New LTPS Driving Circuit with Simultaneous Emission for Mini-LED Backlit Liquid-Crystal Displays

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Keywords: Low-temperature polycrystalline silicon (LTPS), mini light-emitting diode (mini-LED), pulse-width modulation.

ABSTRACT

A mini-LED circuit with simultaneous emission (SE) and pulse-width modulation (PWM) driving method is proposed for liquid-crystal display backlights. Analytical results show that the relative current error rates are below 4.2%, and the power consumption is reduced by 21.83% when mini-LEDs are operated at a high luminous efficacy.

1 Introduction

To compete with the contrast ratio of an organic light-emitting diode (OLED) [1]-[2], the mini light-emitting diode (mini-LED) has been widely used in a direct-lit backlight module that utilizes multi-zone local dimming for realizing high dynamic range (HDR) and improving image quality [3]-[4]. There are two main driving methods, which are the passive matrix (PM) and active matrix (AM) in the mini-LED backlight panel [5]. Many required integrated circuits (ICs) are applied to generate driving currents of mini-LEDs in a PM backlight panel. Also, the emission period is restricted by the resolution in the PM driving method. A complex printed circuit board (PCB) and a large number of source ICs are required for a high-resolution panel with a PM backlight module, resulting in high cost and high power consumption of the mini-LED backlight products. In contrast, the AM driving method is that the source ICs input the data voltage to each pixel, and the storage capacitor in each pixel stores the data voltage. Then, the driving thin-film transistors (TFTs) in the pixel generate the required driving currents according to the data voltages. Thus, the number of source ICs can be reduced, and the resolution of the backlight module can be increased. Although AM method requires more components in the pixel, the power consumption and cost are lower than the PM method. Moreover, the emission period is not restricted by the resolution. Thus, the AM method is used in the mini-LED backlight module, and some related works have been proposed [6]-[8]. Liu *et al*. proposed a mini-LED circuit with pulse-amplitude modulation (PAM) driving method and four mini-LEDs connected in series, improving the VSS I-R rise and power consumption by reducing the driving currents [9]. However, a considerable amount of mini-LEDs increase the cost of the product, and the PAM driving method causes the wavelength shift of LED. In addition, because of the variations of the threshold voltage of the driving TFT in the circuit, uniform driving currents cannot be generated to drive mini-LEDs, resulting in poor image quality [10]. Hong *et al*. proposed a micro-LED pixel circuit with the PWM method to make the LEDs be operated at a high luminous efficacy [11]. Also, the wavelength shifts of LEDs can be improved by using the constant driving current to drive LEDs. However, this circuit cannot compensate for the VSS I-R rise.

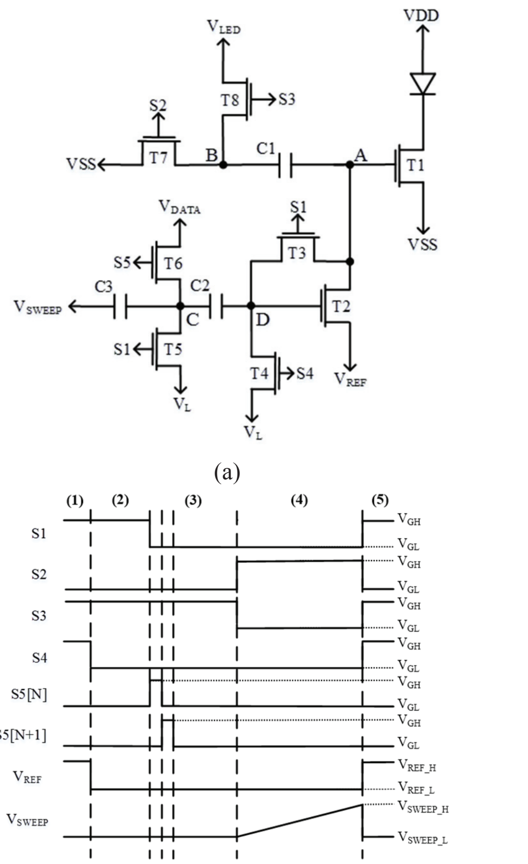


Fig. 1. (a) Proposed mini-LED pixel circuit for backlight and (b) timing diagram.

