Compensated Mini-LED Driving Circuit with Matching TFTs for Reducing Power Consumption

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Keywords: Mini-LED, low-temperature polycrystalline silicon, compensation circuit, power consumption

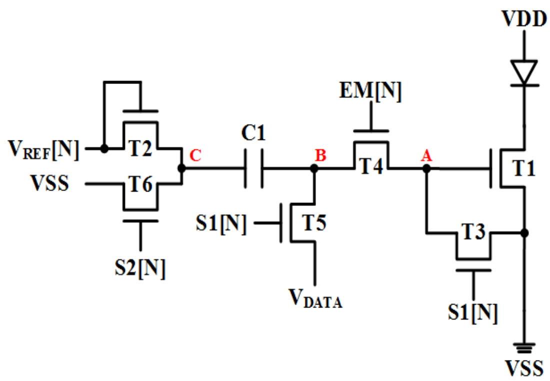
ABSTRACT

This work proposes a mini-LED driving circuit compensating for threshold voltage variations of the LTPS-TFTs and VSS I-R rise. The simulation results indicate that the relative current error rates are less than 10%. Therefore, the proposed circuit providing a uniform image is appreciated for mini-LED backlight applications.

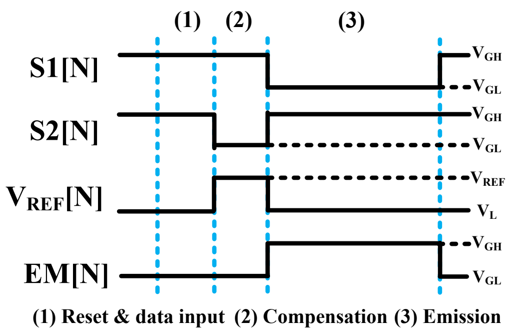
1 Introduction

Nowadays, liquid-crystal display (LCD) is extensively applied in consumer electronics, such as smartphones, TVs, and wearable devices. However, low contrast ratio and low color gamut are critical defects, which severely affect the quality of images. Another widely-used display is organic light-emitting diode (OLED) display, which is famous for its wide viewing angle, thinness, and flexibility [1], [2]. Nevertheless, compared with LCD, OLED displays are limited by material lifetime and mass production capabilities. Recently, mini-LED attracts a lot of attention owing to its several advantages like mature development of display backplanes, high brightness, high color purity, high reliability, and short response time [3]. With characteristics of high peak brightness and outstanding dark images, mini-LED is suitable for next-generation displays to realize high dynamic range (HDR) with higher contrast ratio [4]. At present, many active-matrix (AM) LCDs adopt direct-lit mini-LED backlight module to increase the contrast ratio, accomplishing multi-zone local dimming. Part of mini-LED backlights utilize the global shuttering mode (strobe mode) which can effectively improve moving-picture response time in VR applications, not to adopt the nature of hold-type driving mode as OLED display uses. Hence, mini-LEDs backlight has to output higher current only in specific time during one frame, and the voltage across the VDD and VSS is higher as well while the gate-to-source voltage and the size of driving TFT are limited by panel specifications [5].

Low temperature polycrystalline-silicon (LTPS) thin-film transistors (TFTs) are suitable for the mini-LED driving circuits because of their high reliability and excellent current driving capability which greatly reduce the size of TFTs. However, the mismatch of the threshold voltage (V_{TH}) of LTPS TFTs caused by excimer laser



(a)



(b)

Fig. 1 Proposed mini-LED driving circuit.
(a) Schematic. (b) Timing diagram.

annealing (ELA) process leads to the severe fluctuation of LED currents, decreasing the image quality of displays [6], [7]. To resolve this problem and generate uniform emission currents, Keum et al. presented a pixel circuit with diode-connected structure to provide uniform images [8]. However, there is a huge current during the initial period in this circuit. Mini-LED backlight is more sensitive to the undesirable current because the magnitude of current is higher than that of OLED displays, and this problem will bring out severe power consumption. Besides, VSS current-resistance (I-R) rise increases as the driving current raises. Due to this variation, the voltage of VDD and VSS could shift largely, changing the driving TFT state from saturation region to linear region, and consequently affects the output current. To diminish the influence of VSS I-R rise, Liu et al. proposed a new driving scheme with four mini-LED in series inside a circuit [9]. Nevertheless, this circuit still cannot output stable current because of the lack of compensation mechanism. Therefore, a low power consumption and VSS I-R rise compensation structure are required in mini-LED backlight driving circuit.

