Compact Mini-LED Driving Circuit with Low Power Consumption Structure for Use in LCD Backlight Units

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ABSTRACT

This paper presents a mini-LED driving circuit with low power consumption. To reduce the voltage across current path, the threshold voltage variation of driving TFT is compensated by matching method. Simulations show the proposed circuit has 15.79% lower power consumption than compared circuit with two TFTs on driving current paths.

1 Introduction

Recently, active-matrix organic light-emitting diode (AMOLED) displays become the main developed display technology because of the high contrast ratio and less power consumption [1]-[2]. However, the disadvantages of AMOLED display such as expensive manufacturing processes and the short lifespan caused by the degradation of OLED are still critical issues [3]-[5]. Liquid-crystal displays (LCDs) wouldn't suffer from image burn-in and develop the proven technology, commonly used in most monitor applications. To display the image, LCDs require the light source behind the LCD panel, and the conventional edge-lit backlight modules lead to a poor contrast ratio. Nevertheless, the contrast ratio of LCDs can be improved by changing from the edge-lit backlight module to direct-lit backlight modules which are placed behind the whole LCD panel. Lately, mini-LEDs have been attracted attention from the whole industry owing to several features, including wide color gamut, self-emission, higher brightness, and long lifespan. Based on the superior characteristics, mini-LEDs are widely utilized in the LCD backlight module, increasing the local dimming zones to realize a high dynamic range (HDR). In previous research, the transmittance ratio of LCDs is lower than 7 % [6], so the driving currents of mini-LEDs are increased to the milliampere level to attain sufficient brightness. Low-temperature poly-crystalline silicon thin-film transistor (LTPS TFT) as the driving TFT can generate higher current because LTPS TFTs have great mobility and exceptional driving capability. However, due to the fluctuations of excimer laser annealing (ELA) processes, the threshold voltages (V_{TH}) of LTPS TFTs are varied which causes the nonuniform brightness of the panel [7]-[8]. To solve the problem, many compensation driving circuits were proposed [9]-[10]. The V_{TH} variations of LTPS TFTs are compensated by the diode-connected structure and source follower structure successfully. But the power line current-resistance drop/rise (VDD/VSS I-R drop/rise) still affected the uniformity of driving currents. Moreover, more than one switching TFTs on the driving path increase the voltage across VDD and VSS, bringing the additional static power consumption [11].

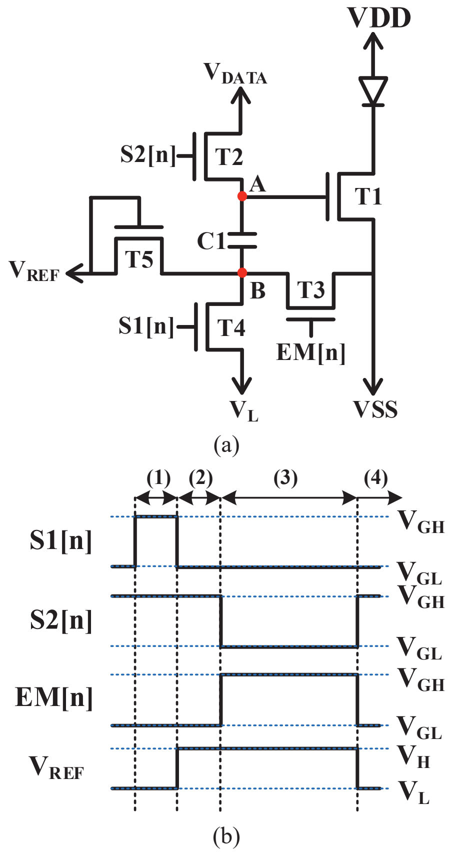

Fig. 1. (a) Proposed mini-LED driving circuit and (b) timing diagram.

In this work, a mini-LED backlight driving circuit consisting of five LTPS TFTs and one capacitor is proposed. The V_{TH} variation of TFT and VSS I-R rises are both detected to eliminate the undesired effects. Additionally, for compensating the V_{TH} variation of driving TFT without placing the switching TFT on the current path, the matching method is adopted in this work. Simulations show the relative error rate of driving current in the proposed circuit can be reduced effectively. To verify the power improvement, the compared results of the previous circuit [12] having the two TFTs on the current path and proposed circuit are also given in this work.