This work proposes a new mini-LED circuit with the simultaneous emission (SE) and PWM driving method for the backlight module. By the SE driving method, only one V_{SWEEP} signal is used and shared by all pixels, reducing the cost of V_{SWEEP} ICs and achieving low cost. In addition, the

TABLE I
DESIGN PARAMETERS OF PROPOSED MINI-LED CIRCUIT AND 6T1C CIRCUIT [12]

8T3C circuit			
$(W/L)_{T1,T2}$ (μm/μm)	1040/(7+7)	$(W/L)_{T3\text{-}T8}$ (μm/μm)	6/(3+3)
C1 (pF)	15	C2 (pF)	3
C3 (pF)	3	VDD (V)	13
S1-S5 (V)	-8 ~ 10	V_{REF} (V)	0 ~ 6.2
V_{DATA} (V)	1.35 ~ 6.9	VSS (V)	6.2
V_{LED} (V)	-4.02	V_{SWEEP} (V)	0 ~ 7
V_L (V)	6.2		
6T1C circuit [12]			
$(W/L)_{T1,T2,T6}$ (μm/μm)	1040/(7+7)	$(W/L)_{T3,T4,T5}$ (μm/μm)	6/(3+3)
C_{ST} (pF)	5	ELVDD (V)	10
V_{SCAN} (V)	-5 ~ 13	VSS (V)	1.3
V_{DATA} (V)	0 ~ 6		

compensation period can be extended and would not be restricted by one scan line time, realizing accurate compensation for the variations of the threshold voltage of TFTs. The turn-off time of the mini-LED with the proposed PWM method can be unaffected by threshold voltage variations. Thus, the uniformity of the display image and the accuracy of the gray level are improved for the mini-LED backlight of an LCD panel.

2 Proposed Mini-LED Circuit

Fig. 1(a) shows the proposed mini-LED pixel circuit that consists of eight TFTs and three capacitors for the LCD backlight. T1 and T2 are matched driving TFTs that can be used to compensate for the variations of the threshold voltage. T3-T8 are switching TFTs, and T2-T6 are applied to control the emission period of LEDs in the proposed mini-LED circuit with the PWM driving method. Fig. 1(b) is the timing diagram of the proposed mini-LED circuit. The operation of the proposed mini-LED circuit can be divided into five periods that are reset, compensation, data input, emission, and turn-off periods.

(a) Reset period

S1 and S4 are at V_{GH}, so the A, C, and D nodes are discharged to V_L. Because VSS is equal to V_L, T1 is operated at the cut-off region. Thus, there is no current through mini-LED, preventing the flicker phenomenon of the display.

(b) Compensation period

S1 is still at V_{GH} to make node C remain at V_L. T3 is turned on, so T2 is a diode-connected structure. When V_{REF} changes from V_{REF_H} to V_{REF_L}, the A and D nodes are discharged to $V_{REF\_L} + V_{TH\_T2}$. Therefore, the voltage across C2 is $V_{REF\_L} + V_{TH\_T2} – V_L$. S3 is kept at V_{GH}, and node B is at V_{LED} to make the voltage across C1 equal $V_{REF\_L} + V_{TH\_T2} – V_{LED}$.

(c) Data input period

S5 is at V_{GH} to turn on T6, so the data voltage can be input to the C node. The voltage of node D is coupled to $V_{REF\_L} + V_{TH\_T2}$ $+(V_{DATA[N]} – V_L)$ by the capacitive coupling of C2. S3 remains at V_{GH} to maintain the B node at V_{LED} and the A node at V_{REF_L} $+ V_{TH\_T2}$.

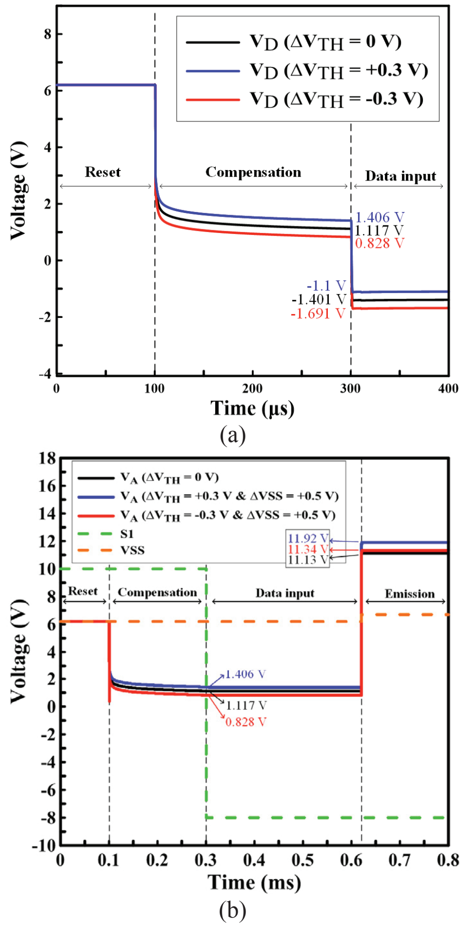


Fig. 2. Transient waveforms of (a) node D and (b) node A with V_{TH} variations of ±0.3 V and V_{SS} I-R rise of 0.5 V.

