Digital PWM Driving MicroLED Pixel Circuit using a-ITZO TFTs

Yong-Duck Kim* **, In Bok Baek, Jong-Heon Yang**, Chun-Won Byun****
, and Bum-Sik Kim*
***Department of Electronic Engineering, Hanyang University, Seoul, South Korea**
****Electronics and Telecommunications Research Institute, Daejeon KOREA**
Email: yongduck@etri.re.kr

Abstract

Micro light-emitting diode (micro-LED) displays show significant potential for large-area display applications; however, challenges such as external quantum efficiency (EQE) variations and wavelength shift remain. To address these issues, a pixel circuit utilizing the pulse width modulation (PWM) driving method is proposed, offering low power consumption and superior display performance for modular displays. Additionally, an external compensation mechanism is introduced to minimize the number of thin-film transistors (TFTs) and input signals required, ensuring enhanced efficiency and simplified design. The proposed 5T1C pixel circuit operates in three distinct periods—initial & programming, emission, and reset—and utilizes amorphous indium-tin-zinc oxide (a-ITZO) TFTs. The circuit operates PWM compensation technique that adjusts pulse width using additional extra-bits, significantly reducing memory requirements and data driver complexity compared to conventional methods. Experimental results demonstrate successful operation of the fabricated a-ITZO TFT pixel array and gate driver, with verified brightness variations across gray levels, confirming its suitability for micro-LED modular displays.

Author Keywords

Micro-LED, large-sized display, pixel circuit, Micro LED panel

1. Introduction

In the large-sized display market, particularly for TVs, there is a growing demand for larger mother glass sizes to improve the yield of display panels. To address these yield challenges, modular displays, which are formed by connecting multiple smaller-sized panels, have gained increasing attention [1-3].

For the modular displays, micro light-emitting diodes (micro LEDs) are being considered due to their attractive characteristics, such as higher luminance, faster response times, longer lifetimes, wider color gamut, and lower power consumption compared to organic light-emitting diodes (OLEDs) [4-5]. However, micro LEDs exhibit variations in external quantum efficiency (EQE) and wavelength shifts depending on the current density. These properties make it difficult to apply pulse amplitude modulation (PAM), commonly used in OLEDs, where brightness is controlled by varying current levels over time. To overcome the limit to apply PAM, most previous researches have focused on developing pixel circuits of pulse width modulation (PWM), where brightness is controlled by varying the duration of current pulses while maintaining a constant current level. This approach effectively addresses the EQE and wavelength shift issues inherent to micro LEDs.

The PWM driving method can be categorized into analog PWM and digital PWM based on its implementation approach. Analog PWM controls the timing using an analog voltage, typically by comparing a ramp signal, where the voltage changes over time with the magnitude of an applied analog data voltage to regulate on/off states. The analog PWM pixel circuit consists of two main parts: a constant current generation (CCG) part for generating a stable current and a PWM part that adjusts timing using an analog voltage [6-7]. The CCG part utilizes an internal compensation method, as employed in conventional OLED pixel circuits, to reduce variations in thin-film transistor (TFT) characteristics and ensure consistent current generation. However, the PWM part introduces timing variations due to TFT characteristic discrepancies, necessitating an internal compensation mechanism. Both the CCG and PWM parts require internal compensation, which increases the number of required TFTs and capacitors such as 13T 4C [6], and 10T 4C [7]. Additionally, implementing 8-bit analog data input requires a data driver similar to those used in OLEDs, along with a sawtooth generation circuit for producing ramp signals with a constant slope. Combined with the various input signals required for compensation, this places a significant burden on the peripheral circuits.

In contrast, the digital PWM driving method divides the frame time into binary-weighted sub-frames, controlling brightness through on/off switching. The applied data voltage is digital, reducing the complexity of comparators and compensation mechanisms compared to analog PWM. This simplicity allows for a more compact implementation with fewer TFTs and capacitors. However, since data must be updated for each sub-frame, the method demands higher operating speeds and increased power consumption.

In this paper, we propose a pixel circuit employing a digital PWM driving method with a simplified structure using micro LEDs, which offer relatively low power consumption. For modular display applications, amorphous indium-tin-zinc oxide (a-ITZO) TFTs are utilized to achieve high uniformity, high mobility, and low off-current characteristics, thereby minimizing power consumption. Additionally, the proposed pixel circuit incorporates a compensation mechanism to suppress variations in device characteristics.

