit grayscale using the gamma correction equation [8]. The PWM data voltage ranged from 7.5 to 15.5 V. Other signal voltages were the same as the simulated values. The spectrum and dominant wavelength at each PWM data were measured by using a spectrophotometer.

The measured wavelength of the fabricated pixel circuit is presented in Table 2. The measured grayscale range was from 80 to 1,020, and the luminance values of the red, green, blue μLEDs were 303, 938, 142 cd/m², respectively. As the grayscale changed from 80 to 1,020, the wavelength shifts of the red, green, and blue μLEDs were 1.0, 2.5, and 0.1 nm, respectively. Wavelength shift occurred even though the constant μLED current was used in the PWM driving. It might originate from the falling time of the μLED current. The fraction of the falling time in the emission time increased at a lower gray level. Consequently, the μLED current is not a constant value in a lower gray level, thus resulting in wavelength shift. However, the maximum rate of change was 0.48%, and this result confirmed that the pixel circuit with PWM efficiently suppressed the wavelength shift of the μLEDs.

We investigated the operation robustness of the PWM pixel circuit under component fluctuation by using a circuit simulation. The variation in the device properties, such as the electrical properties of TFTs and capacitance, can occur due to the degradation and fabrication process deviations. We simulated the emission-time error rate under varying TFT parameters, including $V_{th}$, $\mu_{FE}$, and SS, and capacitances of C1 and C2. The signal timing was set based on Figure 3(b).

Figure 6 shows the simulated emission-time error rate under varying parameters of the driving TFTs (T1, T7), such as $V_{th}$, $\mu_{FE}$, and SS. The emission-time error rate was

| Color | Wavelength (80G) | Wavelength (1020G) | ΔWavelength |
|-------|-----------------|-------------------|-------------|
| Red   | 619.5 nm        | 618.5 nm          | 1.0 nm (0.17%) |
| Green | 526.1 nm        | 523.6 nm          | 2.5 nm (0.48%) |
| Blue  | 461.7 nm        | 461.6 nm          | 0.1 nm (0.03%) |
Figure 6. The simulated emission-time error rate varying (a) $V_{\text{th}}$, (b) $\mu_{\text{FE}}$, and (c) SS of T1 and T7.

calculated as the following equation,

$$\text{Error rate} = \frac{\Delta t_{\text{emi}}}{t_{\text{emio}}}$$

where $\Delta t_{\text{emi}}$ and $t_{\text{emio}}$ are the emission time difference between with and without parameter variations, and emission time without parameter variations, respectively.

Figure 6(a) shows the error rate depending on $V_{\text{th}}$ variation ($\Delta V_{\text{th}}$) and the gray level. We determined the range of $\Delta V_{\text{th}}$ as $\pm 1 \text{V}$ considering the deviation in the LTPS TFT caused by the process and electrical-thermal stress [22]. The maximum error rate of the $\mu$LED emission time was 2.9%, under varying $\Delta V_{\text{th,T1}}$ and $\Delta V_{\text{th,T7}}$ as $\pm 1 \text{V}$, as shown in Figure 6(a). The small error rate was attributed to the internal compensation structure. Since the simulated PWM pixel circuit adopted the diode-connection structure for $V_{\text{th}}$ compensation, nodes A and C were charged by $V_{\text{data,PWM}}+V_{\text{th,T1}}$ and $V_{\text{data,CCG}}+V_{\text{th,T7}}$, respectively, during data writing and $V_{\text{th}}$ compensation period. Therefore, the voltage of nodes A and C was varied according to $\Delta V_{\text{th}}$, and the current of each driving TFT exhibited a constant value regardless of $\Delta V_{\text{th}}$.

However, a small error rate was observed even when the PWM pixel circuit contained an internal compensation structure. The error rate was related to the variation in the voltage of node C. As mentioned earlier, the voltage value of $V_{\text{data,CCG}}+V_{\text{th,T7}}$ was stored in node C during the data writing and $V_{\text{th}}$ compensation of the CCG part. The emission was terminated when the voltage of node C was charged to approximately $V_{\text{DD1}}$. Since the falling time of the $\mu$LED current was related to the transition time of the node C voltage from $V_{\text{data,CCG}}+V_{\text{th,T7}}$ to $V_{\text{DD1}}$, it was affected by $\Delta V_{\text{th}}$. The falling time and emission time decreased with an increase in $V_{\text{th}}$. For this reason, a small error rate in the emission time was still observed by $\Delta V_{\text{th}}$.

Figure 6(b) depicts the emission-time error rate as $\mu_{\text{FE}}$ changed from 70.7 to 86.3 cm$^2$/V-s. The simulated error rate was lower than 0.6%. The $\mu_{\text{FE}}$ is related to the charging time of the $V_{\text{th}}$-compensated $V_{\text{data}}$. Therefore, when $\mu_{\text{FE}}$ decreased, the current through the driving TFTs (T1, T7) decreased and additional time was required to charge $V_{\text{data}}$ in the capacitance (C1, C2). As mentioned earlier, the data writing and $V_{\text{th}}$ compensation for the PWM and CCG part could be completed within 3 and 10 $\mu$s, respectively. Therefore, we set a sufficient time for each period in order to achieve a robust operation upon $\mu_{\text{FE}}$ variation. Additionally, the $\mu_{\text{FE}}$ variation could also change the charging time of C2 from $V_{\text{data,CCG}}+V_{\text{th,T7}}$ to $V_{\text{DD1}}$, it was affected by $\Delta V_{\text{th}}$. The falling time and emission time decreased with an increase in $V_{\text{th}}$. For this reason, a small error rate in the emission time was still observed by $\Delta V_{\text{th}}$.