(d) Emission period

S3 changes to V_{GL} to turn off T8, and S2 is at V_{GH} to make the B node be charged to VSS. The voltage of the A node changes to $V_{REF\_L} + V_{TH\_T2} + VSS – V_{LED}$ through the capacitive coupling of C1 to make T1 be operated at the saturation region. Thus, the driving current of mini-LED is shown as follows.

$$\begin{aligned} I_{LED} &= \frac{1}{2}k(V_{GS} - V_{TH\_T1})^2 \\ &= \frac{1}{2}k[(V_{REF\_L} + V_{TH\_T2} + VSS - V_{LED}) - VSS - V_{TH\_T1}]^2 \\ &= \frac{1}{2}k(V_{REF\_L} - V_{LED})^2 \end{aligned} \quad (1)$$

Owing to the matched driving TFTs, the threshold voltage can be regarded as the same. Thus, V_{TH_T1} and V_{TH_T2} can be canceled in the formula of the driving current, preventing the effect of the variations of the threshold voltage for the driving current. Moreover, when the voltage of VSS rises in the emission period, the voltage of the A node can increase the same voltage through the capacitive coupling of C1 to avoid the effect of the VSS I-R rise.

In this period, the voltage of the V_{SWEEP} signal changes

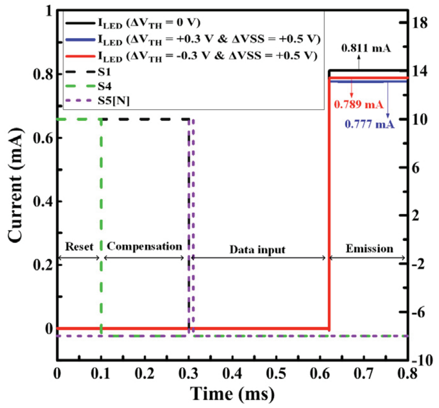


Fig. 3. Driving currents for mini-LED with V_{TH} variations of ±0.3 V and V_{SS} I-R rise of 0.5 V.

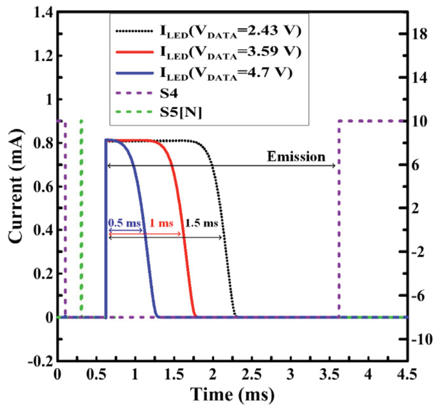
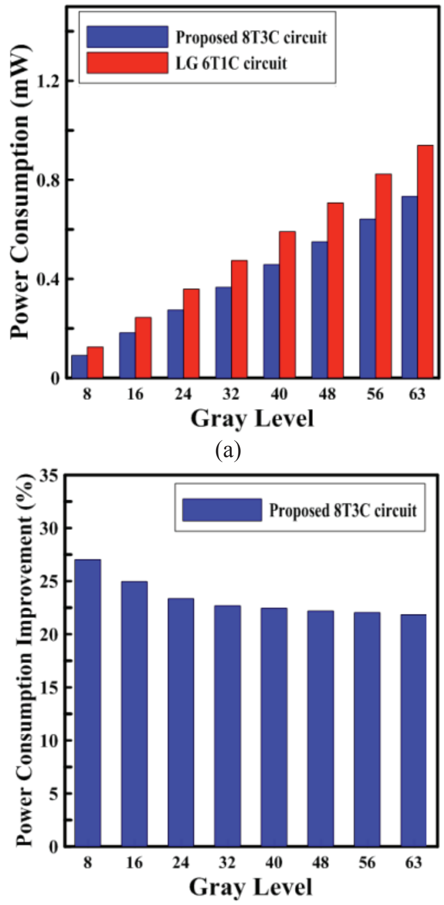


Fig. 4. Transient waveforms of driving currents at low, medium, and high gray levels.

from V_{SWEEP_L} to V_{SWEEP_H}, and the voltage of the D node increases from V_{REF_L} + V_{TH_T2} + ($V_{DATA[N]}$ - V_L) to V_{REF_L} + V_{TH_T2} +($V_{DATA[N]}$ - V_L) + (V_{SWEEP_H} - V_{SWEEP_L}) by capacitive coupling of C2 and C3. As the voltage of the D node makes T2 be operated at the linear region, the voltage of the A node can be discharged to V_{REF_L} for turning off T1. When the smaller voltage of the $V_{DATA[N]}$ is applied, the longer emission period of mini-LED is given, so the data voltage can control the emission period of the PWM circuit. Moreover, the voltage of node D comprising V_{TH_T2} can alleviate the relative time shifts of current pulses in the emission period, realizing the accurate control for the gray level.

