Investigation on the Current Nonuniformity in Current-Mode TFT Active-Matrix Display Pixel Circuitry

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Abstract—Detailed analysis of the mechanisms that cause deviations of the emission current from the input data current in polycrystalline silicon (poly-Si) thin-film transistor (TFT) current-copier active matrix carbon nanotube field emission display (FED) pixel circuits is presented. These effects make the modulated emission current sensitive to the process variations of the circuit elements. Monte Carlo circuit analysis with a Gaussian statistical distribution of all related process parameters in the pixel circuit shows the emission current nonuniformity, and therefore illustrates the importance of improving the poly-Si TFT process for the design of high-resolution and high-brightness current-mode active matrix addressed displays. The analysis is also suitable for design and optimization of other reported current-mode active matrix addressed FED or organic light-emitting displays.

Index Terms—Active matrix, carbon nanotube (CNT), current-copier, current-mode, field emission display (FED), flat-panel display, Monte Carlo, organic light-emitting display (OLED), polycrystalline silicon (poly-Si), thin film transistor (TFT).

I. INTRODUCTION

FIELD emission displays (FED) and organic light-emitting displays (OLEDs) are currently the two most promising display technologies that are likely to replace the dominant liquid crystal display in the future [1], [2]. In both technologies, the luminance of the lighting element is proportional to its current density, and therefore current-mode pixel driving approaches appear to be a natural solution for high quality FEDs or OLEDs. To date, current-copier and current-mirror type pixel circuitry based on amorphous silicon (a-Si) or polycrystalline silicon thin film transistor (poly-Si TFT) technologies have been proposed for the active matrix addressed OLEDs [3], [4]. Lin *et al.* [5] used a current-mirror-based switch-current memory pixel circuit for OLEDs to improve the accuracy and operation frequency, and Levy *et al.* [6] has already designed a CMOS subthreshold-voltage-scaling current-mirror driver for OLED-on-silicon to improve the bandwidth and settling behavior. Recently, the design of poly-Si TFT current-modulated FED pixels based on carbon nanotube (CNT) emitters was also reported [7]. These current-mode pixel drivers greatly improve the display uniformity, compared with the voltage-mode

Fig. 1. Current-copier carbon nanotube (CNT) based FED pixel circuit and its two operation phase: sampling and hold. I_{data} is the input data current, and I_{el} is modulated emission current of the CNT field emission device.

pixel drivers [8], [9], as well as successfully achieving good gray-shade control by continuously modulating the current density of each pixel directly with the input data current.

For the current-copier CNT-FED pixel circuit, as shown in Fig. 1, the operation can be divided into two phases: sampling and hold. During the sampling phase, the video signal is converted to a current signal I_{data} , then sampled into the current sink transistor T_{CS} during row selection. During the hold phase, the current sink transistor T_{CS} reproduces and holds the current signal to drive the lighting element. Theoretically, the modulated emission current I_{el} is equal to the input data current I_{data} , independent of the process variations of the circuit components. However, there are usually some deviations of I_{el} from I_{data} due to several undesired effects which are sensitive to the process variations of circuit components. Thus, the output linearity of the driver circuitry and the emission current uniformity may deteriorate.

In this paper, the mechanisms that cause the current deviations from ideal are carefully investigated for the first time. A modification of the pixel circuitry in Fig. 1, with an additional feedback capacitance between T_{CS} 's source and drain is proposed and analyzed. The Monte Carlo analysis, taking account of the process variations, predicts the performance of the current-copier pixel circuits in a true poly-Si TFT process. The circuit simulation in the work is based on the RPI Polysilicon TFT model using the Silvaco Smart-Spice circuit simulator [10]. The setup for the simulation can be seen in [7]. Although the study in this work is based on the current-copier FED pixel circuit, it is also very suitable for other current-mode active matrix display pixel drivers for FEDs and OLEDs.