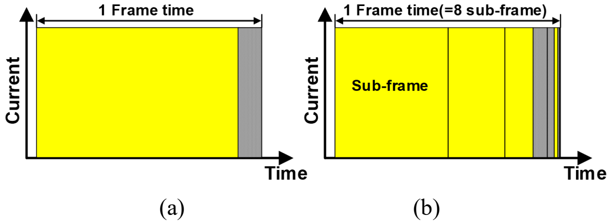

Fig. 1. PWM driving method with (a) analog PWM and (b) digital PWM.

ISSN 0097-996X/25/5603-1711-$1.00 © 2025

2. Conventional Digital PWM Pixel Circuit

As Shown in Fig. 2, pixel circuits employing the digital PWM driving method can be broadly categorized into two types.

The first type, the Display Period Separated (DPS) driving method, separates the addressing time for data input from the emission period. In this method, the number of addressing times is proportional to the number of subframes. Consequently, an increase in the number of subframes and addressing times reduces the available emission time, presenting a significant limitation.

The second type, the Simultaneous Erased Scan (SES) driving method, addresses the emission time reduction issue caused by increased addressing time. This method adjusts operation based on the length of the emission and addressing times for each subframe. For longer emission times, addressing and emission occur simultaneously. For shorter emission times, an erase signal is employed after addressing to turn off the driving transistor, preventing data overlap issues. By utilizing the erase signal, SES achieves a longer emission time compared to DPS. However, while both pixel circuit types allow timing adjustments, they cannot compensate for current variations caused by TFT characteristic deviations.

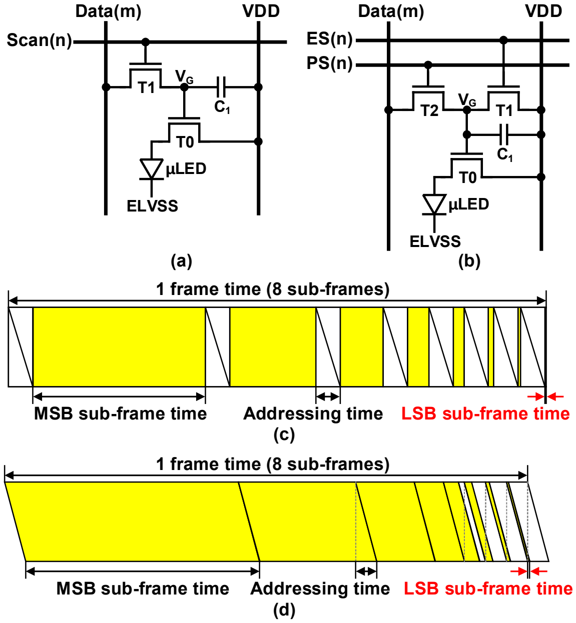

Fig. 2. Pixel circuit of (a) DPS driving, and (b) SES driving, and timing diagram of (c) DPS driving, and (d) SES driving.

3. External Compensated Pixel Circuit

In conventional internal compensation methods used for micro LEDs, a large number of TFTs and signals are required. To minimize these requirements, an external compensation approach is proposed to reduce the number of TFTs and signals. In existing external compensation methods, as shown in Fig. 3, compensation can be achieved using a 3T1C pixel circuit. During display mode, the simultaneous activation of the Gate(n) and Sen(n) signals turns on the M1 and M3 transistors, charging V_G and V_{AN} to V_{DATA} and V_{REF}, respectively. When the Gate(n) and Sen(n) signals are turned off, the emission process begins. During the compensation operation, the simultaneous activation of the Gate(n) and Sen(n) signals allows current or voltage to be sensed externally through Ext(m). Based on the detected variations in current or voltage, the data driver adjusts Data(m) to ensure a consistent current is applied. Consequently, more than 10-bit data voltage is required to implement 8-bit data voltage accuracy.