(e) Turn-off period

S1 and S4 are at V_{GH} to make the voltage of the A and D nodes be discharged to V_L. Thus, T1 can be operated at the cut-off region. According to the above-mentioned operation, the driving currents of the mini-LED backlight are not affected by the VSS I-R rise and the variations of the driving TFTs, achieving a high uniformity of display images. Furthermore, the compensation for the threshold voltage of T2 realizes accurate control for the gray level. The proposed circuit can extend the compensating period by the SE method, improving the effectiveness of the compensation. The V_{SWEEP} signal can also be shared for the entire panel to reduce the cost of the display.



(a)

(b)

Fig. 5. (a) Power consumption and (b) improvement of power consumption of proposed circuit compared with 6T1C circuit [12] at different gray levels.

3 Simulation Results and discussion

To verify the functionality of the circuit, an HSPICE simulator with an n-type LTPS TFT model is used in the simulation. Table I shows the design parameters of the proposed circuit and the previously reported circuit. For a 2-inch mini-LED backlight panel with a resolution of 32 × 32 and frame rate of 90 Hz, the data input period of each row is set to 10 μs. The total data input, compensation, and emission periods are set to 320 μs, 0.2 ms, and 3 ms, respectively. The emission time of mini-LED at the highest gray level is set to 1.5 ms. Figs. 2(a) and 2(b) show the transient waveforms of the D and A nodes when the variation of threshold voltages and the VSS I-R rise are ± 0.3 V and 0.5 V, respectively. Fig. 2(a) shows that the voltages of the D node are 1.406 V and 0.828 V in the compensation period as the threshold voltages vary by 0.3 V and -0.3 V, respectively, indicating that the variations of the threshold voltage of T2 are successfully detected. Moreover, Fig. 2(b) shows that the voltages of the A node are 11.92 V and 11.34 V in the emission period when the variations of the threshold voltage of T1 and T2 are ±0.3 V, and the VSS I-R rise is 0.5 V. The proposed circuit can successfully compensate for the VSS I-R rise and variations of the threshold voltage. Fig. 3 demonstrates the driving currents of mini-LED with the variations of the threshold voltage and the VSS I-R rise. The driving currents generated by the proposed circuit are 0.811 mA, 0.777 mA, and 0.789 mA in the emission period as the V_{TH} varies by ± 0.3 V, and the VSS I-R rise is 0.5 V. Therefore, the relative current error rates are below 4.2 %, ensuring that the proposed circuit can make the mini-LED be operated at the high luminous efficacy and generate uniform driving currents. Fig. 4 shows the emission period of mini-LED at low, medium, and high gray levels. Thus, the proposed circuit can control the different gray levels by the different data voltages, ensuring the functionality of the PWM method. Figs. 5(a) and 5(b) show the power consumption for the proposed and the 6T1C circuits [12]. Fig. 5(a) presents that the power consumption of the proposed circuit is lower than that of the 6T1C circuit over the range of gray levels. Fig. 5(b) presents that the power consumption of the proposed circuit is reduced by 21.83% over the range of gray levels. The above-mentioned simulated results prove that the proposed circuit can successfully generate high uniformity driving currents, reduce power consumption, and accurately control the gray levels.

4 Conclusions

This work proposes a mini-LED pixel circuit for LCD backlight with SE and PWM driving methods. The proposed circuit can compensate for the VSS I-R rise and the variations of the threshold voltage of TFTs, realizing uniform driving currents and accurately controlling the emission period for each gray level. By using the fixed driving current, the mini-LED be operated at high luminous efficacy. Only one TFT is required in the driving current path, reducing power consumption by decreasing the voltage range from VDD to VSS. Therefore, the proposed mini-LED circuit with SE and PWM driving method is suitable for the LCD backlight.

5 Acknowledgements

The work was supported by the Advanced Optoelectronic Technology Center, National Cheng Kung University, under projects from the Ministry of Education and the Ministry of Science and Technology (MOST 111-2218-E-006 -011 -MBK) of Taiwan, as well as AU Optronics Corporation is appreciated for its technical and funding support.

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