Oxide TFT Pixel Circuits and Various Operation Methods for PWM MicroLED Displays

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ABSTRACT

In this paper, pulse width modulation driving micro light-emitting diode pixel circuit using oxide TFTs, and its operations in simultaneous and progressive emission are introduced. In addition, various operation methods, the SWEEP signal generation method based on linear charging of the capacitor and inverter-based PWM driving, are suggested and discussed.

1 Introduction

A micro light-emitting diode (μLED), a next-generation self-emissive diode, offers extensive versatility in display size and form factor and exhibits excellent electrical properties, including high luminance with excellent luminous efficacy, enhanced reliability, short response time, and wide viewing angle [1]-[2]. In addition, μLEDs overcome several limitations of organic LEDs (OLEDs), such as the ‘burn-in’ issue, an inherent and unavoidable drawback of OLEDs, and temperature instability [3]-[4].

However, despite their superior electrical performance, some challenges remain to be addressed. One major challenge is the wavelength shift of μLED’s light depending on its current density. Due to this phenomenon, the μLED displays can suffer from color distortion if the luminance of μLEDs is controlled by adjusting the current level as in conventional OLED displays. Therefore, μLED displays should adopt the pulse width modulation (PWM) method, which adjusts the emission period with constant current for gray-level expression [3]-[4].

In a pixel circuit for PWM driving, the constant current generation (CCG) part and the PWM part are essentially required. Generally, the PWM part utilizes a voltage signal with a ramp waveform, named the SWEEP signal, to control the emission period of the μLED. As the $V_{DS}$ of the driving TFT in the PWM part (DRTPWM) increases with the SWEEP signal voltage, the DRTPWM switches from off-state to on-state at a certain moment. Then, DRTPWM directly affects the operation of the CCG part. Consequently, the CCG part can no longer supply the intended high current, so μLED stops emitting light. However, due to the non-ideal behavior of DRTPWM as a switch, there inevitably exists a falling time of hundreds of microseconds until the LED completely stops emitting light.

This falling time can considerably impact gray-level expression, particularly in low gray levels where the emission time is shorter than the falling time. Furthermore, the necessity of the SWEEP signal in the PWM part presents significant operational complexity, especially when progressive emission is implemented.

In this paper, we introduce a PWM driving μLED pixel circuit using amorphous indium-gallium-zinc oxide (a-IGZO) TFTs and its operation in simultaneous and progressive emission. In addition, we suggest a simple and efficient SWEEP signal generation method based on linear charging of the capacitor. This method only utilizes SCAN signals, so operational complexity in generating ramp waveform voltage signals can be effectively reduced. Meanwhile, we discuss inverter-based PWM driving as an alternative approach to reduce the falling time. We conduct a comparative analysis between the conventional pixel circuit-based approach and the inverter-based approach for PWM driving. Then, their operation advantages and structural limitations for practical implementation are analyzed.

2 PWM driving μLED pixel circuits

We introduce two pixel circuits designed for PWM driving μLED displays using a-IGZO TFTs. Each pixel circuit adopts simultaneous and progressive emission, respectively. Meanwhile, both circuits utilize a source follower structure to sense negative threshold voltage ($V_{TH}$), since a-IGZO TFTs can operate in depletion mode. Additionally, in both CCG and PWM parts, $V_{TH}$ compensation and data input are performed in the same stage, so each part can include only one capacitor. This compact circuit operation simplifies the overall structure and signals. The following sections describe a detailed operation of each pixel circuit.

2.1 μLED pixel circuit with simultaneous emission

Fig. 1 shows the schematic and signal timing diagram of the μLED pixel circuit with simultaneous emission [5]. The pixel circuit is divided into the CCG part consisting of DRTCCG, T1-T5, and CCG, and the PWM part consisting of DRTPWM, T6-T12, and CPWM. DRTCCG and DRTPWM are driving TFTs of each part, and T1-T12 are switching TFTs (SWTs). This circuit requires only one SWEEP signal because every horizontal line (H-line) can share the identical SWEEP signal, and all LEDs emit light at the same time in simultaneous emission.
The operation of this circuit is divided into four stages: (1) reset, (2) PWM data input and DRT CCG compensation, (3) CCG data input and DRT CCG compensation, and (4) μLED emission. In stages (2) and (3), the data voltage is applied to the left node of the storage capacitor, while $V_{TH}$ is sensed at the right node of it. By using this operation scheme, $V_{TH}$ compensation and data input can be compactly performed within the same stage. In stage (4), when the SWEEP signal voltage reaches a certain threshold, the DRT PWM turns on and discharges the CCG. This threshold value varies depending on the PWM data voltage ($V_{DATA,PWM}$) and determines the emission period.

