The Pixel Circuit Compensating for Strain Effect and Threshold Voltage Variation in Stretchable Display

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ABSTRACT

The stretchable display pixel circuits, which compensate for strain and the threshold voltage variation, have been proposed. The capacitive-type strain sensor is exploited to detect and compensate for the luminance reduction caused by stretching. The simulation results show that the proposed circuits have excellent compensation ability when the strain is applied.

1 Introduction

The stretchable display has been intensively investigated since it is expected to be the ultimate form of the deformable display. Since the display pixel devices such as organic light-emitting diode (OLED) and thin-film transistors (TFTs) are vulnerable to the mechanical stress, many studies have focused on protecting the devices from external strain. Among them, the structure with the rigid island is the most widely used [1-2]. In this structure, each pixel circuit is mounted on the rigid island, and the flexible interconnections connect these rigid islands. As shown in Fig. 1, the pixel devices on the rigid island can be protected from external stress because the strain is concentrated on the interconnection.

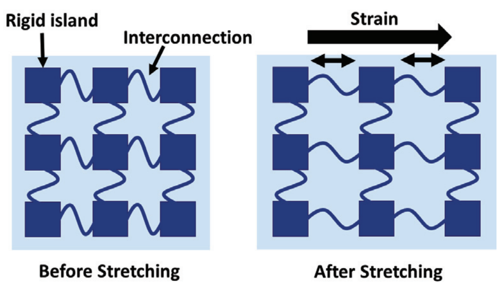

Fig. 1 The rigid-island structure stretchable display before and after stretching

Even though a rigid island structure can minimize mechanical stress, several problems related to the image quality still exist. One of them is the threshold voltage (V_{th}) variation of the driving TFT due to the voltage bias or temperature change, which eventually degrades the uniformity of the display image. Therefore, the threshold voltage of the driving TFT must be compensated to get high-quality display image.

Another issue is the luminance degradation due to the stretching of the panel. It is well known that the luminance (L) of the display can be described as following equation:

$$L = \eta \frac{I_{OLED}}{A}$$

where η is an OLED efficiency, I_{OLED} is a current flows through the OLED, and A is the area that one pixel should emit light. When the strain ϵ is applied to the panel, the area A increased to $A(1+\epsilon)$, so that the luminance eventually decreases by $(1+\epsilon)$ times.

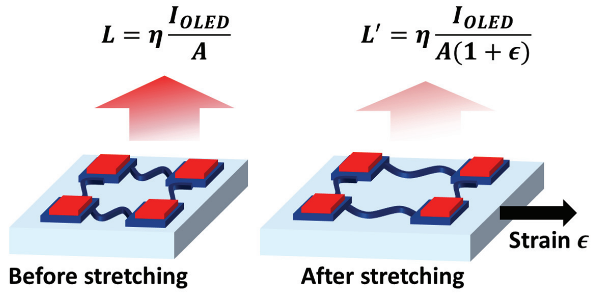

Fig. 2 The luminance reduction caused by display stretching

Herein, we introduce the pixel circuits for the stretchable display which can compensate for the V_{th} variation of TFT and luminance degradation caused by the display stretching. The pixel circuits are composed of indium-gallium-zinc-oxide (IGZO) TFTs, storage capacitors, and a capacitive-type stretchable strain sensor. The HSPICE simulation results show that the proposed circuits can effectively compensate the threshold voltage variation and the strain effect.

2 The proposed pixel circuits

We introduce several pixel circuits for the stretchable display which can compensate for both V_{th} variation and strain effect. The driving period of the proposed circuit is divided into 4 stages: (A) reset (B) V_{th} compensation (C) data input and (D) emission. The proposed circuits basically have the capacitive-type strain sensor C_s connected with the storage capacitor C_{st} in series, and the overdrive voltage of the driving TFT during OLED emission is expressed as $Vdata\left(\frac{Cs}{Cs+Cst}\right)$, where $Vdata$ denotes data voltage.