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Fig. 2. Variation of the T_{CSS} gate/source voltage V_{gs}^{CS} and drain/source voltage V_D^{CS} when the pixel circuit in Fig. 1 shifts from sampling phase to hold phase: $\Delta V_{gs,SW2}^{CS}$ is the falling part due to charge injection and clock feed-through effects on T_{SW2} , $\Delta V_{gs,cp}^{CS}$ is the rising part due to T_{CSS} drain-to-gate coupling, and ΔV_D^{CS} is T_{CSS} drain/source voltage variation.

II. ANALYSIS OF THE CURRENT ERRORS

For the current-copier FED pixel shown in Fig. 1, in a realistic case, the finally modulated emission current is given by [11]

$$I_{el} = \left(\sqrt{I_{data}} - \sqrt{\beta_{CS}} \cdot \Delta V_{gs}^{CS} \right)^2 + \lambda \cdot \Delta V_D^{CS} \quad (1)$$

where $\beta_{CS} = (1/2) \cdot (W/L) \mu_{FE} \cdot C_{ox}$ is the transconductance factor of T_{CS} , ΔV_{gs}^{CS} and ΔV_D^{CS} are the gate stored voltage and the drain voltage shift which occurs when the pixel operation changes from the sampling phase to the hold phase, and λ is a constant associated with the channel length modulation and the kink effects of the poly-Si TFTs.

Equation (1) shows that ΔV_{gs}^{CS} and ΔV_D^{CS} may cause deviation of I_{el} from I_{data} . As illustrated in Fig. 2, ΔV_{gs}^{CS} is composed of two parts: the falling part $\Delta V_{gs,SW2}^{CS}$ due to the charge injection and clock feed-through effects on T_{SW2} and the rising part $\Delta V_{gs,cp}^{CS}$ due to T_{CSS} drain-to-gate coupling. The following discussions will analyze the two parts of ΔV_{gs}^{CS} and present the mechanisms that produce ΔV_{gs}^{CS} , ΔV_D^{CS} as well as the relations between I_{el} , ΔV_{gs}^{CS} , ΔV_D^{CS} and the circuit components.

A. Impacts of T_{SW2} s Switching Effects

The main factor that induces the sampled V_{gs}^{CS} error is the charge injection and clock feedthrough effects of T_{SW2} . In Fig. 1, as V_{scan} begins to fall to turn off the switch, mobile charges exit through both the drain end and the source end of T_{SW2} . The charges transferred to the C_S cause a reduction to the sampled voltage, which can be expressed as [12]

$$\Delta V_{ch} = \frac{pWLC_{ox}(V_{scan} - V_T^{SW2} - \eta V_{gs}^{CS})}{C_S + C_{gs}^{CS}} \quad (2)$$

where V_T^{SW2} is T_{SW2} s threshold voltage, p denotes the fraction of the channel charge that flows into C_S , depending on the voltage swing and falling rate of V_{scan} . A higher swing or quicker falling rate of V_{scan} will cause larger p . ηV_{gs}^{CS} represents the average channel potential, which is dependent on the input data current.

(a)

(b)

Fig. 3. Impacts of C_S with different I_{data} . (a) Dependence of $\Delta V_{gs,SW2}^{CS}$, which is illustrated in Fig. 2, on C_S . (b) Dependence of $\sqrt{I_{data}} - \sqrt{I_{el}}$ on C_S .

At the same time, when V_{scan} switches from high to low, the voltage difference in V_{scan} switching may be coupled into the sampled point with the clock feed-through effect, and give rise to ΔV_{cl} , which is given by

$$\Delta V_{cl} = \frac{V_{scan} \cdot C_{gs}^{SW2}}{C_{gs}^{SW2} + C_S} \quad (3)$$

For the self-aligned TFT technology, $C_{gs}^{SW2} \approx (1/2)(W \cdot L)_{SW2} \cdot C_{ox}^{SW2}$ is much smaller than C_S . Thus, the total amount that the settling voltage V_{gs}^{CS} is pulled down can be approximated as

$$\begin{aligned} \Delta V_{gs,SW2}^{CS} &= \Delta V_{ch} + \Delta V_{cl} \\ &= \frac{(W \cdot L)_{SW2} C_{ox}^{SW2}}{C_S} \\ &\quad \times \left[p(V_{scan} - V_T^{SW2} - \eta V_{gs}^{CS}) + \frac{1}{2} V_{scan} \right] \end{aligned} \quad (4)$$