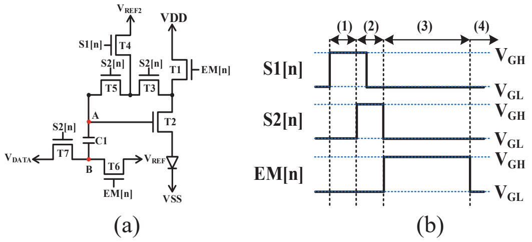

Fig. 2. (a) Compared mini-LED driving circuit [12] and (b) timing diagram.

Table I
PARAMETERS OF PROPOSED CIRCUIT AND COMPARE CIRCUIT

Proposed Circuit			
VDD (V)	16	$(W/L)_{TLED}$ (μm)	1040/(7+7)
VSS (V)	8	$(W/L)_{T1,T5}$ (μm)	1040/(7+7)
V_L (V)	-3	$(W/L)_{T2\sim T4}$(μm)	6/(3+3)
V_{REF} (V)	-3~0	C1 (pF)	3
SCAN (V)	-12~6	C_{LED} (pF)	0.2
Compared Circuit [12]			
VDD (V)	7.5	$(W/L)_{TLED}$ (μm)	1040/(7+7)
VSS (V)	-2	$(W/L)_{T1,T2}$ (μm)	1040/(7+7)
SCAN (V)	-4~14	$(W/L)_{T3\sim T6}$ (μm)	6/(3+3)
C1(pF)	3	C_{LED} (pF)	0.2

2 Proposed Circuit and Operation

Figs. 1(a) and (b) are the schematic and the timing diagram of the proposed mini-LED driving circuit. The driving TFT (T1) is used for generating the emission current. Since the characteristics of LTPS TFTs are similar in the same width and length, the size of matching TFT (T5) is equal to T1 to compensate for the variation of V_{TH}. Thus, there is only the driving TFT on the current path, decreasing voltage across the VDD and VSS. The following sections describe the detailed operation of the proposed circuit.

2.1 Reset period

T2 and T4 are turned on as S1[n] and S2[n] are high (V_{GH}). Because V_{REF} is at V_L, T5 is turned off. Voltage of node A (V_A) and node B (V_B) are reset to V_{DATA} and V_L, respectively. Notably, the value of VSS is higher than V_{DATA} to avoid the flicker phenomenon of mini-LED.

2.2 Compensation period

In this period, S1[n] turns to low (V_{GL}), so T4 is turned off. V_{REF} is changed from V_L to V_H, and thus T5 is turned on. Meanwhile, the source-follower structure of T5 charges V_B to V_H-V_{TH_T5}, where V_{TH_T5} is the threshold voltage of T5 matched to V_{TH} of T1. V_{DATA}, being the same value in the reset period still applied to node A. The voltage across the capacitor (V_{C1}) is:

$$V_{C1} = V_{DATA} - V_H + V_{TH\_T5} \quad (1)$$

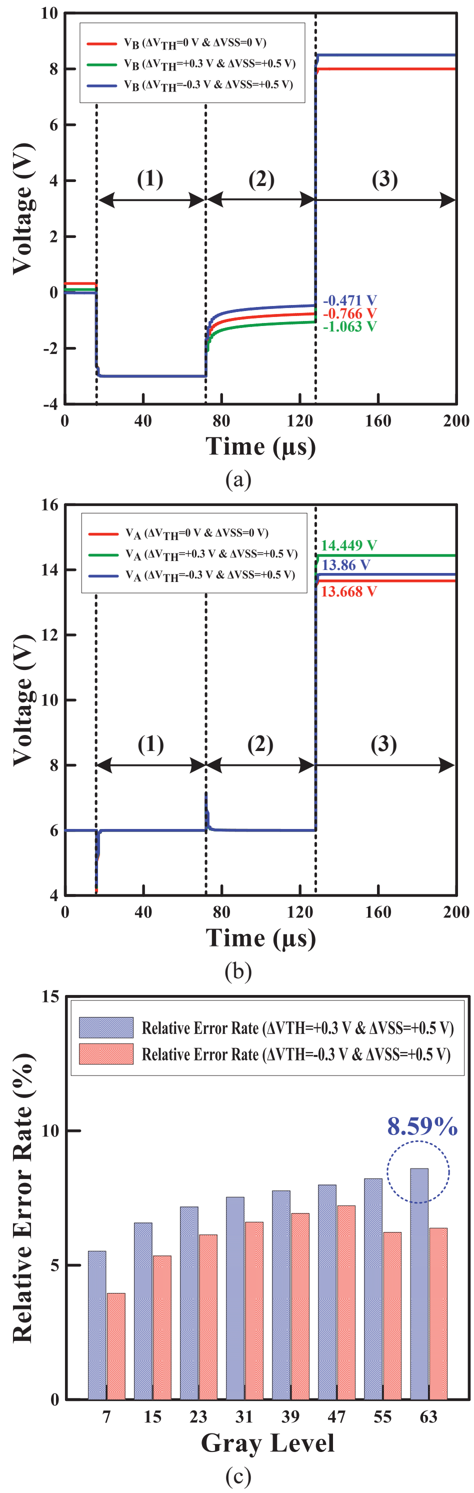

Fig. 3. Transient waveforms of (a) V_B, (b) V_A and(c) relative error rates with ΔV_{TH} is ±0.3 V and VSS I-R rise is 0.5 V.

Therefore, the V_{DATA} and V_{TH_T5} are stored at C1 to compensate for the V_{TH} variation of T1 and decide the gray level of the image.

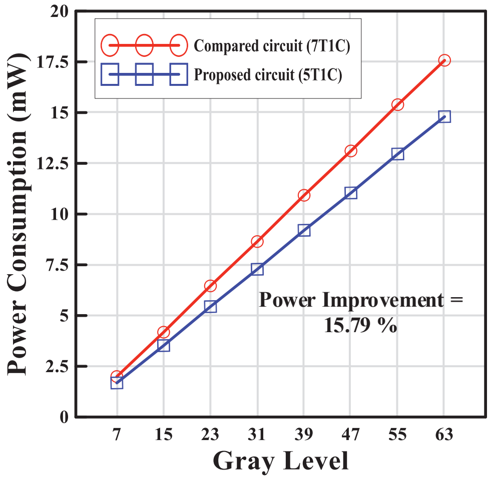

Fig. 4. Power consumption of compared 7T1C circuit and proposed circuit.

2.3 Emission period:

EM[n] is V_{GH} to turn on T3, and V_B is set to VSS. Since VSS is higher than V_{REF}, the gate and source of T5 are connected to turn off T5, preventing the direct current path from VSS to V_{REF}. V_A is boosted by the charge conservation of C1, and the voltage is as shown below:

$$V_A = VSS + V_{DATA} - V_H + V_{TH\_T5} \quad (2)$$

According to V_A, T1 is turned on to generate the driving current (I_{LED}), which can be defined as the following equation:

$$\begin{aligned} I_{LED} &= \frac{1}{2}k(V_{GS} - V_{TH})^2 \\ &= \frac{1}{2}k(VSS + V_{DATA} - V_H + V_{TH\_T5} - VSS - V_{TH\_T1})^2 \\ &= \frac{1}{2}k(V_{DATA} - V_H)^2 \end{aligned} \quad (3)$$

where k is $\mu \cdot C_{ox} \cdot W/L$ of T1. By the matching method, the electrical characteristics of T1 are similar to T5, and thus the V_{TH_T1} can be eliminated in Eq. (3). Additionally, the driving current is independent of VSS I-R rises because stored V_{C1} which is the gate-to-source voltage (V_{GS}) of T1 remains consistently. The proposed circuit can generate a high uniform driving current despite the variation of V_{TH} and VSS.

2.4 Turn-off period:

S2[n] goes to V_{GH} to turn on T2. V_{DATA} which is lower than VSS is set to the gate of T1. Therefore, T1 is turned off to suspend the emission of mini-LED.

Following the operations mentioned above, the proposed circuit compensates for the variations of VSS and V_{TH} successfully to increase the image quality. With low power consumption and high uniform brightness, the mini-LED driving circuit in this article is suitable for backlight modules of LCDs.