The strain effect compensation can be done in real-time during the (D) emission stage. As previously mentioned, when the strain ϵ is applied, the luminance of the display decreased to $L/(1+\epsilon)$. To maintain the luminance same as before stretching, the equation of I_{OLED} should be increased by $(1+\epsilon)$ times as following equation:

$$I_{OLED}(1+\epsilon) = k\left\{Vdata\left(\frac{\text{Cs}}{\text{Cs}+\text{Cst}}\right)\sqrt{1+\epsilon}\right\}^2,$$

, where $k=\frac{1}{2}\mu C_{ox}\frac{W}{L}$. The equation can be rewritten as follows:

$$I_{OLED}(1+\epsilon) = k\left\{Vdata\left(\frac{\text{Cs}}{\text{Cs}+\text{Cst}}\right)\left(1+\frac{\epsilon}{2}\right)\right\}^2.$$

The stretchable capacitive-type strain sensor consists of two parallel electrode and a soft dielectric material. The sensor can detect the strain by the change of the capacitance. If the width, length, and thickness of the capacitive-type strain sensor are w_0, l_0, and d_0, respectively, the initial capacitance of the sensor can be described as following equation:

$$\text{Cs} = \varepsilon_0\varepsilon_r\frac{w_0 l_0}{d_0}$$

where ε_0 is the vacuum permittivity and ε_r is the dielectric constant, respectively. If the external strain ϵ is applied on the uniaxial direction, the capacitance of the sensor can be obtained as follow:

$$\text{Cs}' = \varepsilon_0\varepsilon_r\frac{w_0(1+\epsilon)l_0(1-\nu\epsilon)}{d_0(1-\nu\epsilon)} = \text{Cs}(1+\epsilon)$$

Therefore, the overdrive voltage of driving TFT after strain is applied can be described as follows:

$$Vdata\frac{\text{Cs}(1+\epsilon)}{\text{Cst}+\text{Cs}(1+\epsilon)}$$

If we assume ϵ is not too large, the equation can be approximated by Taylor expansion:

$$Vdata\frac{\text{Cs}(1+\epsilon)}{\text{Cst}+\text{Cs}(1+\epsilon)} = Vdata\frac{\text{Cs}(1+\epsilon)}{(\text{Cst}+\text{Cs})\left(1+\frac{\epsilon\text{Cs}}{\text{Cs}+\text{Cst}}\right)}$$
$$\approx Vdata\frac{\text{Cs}(1+\epsilon)}{\text{Cst}+\text{Cs}}\left(1-\frac{\epsilon\text{Cs}}{\text{Cs}+\text{Cst}}\right)$$
$$\approx Vdata\frac{\text{Cs}}{\text{Cs}+\text{Cst}}\left(1+\frac{\epsilon\text{Cst}}{\text{Cs}+\text{Cst}}\right)$$

When $\text{Cs}=\text{Cst}$, the equation can be transformed as follows:

$$\frac{V_{gs}}{2}\left(1+\frac{\epsilon}{2}\right)$$

Thus, we can confirm that I_{OLED} increased to $I_{OLED}(1+\epsilon)$, which results the compensation of luminance degradation due to the display deformation.

2.1 6T2C with 1 strain sensor

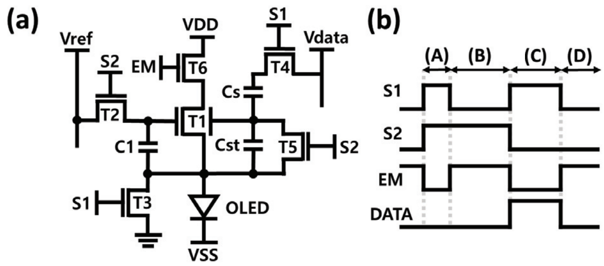

Fig. 3 (a) The schematic of 6T2C pixel circuit for stretchable display and (b) the control signals

The proposed pixel circuit with 6 TFTs (T1-T6), 2 storage capacitors (C1, Cst), and 1 capacitive-type strain sensor (Cs) is shown in Fig. 3. The double-gate (DG) structure TFT is adopted as the driving TFT (T1). S1, S2, and EM signals are used to control the switching TFTs.