The simulation is performed for modular-type 480×270 resolution display tiles. The one horizontal time (H-time) for PWM data input and DRT PWM compensation is set to 9 μs, considering 270 H-lines and ensuring sufficient emission time of approximately 6 ms. Fig. 2 shows the transient waveforms of μLED current according to $V_{DATA,PWM}$ and the current error rates of the third frame. The falling time is 324 μs, so the theoretically achievable minimum gray level is about 60 G. At 60 G, the error rate remains below 5 %.

### 2.2 μLED pixel circuit with progressive emission

Recently, there has been a growing interest in adopting the progressive emission for μLED displays. The progressive emission can minimize instantaneous power consumption and IR drop, as the number of H-lines emitting light at the same time can be greatly reduced. In addition, flickering issue can decrease, and the flexibility in emission time can increase.

Fig. 3 shows the schematic and signal timing diagram of the μLED pixel circuit with progressive emission. The pixel circuit is divided into the CCG part consisting of DRT CCG, T1-T5, T14, and C CCG, and the PWM part consisting of DRT PWM, T6-T13, and CPWM. The circuit operation conditions are set to be the same as in the simultaneous emission to ensure synchronized operation across the emission scheme.

Meanwhile, in the progressive emission, the operation of the PWM part and CCG part is performed at the same time, so interference between each part can occur. To avoid this issue, an additional SWT is inserted between the PWM and CCG parts. Additionally, another SWT, T10, should be added for the reset stage. This results from the line-by-line operation of progressive emission, where the signals cannot be shared across multiple lines. Even though the total number of TFTs increases by two, the number of SCAN signals, excluding EM and SWEEP signals, can be reduced by half, as both parts can utilize the same signals.

The operation of this circuit is divided into three stages: (1) reset, (2) data input and DRT compensation, and (3) μLED emission. The operations are identical to those in simultaneous emission, except that both CCG and PWM parts perform $V_{TH}$ compensation and data input in the same stage. The one H-time, equivalent to the duration of the SCAN2[N] on time, is set to 30.7 μs, considering a refresh rate of 120 Hz and 270 H-lines. The emission time is set to be short, approximately 2 ms.

Fig. 4 shows the transient waveforms of μLED current according to $V_{DATA,PWM}$ and the current error rates of the
third frame. The falling time is reduced to 137 μs, which results from the steep slope of SWEEP[N] signal due to the short emission time [6]. However, it is worth noting that the actual decrease rate of falling time is smaller than that of emission time. As a result, the theoretically achievable minimum gray level increases to about 70 G. Even so, the error rate is only under 3 % at 70 G.

Meanwhile, the progressive emission requires line-by-line SWEEP[N] signals, as each H-line emits light independently. Consequently, the number of drivers and corresponding clock signals needs to increase, leading to a higher operational complexity in the display panel. To address this challenge, we introduce a simple and efficient method for generating SWEEP signals [7].

3 SWEEP[N] signal generation method using Cline

The suggested method is to generate a SWEEP[N] signal by linearly charging the capacitor with a constant current. The constant current is supplied by the sweep signal by linearly charging the capacitor with a constant voltage. The constant current is achieved using the SG method. While this paper introduces a line-by-line approach for the SG method, utilizing Cline can be susceptible to noise caused by other signal lines. Hence, to address this instability, the suggested SG method can be implemented within each pixel circuit, allowing a pixel-by-pixel approach.

4 Inverter-based PWM driving μLED pixel circuit

Meanwhile, achieving accurate grayscale expression in low-brightness areas is crucial. However, the falling time negatively impacts expressions in low gray levels where the emission time is very short. Thus, reducing the falling time is the key to enhancing PWM driving performance. In this regard, we introduce an alternative approach for PWM driving using an inverter. This approach can take advantage of the inverter for faster switching and reduced falling time.