Figs. 3 and 4 show the dependence of $\Delta V_{gs,SW2}^{CS}$, I_{el} on C_S and the dimensions of T_{SW2} , respectively. They fit the linear relations of $\Delta V_{gs,SW2}^{CS} \sim 1/C_S$, $(\sqrt{I_{data}} - \sqrt{I_{el}}) \sim 1/C_S$, $\Delta V_{gs,SW2}^{CS} \sim W_{CS}$, and $(\sqrt{I_{data}} - \sqrt{I_{el}}) \sim W_{CS}$, derived from (1) and (4). The decrease of $\Delta V_{gs,SW2}^{CS}$ with increased

Fig. 4. Impacts of T_{SW2} 's width W_{SW2} with different I_{data} . (a) Dependence of T_{CS} 's gate/source voltage change $\Delta V_{gs,SW2}^{CS}$, which is illustrated in Fig. 2, on W_{SW2} . (b) Dependence of $\sqrt{I_{data}} - \sqrt{I_{el}}$ on W_{SW2} .

I_{data} shown in Figs. 3 and 4 also agrees with (4), since a larger I_{data} brings a larger ηV_{gs}^{CS} , which causes smaller $\Delta V_{gs,SW2}^{CS}$ according to (4).

Based on the above arguments, $\Delta V_{gs,SW2}^{CS}$ can be minimized by using the largest C_s possible, using minimum-geometry T_{SW2} , keeping the V_{scan} swings as small as possible and slowing the falling rate. However, decreasing T_{SW2} s length will cause larger leakage current in the hold phase; increasing C_s and decreasing T_{SW2} s width will prolong the required settling time; lowering the V_{scan} swing will increase T_{SW1} , T_{SW2} s ON resistance and thereafter the settling time; finally, the limited pixel select-on time makes it difficult to slow V_{scan} s falling rate too much. That implies some compromises are necessary to be considered in the design to achieve the best performance, and $\Delta V_{gs,SW2}^{CS}$ is difficult to be completely eliminated.

B. T_{CS} Drain-to-Gate Coupling

Another effect that contributes to the sampled V_{gs}^{CS} error is the drain-to-gate coupling of T_{CS} through the drain/gate capacitance C_{gd} . When the circuit switches from the sampling phase to the hold phase, the increase of V_D^{CS} may be coupled to the gate with the parasitic drain/gate capacitance C_{gd} , and increase

Fig. 5. Dependence of $\Delta V_{gs,cp}^{CS}$, which is illustrated in Fig. 2, on ΔV_D^{CS} , with different additional feed-back capacitances C_f between T_{CS} s drain and gate. (a) $C_f = 0.02 \text{ pF}$. (b) $C_f = 0.01 \text{ pF}$. (c) $C_f = 0$.

Fig. 6. Dependence of $\Delta V_{gs,cp}^{CS}$, which is illustrated in Fig. 2, on the additional feed-back capacitance C_f between T_{CS} s drain and gate.

the V_{gs}^{CS} with a certain amount $\Delta V_{gs,cp}^{CS}$, which can be expressed as [12]

$$\Delta V_{gs,cp}^{CS} = \frac{\Delta V_D^{CS} \cdot C_{gd}}{C_s + C_{gd}}. \quad (5)$$

For the self-aligned TFT technology, the C_{gd} is mainly composed of the gate/channel capacitance, which depends on the operation state. With the increased drain voltage, the depletion region near the drain increases and C_{gd} decreases. Thus, $\Delta V_{gs,cp}^{CS}$ may decrease with increased V_D^{CS} in this case, as shown in Fig. 5(c). If adding a larger feedback capacitance C_f between the gate and drain of T_{CS} , $C_{gd} \approx C_f$, and in Fig. 5(a) and (b), $\Delta V_{gs,cp}^{CS}$ has a linear rise while increasing V_D^{CS} , which accords with (5). The linear relation between $\Delta V_{gs,cp}^{CS}$ and C_{gd} from (5) also fits the simulation results in Fig. 6.