3 Simulation Results and Discussions

The functionality of the proposed circuit is verified by HSPICE simulator whose Rensselaer Polytechnic Institute poly-silicon TFT model (Level 62) is used. The designed specification of this work is based on a 5.23-inch LCD, adopting AM mini-LED backlight modules with 48 × 48 dimming zones and a frame rate of 90 Hz. Fig. 2(a) and (b) show the structure and timing diagram of the compared circuit. Table I indicates the parameters of the proposed circuit and the compared 7T1C circuit [12], including the aspect ratio of TFTs, the voltage of power supplies, capacitances, and voltage swings of control signals. Noticeably, the diode-connected TFT (T_{LED}) and capacitance (C_{LED}) are in parallel to emulate the electrical characteristic of mini-LED. Fig.3(a) captures the waveforms of V_B in the reset, compensation, and the beginning of the emission period. After V_D is reset to -3 V at first period, V_B are charged to -0.471 V, -0.766 V, and -1.063 V through source follower structure when V_{TH} of T1 and T5 are varied by $\pm$0.3 V. The V_{TH} variations of T5 are sensed as differences of V_B are 0.295 V and -0.297 V which are almost equal to $\pm$0.3 V. Fig. 3(b) plots swings of V_A when V_{TH} of T1 and T5 are varied by $\pm$0.3 V and VSS I-R rises 0.5 V. During the emission period, the deviation of V_A are 0.192 V and 0.781 V which are similar to total variation + 0.2 V (ΔVSS+ ΔV_{TH} (-0.3 V) = +0.2 V) and +0.8 V (ΔVSS+ ΔV_{TH} (+0.3 V) = +0.8 V). Fig. 3(c) shows the relative current error rates at different gray levels after compensation. The relative error rates between I_{LED} without any variation (I_{LED_0}) and I_{LED}s with VSS and V_{TH} variations are calculated by the following equation:

$$Error\ rate = \frac{|I_{LED\_0} - I_{LED(\Delta V_{TH}=\pm 0.3\,V\ \&\ \Delta VSS=+0.5\,V)}|}{I_{LED\_0(\Delta V_{TH}=0\,V\ \&\ \Delta VSS=0\,V)}} \times 100\% \quad (4)$$

The maximum error rate is 8.59% when V_{TH} is varied by +0.3V and VSS rises 0.5 V at the highest gray level. According to the above simulations, the performance of the compensation in this work is established because the effects of variations are reduced efficiently. To evaluate the power reduction of the proposed circuit, the fair comparison with the previous work [12] will be given. The parameters of both circuits are equal, including the sizes of TFTs, capacitance, and driving voltage in every gray level. Fig. 4 indicates the power consumption of specific gray levels in the compared circuit and the proposed circuit. While the switching TFTs are removed from the driving current path in this work, the voltage across VDD and VSS (V_{total}) is only determined by the forward voltage of mini-LED (V_{LED}) and drain-to-source voltage of T1 (V_{DS_T1}). The power consumption (P) can be expressed as:

$$P_{5T2C} = I_{LED} \times V_{total} = I_{LED} \times (V_{DS\_T1} + V_{LED}) \quad (6)$$

$$P_{7T1C} = I_{LED} \times V_{total} = I_{LED} \times (VDD - VSS) \quad (7)$$

The power improvement of this work can also be calculated further:

$$Power\ Improvement = \frac{P_{7T1C} - P_{5T1C}}{P_{7T1C}} \times 100\% \quad (8)$$

In every gray level, the proposed circuit ameliorates 15.79% power consumption better than the 7T1C circuit. The effectiveness of the compensation and power consumption reduction in this work is demonstrated by the simulations, hence the proposed circuit is applicable to the mini-LED backlight modules used for LCDs.

4 Conclusions

A mini-LED driving circuit of the LCDs backlight module with low power consumption is presented in this article. To improve the image quality, the V_{TH} and VSS variation are compensated. The relative error rates are below 8.59%, proving the capability of the compensation of the proposed circuit. By placing only driving TFT on the driving current path, the static power consumption is reduced. Compared with the 7T1C circuit, the power improvement is boosted by 15.79% in the whole gray levels. In conclusion, the proposed circuit can generate a uniform driving current and reduce power consumption.

5 Acknowledgment

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