After C1 stores V_{th} through the source-follower method at stage (B), the voltage become $Vdata\left(\frac{\text{Cs}}{\text{Cs}+\text{Cst}}\right)$ at stage (C). Since the changes of V_{th} in DG structure TFT is linear with the difference of the opposite gate voltage [5], V_{th} of T1 can be described as follows:

$$V_{th} - \alpha\left(Vdata\left(\frac{\text{Cs}}{\text{Cs}+\text{Cst}}\right)\right)$$

, where α is a coefficient related to the insulator thickness.

Thus, the OLED current at stage (D) can be calculated as follows:

$$I_{OLED} = k\left[V_{th}-\left\{V_{th}-\alpha\left(Vdata\left(\frac{\text{Cs}}{\text{Cs}+\text{Cst}}\right)\right)\right\}\right]^2$$
$$= k\left\{\alpha\cdot Vdata\left(\frac{\text{Cs}}{\text{Cs}+\text{Cst}}\right)\right\}^2$$

2.2 5T2C with 1 strain sensor

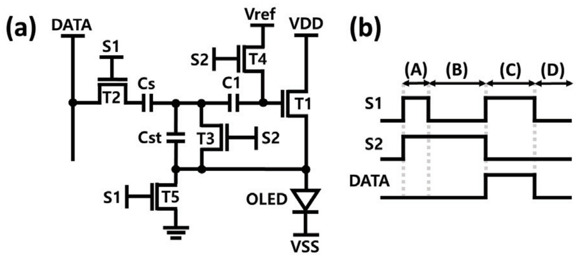

Fig. 4 (a) The schematic of 5T2C pixel circuit for stretchable display and (b) the control signals

Fig. 4 shows another pixel circuit, consisting of 5 single-gate TFTs (T1-T5), 2 storage capacitors (Cs, C1), and 1 capacitive-type strain sensor (Cs). S1 and S2 signals are used to control the switching TFTs. The circuit has an advantage in fabrication because the single-gate structure is simpler than DG one.

After the V_{th} of T1 is stored in C1 at (B) stage, $Vdata$

comes through T2 and is, divided by Cs and Cst capacitors. The voltage between the gate and source node of the T1 can be expressed as follows:

$$Vdata\left(\frac{\mathrm{Cs}}{\mathrm{Cs}+\mathrm{Cst}}\right)+V_{th}$$

Thus, the OLED current can be described as follows:

$$I_{OLED}=k\left\{Vdata\left(\frac{\mathrm{Cs}}{\mathrm{Cs}+\mathrm{Cst}}\right)+V_{th}-V_{th}\right\}^2$$
$$=k\left\{Vdata\left(\frac{\mathrm{Cs}}{\mathrm{Cs}+\mathrm{Cst}}\right)\right\}^2$$

2.3 5T1C with 1 strain sensor

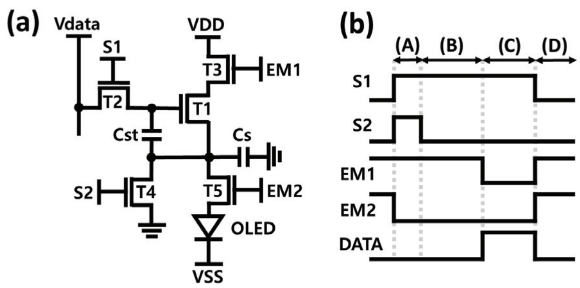

Fig. 5 (a) The schematic of 5T1C pixel circuit for stretchable display and (b) the control signals

The proposed pixel circuit consisted of 5 TFTs (T1-T5), 1 storage capacitor (Cst), and 1 capacitive-type strain sensor (Cs) is shown in Fig. 5. S1, S2, EM1, and EM2 signals are used to control the switching TFTs.