This work presents a mini-LED backlight driving circuit that is based on LTPS TFTs consisting of six TFTs and one capacitor (6T1C). The proposed circuit compensates for the variation of the V_{TH} and VSS I-R rise to generate uniform currents and achieve high image quality. Additionally, only one TFT is on the emission current path in this proposed circuit, which decreases the voltage across VDD and VSS and sequentially reduces the power consumption. Simulation results prove that the proposed circuit can perform precise compensation and generate the uniform mini-LED current for backlight modules. The proposed circuit with matched-TFT compensation scheme also performs lower power consumption than the compared 6T1C circuit designed by Shin et al. [10] across all gray levels. Therefore, the proposed circuit is able to provide accurate emission currents and decrease power consumption for mini-LED backlight applications.

1.1 Circuit Operation and Driving Scheme

Figs. 1 (a) and (b) present the schematic and the related timing diagram of the proposed mini-LED backlight driving circuit which consists of four switching TFTs (T3, T4, T5, and T6), one driving TFT (T1), one matched TFT (T2), one capacitor (C1), and four control signals (S1[N], S2[N], V_{REF}[N], and EM[N]). The operation of the proposed circuit is divided into three periods described as follows.

1.2 Reset & data input period:

S1[N] and S2[N] are high to turn on T3, T5, and T6. EM[N] is low to turn off T2 and T4. Data voltage (V_{DATA}) is input to node B through T5. VSS is applied to node A and C through T3 and T6, respectively. Simultaneously, the gate-to-source voltage (V_{GS}) of the driving TFT, T1, is 0 V to prevent current from flowing through T1, avoiding the image flicker phenomenon.

1.3 Compensation period:

S2[N] goes low to turn off T6, and V_{REF} is applied to the gate and drain nodes of T2 which is matched to the driving TFT (T1). Therefore, T2 forms a diode-connection type to charge node C until T2 is turned off. Finally, the voltage of node C (V_C) will be charged to V_{REF} - V_{TH} where V_{TH} is the threshold voltage of the matched TFT, T2. The voltage of node B (V_B) is still kept at V_{DATA} through T5, so the voltage across the capacitor (C1) is:

$$V_{C1}=V_{DATA}-V_{REF}+V_{TH} \qquad (2.1)$$

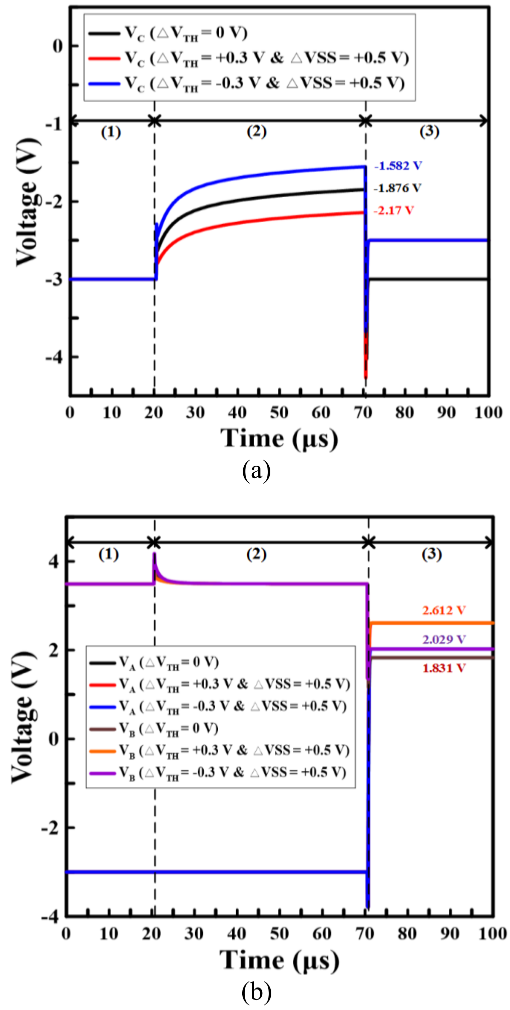


Fig. 2 Transient waveforms of (a) node C (b) node A and node B of proposed circuit as V_{TH} varies ±0.3 V and VSS rises 0.5 V.

In addition, node A (V_A) still maintains the voltage of V_{SS} to make T1 and mini-LED off.