C. The Impacts of T_{SW1} ON-Resistance

When the data current is sampled into the current sink transistor T_{CS} , the nonzero resistance of T_{SW1} causes a voltage drop ΔV_{SW1} on the switch. So there is

$$V_{DS}^{CS} = V_{GS}^{CS} - \Delta V_{SW1} \quad (6)$$

where

$$\Delta V_{SW1} = \frac{I_{data}}{\mu_{SW1} \cdot \left(\frac{W}{L}\right)_{T_{SW1}} \cdot (V_{GS}^{SW1} - V_T^{SW1})} \quad (7)$$

and

$$V_{GS}^{T_{SW1}} = V_{scan} - I_{data} \cdot r_o^{CS}. \quad (8)$$

ΔV_{SW1} must be kept small enough ($\Delta V_{SW1} < V_T^{CS}$), otherwise T_{CS} will be drawn into the triode operation region and bring a large sampled error of V_{gs}^{CS} for reproducing the sampled current during hold phase. In the final design, ΔV_{SW1} can easily be made small enough. But its being sensitive to the process parameter variations of both T_{CS} and T_{SW1} , as seen from (6)–(8), may give rise to some variations of sampled V_{gs}^{CS} and V_D^{CS} . The larger ΔV_{SW1} will cause smaller V_D^{CS} , and for a given input data current, the smaller V_D^{CS} induces larger V_{gs}^{CS} based on (9). Thereafter, a larger emission current will be reproduced during the hold phase.

$$I_{data} = g_m^{CS} \cdot V_{gs}^{CS} + \lambda \cdot V_D^{CS}. \quad (9)$$

Fig. 7 shows the linear relation between ΔV_{SW1} and the L/W of T_{SW1} , and the increased $\Delta I_{err} = I_{el} - I_{data}$ with increasing L/W of T_{SW1} , which agrees with the above arguments very well. From (9), increasing the conductance g_m^{CS} of T_{CS} may cause a decrease of V_{gs}^{CS} . But, the increase of the conductance g_m^{CS} will also increase ΔV_{SW1} , reduce V_D^{CS} , and finally lower the V_{gs}^{CS} . Therefore, an increase of ΔI_{err} with increased carrier effective mobility of T_{CS} and μ_{CS} can be found in Fig. 8.

III. CURRENT-COPIER PIXEL CIRCUIT WITH A FEEDBACK CAPACITANCE

The main factor that induces the deviation of I_{el} from I_{data} is charge injection and clock through effects of T_{SW2} , and is possibly partially cancelled by adding a dummy transistor [13] or using a CMOS transmission gate instead of the n-TFT switch [14]. However, they both increase the pixel complexity with an additional TFT and input pulse signal. From Fig. 2, it is seen that the $\Delta V_{gs,cp}^{CS}$ may counteract $\Delta V_{gs,SW2}^{CS}$. In fact, as illustrated in (5), Figs. 6 and 7, since the curve of $\Delta V_d^{CS} \sim I_{data}$ has a similar change with that of $\Delta V_{gs,SW2}^{CS} \sim I_{data}$ (Fig. 9), choosing a suitable C_f may produce a $\Delta V_{gs,cp}^{CS}$ that can effectively reduce $\Delta V_{gs,SW2}^{CS}$ over the whole current range. Fig. 10 shows the improved linearity of the pixel circuit with adding a feedback capacitance C_f between T_{CS} gate and drain.

IV. CURRENT NONUNIFORMITY DUE TO PROCESS VARIATIONS

To predict the emission current nonuniformity of the pixel circuitry fabricated in a true poly-Si TFT foundry process, Monte

Fig. 7. Dependence of voltage drop on T_{SW1} ΔV_{SW1} and $\Delta I_{err} = I_{el} - I_{data}$ on T_{SW1} 's length-to-width ratio $(L/W)_{SW1}$.