Figure 6(c) shows the error rate of the emission time as SS changed from 0.27 to 0.35 $\mu$V/dec. The simulated error rate exhibited a negligible value lower than 0.5%. SS affected the voltage of nodes A and C during circuit operation. As SS increased, the drain–source current ($I_{\text{DS}}$) under a low gate–source voltage ($V_{\text{GS}}$) increased.
Figure 7. The simulated emission-time error rate varying the capacitance of C1 and C2.

and $I_{DS}$ under a high $V_{GS}$ decreased. As a result, the SS variation could result in the $V_{th}$-compensated voltage and charging time. In particular, a large SS is expected to lead to the storage of a higher voltage level in C2 and a lower charging time, with an opposite effect on the emission time. Consequently, the SS variation exhibited a negligible effect, as shown in Figure 6(c).

Figure 7 depicts the error rate depending on the variation in C1 and C2. The maximum simulated error rate was 4.0%. The relationship between capacitance variation and the error rate can be explained by the parasitic capacitance of switching TFTs. After the data writing and $V_{th}$ compensation was completed, a high-level voltage was applied to the switching TFTs in the diode-connection structure. Subsequently, the stored voltage level of node A could be slightly increased by the kickback effect due to the parasitic capacitance of T3, and the emission time linearly decreased as the capacitance increased. Consequently, the error rate depending on the capacitance variation could be reduced by increasing the capacitance or decreasing the parasitic capacitance.

5. Conclusion

We investigated the operation robustness of a p-type LTPS TFT-based μLED pixel circuit by using the PWM method under component fluctuations. The timing diagram was designed to obtain a sufficient time for the compensation, and the size of circuit components was selected in order to ensure a stable circuit operation. The measured and simulated results indicated that the PWM pixel circuit exhibited a well-operated internal compensation and modulated the grayscale with the PWM data. Furthermore, the simulated emission-time error rate exhibited a sufficiently small value (lower than 4.0%) under varying $V_{th}$, $\mu_{FE}$, and SS values of the driving TFTs and capacitance. Therefore, we confirmed that the pixel circuit using PWM exhibited robust operation and excellent component tolerance under property deviations of circuit components.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Notes on Contributors

Jongsu Oh received his BS and PhD degrees from the Department of Electrical and Computer Engineering, Sungkyunkwan University, Suwon, South Korea in 2020. He is currently a senior engineer at Samsung Electronics in Suwon. His current research interests are designs of pixel circuits and gate driver circuits employing low-temperature poly-Si TFTs and oxide TFTs for display panels.

Jin-Ho Kim received his PhD degree from the Department of Electrical and Computer Engineering, Sungkyunkwan University, Suwon, South Korea in 2018. He is currently a principal engineer at Samsung Electronics in Suwon. His current research interests are designs of pixel circuits and gate driver circuits employing low-temperature poly-Si TFTs and oxide TFTs for display panels.

Eun Kyo Jung is currently pursuing a combined master’s degree and doctor’s degree with the Nano Electronics and Microfluidic Sensors Laboratory, Sungkyunkwan University, Suwon, South Korea. His current research interests include the design and analysis of gate driver circuits and pixel circuits.

Jongsul Min received his bachelor’s degree in 1991 and master’s degree in 2003 from the electronic engineering in Korea University, Seoul, Korea. He is currently a corporate vice president at Samsung Electronics in Suwon, Korea. His current research interest is micro light-emitting diodes (μLEDs).

Hwarim Im received his BS and PhD degrees in electrical engineering and computer science from Seoul National University, Seoul, South Korea in 2010 and 2016, respectively. He worked as a senior engineer at Samsung Display from 2016 to 2021. Since 2021, he has been a research professor at Sungkyunkwan University. His current research interests include physics of thin-film devices, and thin-film transistor-based circuits and electronics.
Yong-Sang Kim received his BS and PhD degrees in electrical engineering from Seoul National University in 1988 and 1994, respectively. Since 2013, he has been a professor at the Department of Electrical and Computer Engineering, Sungkyunkwan University. He was also a professor at Myongji University from 1995 to 2013. He is currently the director of the Nano Electronics and Microfluidic Sensor Laboratory, Sungkyunkwan University, where he has several research works focused on oxide TFTs, transistor-based biosensor, organic solar cells, and solution-processing technologies for organic electronic devices. His research interests include the design, fabrication, and characterization of AMLCD and AMOLED TFT backplane with a-Si:H TFTs, a-IGZO TFTs, and LTPS TFTs, as well as numerical simulation using TCAD and SmartSpice. Another specific topic in his research activities involves the gate scan driver circuit for display backplane and compensation circuit for AMOLED pixel circuit design.

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