1.4 Emission period:

During this period, S1[N] becomes low to turn off T3 and T5, and V_L is supplied by V_{REF} to turn off T2. S2[N] and EM[N] are high to turn on T6 and T4, so V_C turns to VSS. Due to charge conservation, V_B is boosted by the capacitor (C1) to the voltage as shown in the following equation:

$$V_B=VSS-V_{REF}+V_{TH}+V_{DATA} \qquad (2.2)$$

Besides, the voltage of V_A is equal to V_B through sharing charge method because T4 is turned on. At the same time, the V_{GS} of driving TFT (T1) is higher than the threshold voltage of T1, making the mini-LED emission. The emission current (I_{LED}) can be derived as follows:

$$
\begin{aligned}
I_{LED} &= \frac{1}{2}k(V_{GS}-V_{TH})^2 \\
&= \frac{1}{2}k(V_{SS}-V_{REF}+V_{TH}+V_{DATA}-V_{SS}-V_{TH})^2 \\
&= \frac{1}{2}k(V_{DATA}-V_{REF})^2 \qquad (2.3)
\end{aligned}
$$

where k is $\mu \cdot C_{OX} \cdot W/L$. According to Eq. (2.3), the mini-LED current is independent of the threshold voltage of T1 and VSS I-R rise, therefore the mini-LED driving circuit can generate uniform emission currents.

TABLE 1
PARAMETERS OF PROPOSED CIRCUIT

Proposed Circuit			
VDD (V)	3.9	C1 (pF)	5
VSS (V)	-3	$(W/L)_{LED}$ (μm)	(26/7)*40
V_{DATA} (V)	0~3.49	$(W/L)_{T1\sim T2}$ (μm)	(26/7+7)*40
V_{REF} (V)	-3 / -1	$(W/L)_{T3\sim T6}$ (μm)	6/3+3
SCAN (V)	-4 / 8		
Compared Circuit			
ELVDD (V)	10	C_{ST} (pF)	5
VSS (V)	1.3	$(W/L)_{LED}$ (μm)	(26/7)*40
V_{DATA} (V)	0~6	$(W/L)_{T1}$(μm)	(26/7+7)*40
SCAN (V)	-3 / 15	$(W/L)_{T2\sim T6}$ (μm)	6/3+3

2 Results and Discussions

To verify the feasibility of the proposed backlight driving circuit, the simulation of the circuit is performed with the specifications of 32×32 resolution and 90 Hz frame rate for two-inch panel by HSPICE simulator utilizing the RPI model (level = 62). Table 1 shows the simulated parameters of power supplies, control signals, capacitors, mini-LEDs device, and TFTs which are connected in series to restrain leakage current in the proposed circuit and compared 6T1C circuit. Fig. 2 (a) reveals the simulated transient voltage waveforms of the node C of proposed 6T1C circuit when V_{TH} varies ±0.3 V and VSS rises 0.5 V. The proposed circuit detects the variations of +0.294 V and -0.294 V, which is almost identical to the 0.3 V variation of V_{TH}. Fig. 2 (b) illustrates the simulated transient voltage waveforms of the node A and node B in the proposed driving circuit with the V_{TH} of the driving TFT (T1) and matched TFT (T2) both varies by ±0.3 V and VSS rises by 0.5 V. The difference of the voltage stored in node A almost equals the total variations of +0.8 V (V_{TH} +0.3 V & VSS I-R rise +0.5 V) and +0.2 V (V_{TH} -0.3 V & VSS I-R rise +0.5 V), verifying the capability of V_{TH} variation and VSS I-R rise compensation. Fig. 3 (a) shows that the relative current error rates of the mini-LED driving current across all gray levels are all below 1.41% as V_{TH} of the driving TFT (T1) and matched TFT (T2) both varies by ±0.3 V, proving that the proposed circuit can effectively compensate for V_{TH} variation of the driving TFT. Furthermore, 0.5 V variation of VSS I-R rise is added to the simulation, and the outcome is revealed in Fig. 3 (b). Based on Fig. 3 (b), the relative mini-LED current error rates are all below 9.77% when V_{TH} variations are ±0.3 V and the VSS I-R rise is 0.5 V. Therefore, this driving circuit can perform precise compensation and generate the uniform mini-LED current for mini-LED backlight modules.