Fig. 8. Dependence $\Delta I_{err} = I_{el} - I_{data}$ on T_{CS} 's effective carrier mobility μ_{CS} of with different input data current I_{data} .

Fig. 9. Similar variations of $\Delta V_{gs,SW2}^{CS}$ and ΔV_D^{CS} with I_{data} for the pixel circuit with an additional feed-back capacitance C_f between T_{CS} drain and gate.

Fig. 10. Improved output linearity of the current-copier circuit with a feedback capacitance C_f , between the gate and drain of T_{CS} .

Carlo analysis was performed with the Gaussian statistical distribution of all related process parameters in the circuit as shown in Table I. The nonuniform current-voltage characteristics and the standard deviation current errors of the triode field emitter model used for the simulation are shown in Fig. 11.

The distribution histogram of I_{el} obtained by Monte Carlo analysis in Fig. 12 shows the circuit with a feedback capacitance C_f , provides better current-copy accuracy, but it has a little worse uniformity due to the additional parameter C_f , which is also shown in Fig. 13. Although compared with the original current-voltage characteristics shown in Fig. 11, the standard deviation error for the emission current has been greatly reduced and therefore a much higher uniformity obtained, the increasing standard deviation of I_{el} with the increased I_{data} signifies the importance for improving the process for building high-resolution and high-brightness current-mode active matrix addressed displays. Fortunately, because the human eye is not sensitive to a smooth luminance variation in the long-range regime (a range of viewing angles from about 30° to 60°) [15] and the TFT technology in a short-range regime can show good uniformity of the electrical characteristics, it is very promising to design the cur-

Fig. 11. (a) Current-voltage characteristics of the triode field emitter model for statistical simulation. (b) Standard deviation error of the field emission current with different gate voltages of the triode field emitter model.

TABLE I
GAUSS DISTRIBUTION OF THE PROCESS PARAMETERS
FOR SPICE MONTE CARLO ANALYSIS

Parameters	Normal value	Related variation	σ
$V_T(T_{CS,SW1,SW2})$	1.5 V	20%	3
$V_T(T_{HV})$	3.1 V	20%	3
$\mu(T_{CS,SW1,SW2})$	130 $\text{cm}^2/\text{V}\cdot\text{s}$	20%	3
$\mu(T_{HV})$	100 $\text{cm}^2/\text{V}\cdot\text{s}$	20%	3
kink effect factor ($T_{CS,SW1,SW2}$)	19.3	15%	3
kink effect factor (T_{HV})	20.8	15%	3
$W, L(T_{CS})$	10 μm	10%	3
$W(T_{SW1,SW2})$	20 μm	10%	3
$L(T_{SW1,SW2})$	5 μm	10%	3
$W(T_{HV})$	15 μm	10%	3
$L(T_{HV})$	30 μm	10%	3
C_S	0.4 pF	10%	3
C_f	0.01 pF	10%	3

rent-mode pixel circuit for produce FEDs or OLEDs with good enough luminance uniformity.

Fig. 12. I_{el} distribution with different input I_{data} obtained by Monte Carlo statistical analysis with the Gaussian distribution of process parameters shown in Table I.

Fig. 13. Standard deviation of I_{el} obtained from the Monte Carlo analysis results.

V. CONCLUSION

The factors that contribute to the current nonuniformity in the poly-Si TFT current-copier FED pixel circuit are carefully investigated, including; 1) the charge injection and clock feedthrough effects, 2) drain-to-gate coupling of the current sink TFT and, 3) the ON-resistance of the switch TFT. Detailed analysis of the modulated emission current varying with the circuit component parameters is very important for designing

and optimizing the pixel circuit for high performance displays. It is also found that through adding a feedback capacitance, the output linearity of the circuit can be improved at some comprise of emission current uniformity. Monte Carlo analysis shows the nonuniformity of the current-copier circuit, and proves the importance of greatly improving the process to develop high-resolution and high-brightness active matrix addressed displays. The work in this paper is also useful to analyze and optimize other current-mode active matrix pixel drive circuits that have been reported.

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