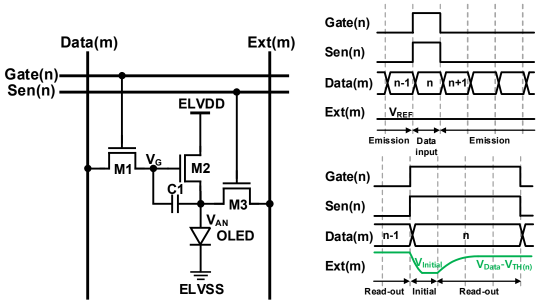

Fig. 3. External compensated 3T 1C pixel circuit and 2 period timing diagrams

4. Proposed Digital PWM Driving Pixel Circuit with External Compensation Method

As shown in Fig.4, The proposed pixel circuit is composed of 5T 1C and operates through three periods. First, initial & programming period: During this period, the Scan(n) signal is set to high, while the Reset(n) signal remains low. This activates the M2 and M3 transistors, enabling the driving transistor (M1) gate to be charged with the data voltage and the source to be charged with the initial voltage. Simultaneously, the anode voltage of the micro LEDs is initialized. Second, emission period: Both the Scan(n) and Reset(n) signals are set to low, allowing the driving transistor (M1) to control the on/off state of the micro-LED according to the applied data voltage. Third, reset period: The Reset(n) signal is set to high, and the Scan(n) signal is set to low. This activates the M4 and M5 transistors, resetting the gate and source voltages of M1, turning it off. The M5 transistor, added to this design, resolves the issue of slow LED turn-off caused by residual source voltage. Since the a-ITZO TFT exhibits depletion characteristics, V_{Reset} is set lower than V_{INIT}, ensuring V_{GS} is below 0V.

The proposed external compensation mechanism, depicted in Fig. 4, operates in two periods: The proposed external compensation mechanism, depicted in Fig. 4, operates in two periods: In initial period, the reset(n) signal is set to high, initializing the gate and source of M1 via M4 and M5. In programming & read-Out period, the Scan(n) signal is set to high, transmitting the data voltage to V_G through M2 while allowing the current to be read out via M3.

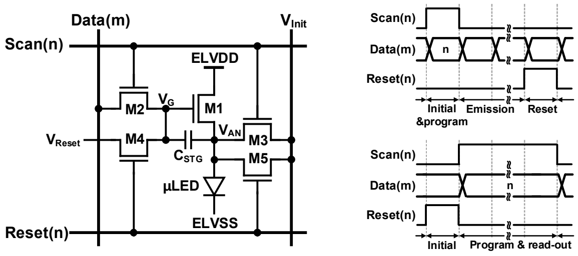

Fig. 4. Proposed pixel circuit 5T 1C pixel circuit and timing diagram

In conventional external compensation methods, as shown in Fig. 5(a), the current generated by the pixel circuit is converted to voltage through a charge integrator, digitized using an analog digital converter (ADC), and stored in memory. A look-up table compares the measured values with the input data to compensate for differences. This approach requires high-precision 10-bit data, demanding significant memory for storing multiple current levels and increasing the data driver size by more than four times.

In contrast, the proposed external compensation method, as shown in Fig. 5(b), simplifies the process by leveraging the on/off nature of PWM driving. Only a single current level is measured and stored in memory, reducing memory requirements significantly. Instead of adjusting amplitude to compensate for current variations, the proposed method adjusts pulse width using additional extra-bits alongside the standard 8-bit data. For example, if the pixel current exceeds the reference current, compensation is achieved by reducing time gradation without using extra bits. Conversely, if the pixel current is below the reference, extra bits are employed to extend the pulse width. The length of the emission time for these extra bits is configured to accommodate current variations. If a maximum current variation of 20% is anticipated, an additional 20% emission time can represent the gradation. This approach enables effective external compensation without significant increases in data driver complexity or memory requirements.