The SG circuit should be designed with a similar structure and operation as the CCG part to enable the SG circuit to utilize existing SCAN signals. Fig. 6 shows an example of the SG circuit and the corresponding signal timing diagram for the entire system. This system utilizes the pixel circuit and operation presented in Fig. 3. As shown in the signal timing diagram, the introduction of the SG circuit and its integration into the pixel circuit eliminate the need for the conventional SWEEP[N] signal. Fig. 7 compares the transient waveforms of μLED current when using the conventional SWEEP[N] signal and SG circuit. The graphs exhibit nearly identical waveforms, indicating that the same PWM driving can be achieved using the SG method.

While this paper introduces a line-by-line approach for the SG method, utilizing Cline can be susceptible to noise caused by other signal lines. Hence, to address this instability, the suggested SG method can be implemented within each pixel circuit, allowing a pixel-by-pixel approach.
Fig. 8 shows the schematic and signal timing diagram of the n-type only inverter-based μLED pixel circuit with progressive emission. The pixel circuit is divided into the CCG part consisting of DRTCCG, T1-T6, and CCCG, and the PWM part consisting of DRTPWM, T7-T12, and CPWM.

The operation of this circuit is also divided into three stages: (1) reset, (2) data input and DRT compensation, and (3) μLED emission. As the operation of the CCG part remains unchanged from the previous circuits, the following description focuses only on the operation of the PWM part. In stage (1), positive $V_{REF1}$ is stored in $C_{INV2}$. This stage is essential for the n-type only inverter, as it cannot properly sense the switching threshold of the inverter ($V_m$) without positively shifting $V_{TH}$ of the bottom transistor, T8. In stage (2), $V_{DATA,PWM}$ is applied to the left node of $C_{INV1}$, while $V_m$ is sensed at the right node of it. In stage (3), when the SWEEP signal voltage reaches a certain threshold, the output voltage of the inverter switches to ELVDD. At this point, T6 turns on and discharges the $C_{CCG}$. Since the output voltage of the inverter switches very rapidly, the falling time can be significantly reduced.

Fig. 9 shows the transient waveforms of μLED current according to $V_{DATA,PWM}$ and the current error rates of the third frame. The falling time is extremely reduced to 6.2 μs, so the achievable minimum gray level is also considerably lowered to below 20 G. However, the introduced n-type only inverter-based PWM part exhibits structural instability due to consecutive switching at the left node of the $C_{INV1}$, resulting in unintended node voltage fluctuations during its inevitable floating state between consecutive switching operations. This instability can result in a significant $V_m$ compensation error, so achieving precise grayscale expression under DRTPWM variation is challenging with the introduced circuit. The error rates at 50 G are already over 10%. These results indicate that the introduced inverter-based approach may not yet be suitable for PWM driving. To address this challenge, further research on a more stable inverter-based PWM driving should be conducted, ensuring that both nodes of the capacitor storing $V_m$ are not floated during signal switching.

5 Conclusions

In this paper, we introduced PWM driving μLED pixel circuits using a-IGZO TFTs and discussed various approaches to improve the circuit operation. We compared and analyzed the characteristics of simultaneous emission and progressive emission based on the introduced pixel circuit. By adopting progressive emission, the number of signals can be reduced, whereas the number of TFTs slightly increases. Additionally, we suggested a SWEEP signal generation method based on linear charging of the capacitor. The simulation result indicates that the SG method can efficiently achieve the same operation as the conventional SWEEP[N] signal. Meanwhile, we employed n-type only inverter-based PWM driving to reduce the falling time. However, we found that the introduced inverter-based pixel circuit is may still be unsuitable for PWM driving since the introduced circuit exhibits inherent structural instability caused by consecutive switching and consequent node floating. Therefore, further research regarding stable structures, which can reliably store $V_m$ during signal switching, should be conducted to make the extremely short falling time employing the inverter-based structure. We expect that this paper can expand the understanding of PWM driving μLED pixel circuits.

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