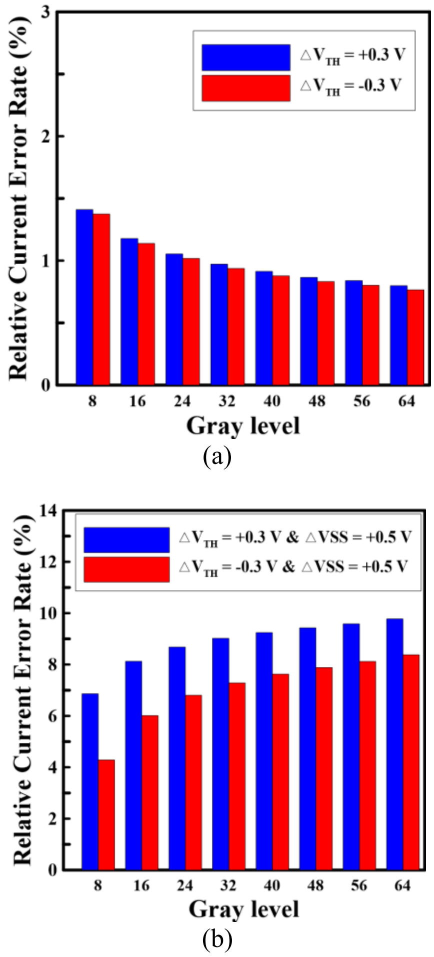
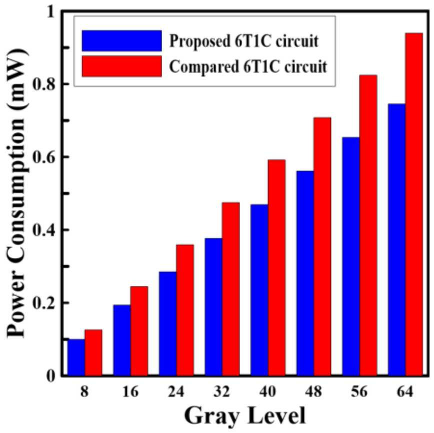


Fig. 3 (a) Relative current error rates when ΔV_{TH} is ±0.3 V. (b) Relative current error rates when ΔV_{TH} is ±0.3 V and VSS I-R rise is +0.5 V.

On the other hand, this mini-LED backlight adopts the global shuttering mode (strobe mode), so during the 1500-μs emission time, the mini-LED current is up to 800 μA or more to achieve desired luminance. As a result, the voltage of VDD – VSS is higher to drive this mini-LED current while the gate-to-source voltage and the size of driving TFT are limited by panel specifications, and the power consumption consequently increases. To reduce the power consumption, this proposed driving circuit utilizes matched-TFT compensation scheme in which the switch TFT can be removed on the emission path. For above-mentioned reasons, the voltage across



(a)

Fig. 4 Comparisons of power consumption of proposed circuit and compared 6T1C circuit.

VDD and VSS decreases because the voltage drop on the switch TFT is not taken into consideration anymore. To validate the effectiveness of the power consumption improvement, the proposed circuit is compared with the 6T1C driving circuit proposed by Shin et al. [10]. Between the two circuits, the voltage of VDD – VSS is 6.9 V and 8.7 V, respectively. Fig. 4 shows that the proposed circuit with the matched-TFT compensation scheme performs lower power consumption than the compared 6T1C circuit across all gray levels. The power consumption improvement is up to 20.69%, demonstrating the proposed mini-LED driving circuit can indeed reduce power consumption.

3 Conclusions

This work presents a mini-LED driving circuit, which can avoid the image flicker phenomenon, effectively compensating for threshold voltage variations and VSS I-R rises. Furthermore, this proposed 6T1C circuit can reduce power consumption, as only one driving TFT exists on the emission current path. Simulation results verify that the relative error rates are under 1.41% across all gray levels when the driving TFT varies by ±0.3 V. In addition, the power consumption improvement is 20.69% compared with the 6T1C driving circuit designed by Shin et al. Therefore, the proposed mini-LED circuit providing uniform currents is suitable for mini-LED backlight applications.

Acknowledgment

This work was supported in part by the Advanced Optoelectronic Technology Center, National Cheng Kung University, Tainan, Taiwan, and the Ministry of Science and Technology of Taiwan under Projects of 110-2622-E-006 -021 -, as well as AU Optronics Corporation is appreciated for its technical and funding support.

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