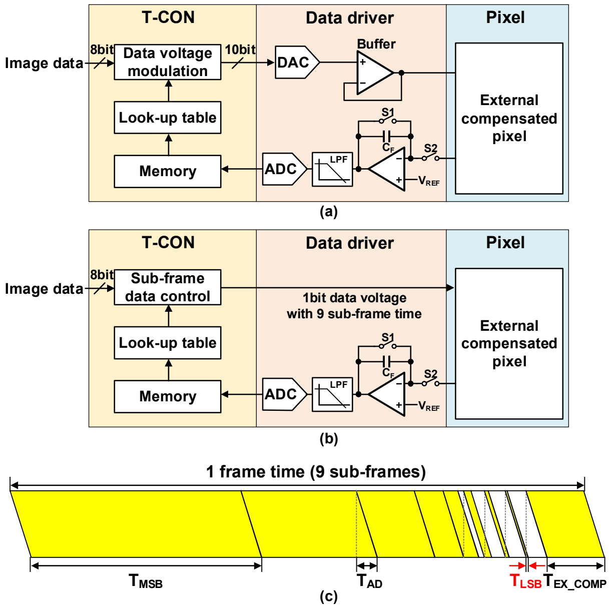

Fig. 5. (a) Conventional PAM external compensation method, (b) proposed PWM external compensation method, and (c) timing diagram with external compensation

5. Experiment Results

For micro-LED panels, the gate driver is designed to as shown in Fig. 6. The proposed gate driver is designed to ensure that the V_{GS} of the driving transistor (M17) remains negative by utilizing V_{SS} and V_{SSL}, against depletion-mode operation. A series two-transistor technique is employed to maintain the voltage at the Q node even during bootstrapping operation. Additionally, this gate driver requires only two clock signals, minimizing the number of input signals needed.

The proposed pixel circuit and gate driver are fabricated a-ITZO TFT. The threshold voltage (V_{TH}), mobility, and subthreshold swing (SS) of the fabricated a-ITZO TFT were −1.1 V, 25.4 cm^2 /V·s, 140mV/dec, respectively. The Micro-LED pixel array is composed of 32x18 array as shown in Fig. 7. For measure the gate driver and pixel array, Oscilloscope, signal control board, power supply is used. The measurement results of gate driver are shown in Fig. 8 under 173khZ with 5KΩ, 50PF 120Hz).

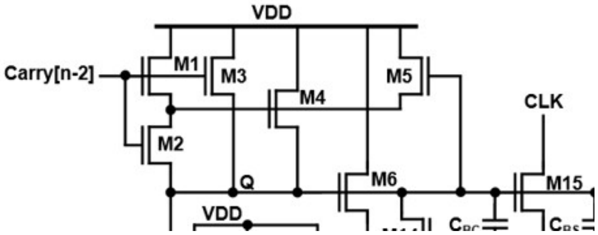

Fig. 6. Schematic and timing diagram of gate driver.

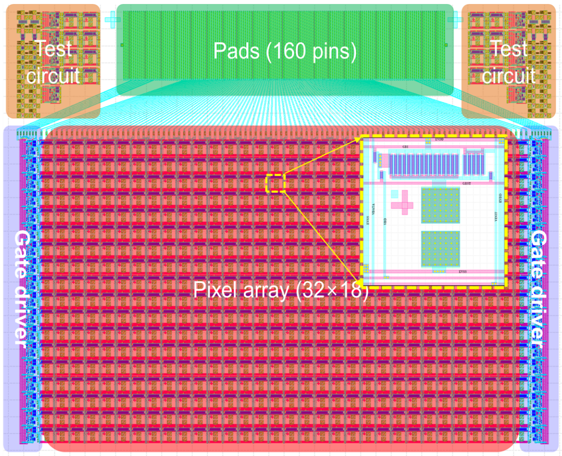

Fig. 7. Layout of Micro LED arrays with gate driver & pixel array.

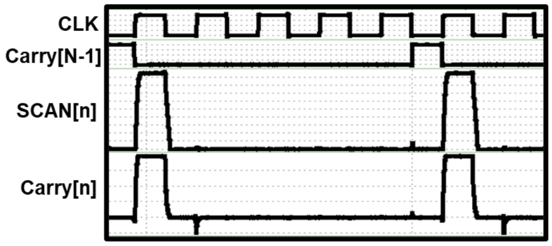

Fig. 8. The measurement results of proposed gate driver.

Fig. 9 shows the measured micro LEDs panel operation. To verify the operation of the proposed pixel circuit, the brightness variation was measured across different gray levels. It was confirmed that the pixel was completely off at 0 gray, while the brightness increased progressively at gray levels of 64, 128, and 256.

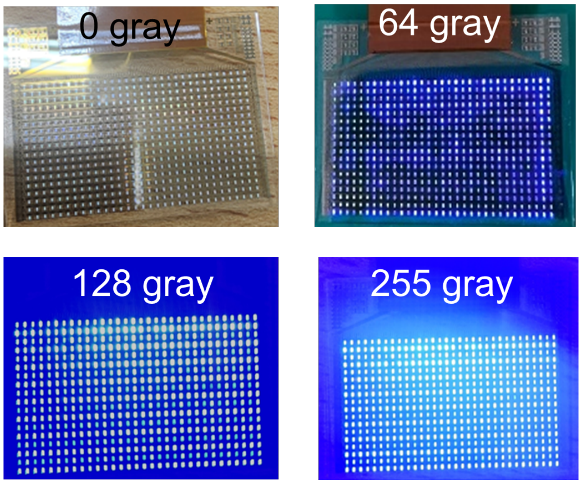

Fig. 9. The measurement results of micro LED panel at 0, 64, 128 and 255 gray levels.

6. Conclusions

The proposed a 5T1C pixel circuit employing a digital pulse width modulation (PWM) driving method for micro LEDs modular displays, addressing challenges such as EQE variations and TFT characteristic discrepancies. By leveraging amorphous indium-tin-zinc oxide (a-ITZO) TFTs, the circuit achieved high uniformity, mobility, and low off-current, while the external compensation mechanism minimized the number of TFTs and input signals required. Experimental results demonstrated the effectiveness of the proposed circuit, with successful brightness control across varying gray levels and reduced memory requirements compared to conventional methods. The PWM-based compensation mechanism, utilizing extra bits for pulse width adjustments, effectively mitigated current variations without significantly increasing circuit complexity or power consumption.

7. Acknowledgements

This work was supported by Electronics and Telecommunications Research Institute (ETRI) grant funded by the Korea government. [21ZB1200, The Development of the Technologies for ICT Materials, Components and Equipment]. This work was supported by the Technology Innovation Program (RS-2024-00408495, Development of oxide thin film transistor backplane technology for seamless Micro-LED modular display with high frame rate above 240 Hz and low power consumption below 85 mW) funded By the Ministry of Trade, Industry & Energy(MOTIE, Korea)

8. References

[1] Oh CH, Shin HJ, Nam WJ, Ahn BC, Cha SY, Yeo SD, editors. 21.1: Invited paper: Technological progress and commercialization of OLED TV. SID Symposium Digest of Technical Papers; 2013: Wiley Online Library.

[2] Shin H-J, Choi S-H, Kim D-M, Han S-E, Bae S-J, Park S-K, et al., editors. 45-1: A novel 88-inch 8K OLED display for premium large-size TVs. SID Symposium Digest of Technical Papers; 2021: Wiley Online Library.

[3] Huang Y, Hsiang EL, Deng MY, Wu ST. Mini-LED, Micro-LED and OLED displays: Present status and future perspectives. Light: Science & Applications. 2020 Jun 18;9(1):1-6.

[4] Wu T, Sher C-W, Lin Y, Lee C-F, Liang S, Lu Y, et al. Mini-LED and micro-LED: promising candidates for the next generation display technology. Applied Sciences. 2018;8(9):1557.

[5] Z. Y. Fan, J. Y. Lin, and H. X. Jiang, “III-nitride micro-emitter arrays: Development and applications,” J. Phys. D Appl. Phys., vol. 41, no. 9, Apr. 2008, Art. no. 094001.

[6] J. -H. Park, K. -S. Kang, C. Park and S. -Y. Lee, "A New 13T4C LTPO MicroLED Pixel Circuit Producing Highly Stable Driving Current by Minimizing Effect of Parasitic Capacitors and Stabilizing Capacitor Nodes," in IEEE Journal of the Electron Devices Society, vol. 12, pp. 472-478, 2024

[7] E. K. Jung, S. -H. Ahn, S. Hong, H. Im and Y. -S. Kim, "Micro Light-Emitting Diode Pixel Circuit Based on Indium–Gallium–Zinc Oxide Thin-Film Transistors Using Pulse Width Modulation," in IEEE Electron Device Letters, vol. 44, no. 9, pp. 1484-1487, 2024