At the end of the stage (B), the source node voltage of T1 becomes $V_{ref}-V_{th}$. When the gate node voltage changes to $Vdata$ at stage (C), the source node voltage of T1 increased as follows:

$$\left(Vdata-V_{ref}\right)\frac{\mathrm{Cst}}{\mathrm{Cs}+\mathrm{Cst}}+V_{ref}-V_{th}$$

Thus, the voltage between gate and source node of T1 becomes $\left(Vdata-V_{ref}\right)\frac{\mathrm{Cs}}{\mathrm{Cs+Cst}}+V_{th}$, and the OLED current can be expressed as following equation:

$$I_{OLED}=k\left\{\left(Vdata-V_{ref}\right)\frac{\mathrm{Cs}}{\mathrm{Cs}+\mathrm{Cst}}\right\}^2$$

3. Simulation Results

The measured and fitted transfer characteristics of IGZO TFT are shown in Fig. 6. The parameters of the level 62 RPI TFT model in HSPICE were used in fitting. The mobility and the V_{th} of the TFT are 7.64 $\mathrm{cm}^2/V\cdot s$ and -0.68 V, respectively. In this paper, only the simulation results of 5T1C circuit in Section 2.2 are attached, but the results of other circuits appear on similar level.

Fig. 7 depicts the simulation results of the V_{th} compensation error rate when V_{th} is shifted $\pm 0.5\,V$. The error rate was calculated by following equation:

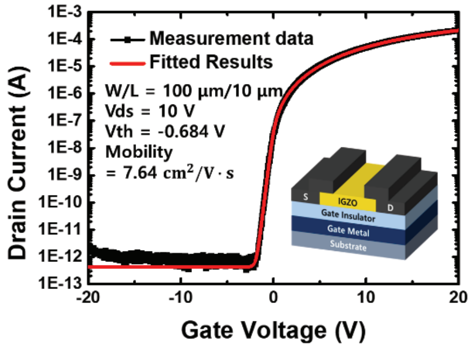

Fig. 6 The measured and fitted transfer curve of the fabricated InGaZnO TFT

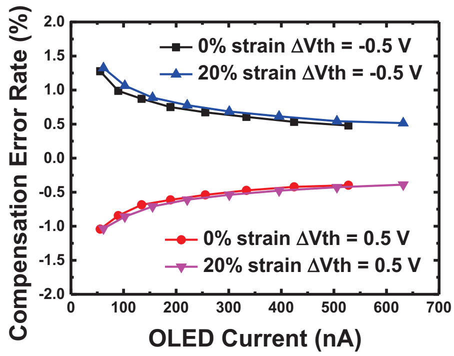

Fig. 7 The threshold voltage compensation error rate under 0% and 20% strain

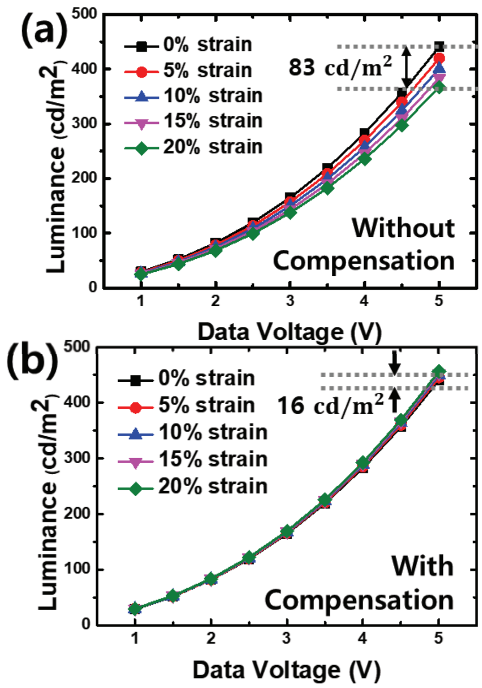

Fig. 8 The luminance as a function of data voltage (a) without and (b) with compensation

$$\frac{|I_{\Delta V_{th}=0} - I_{\Delta V_{th}=\pm 0.5}|}{I_{\Delta V_{th}=\pm 0.5}} \times 100(\%)$$

, where $I_{\Delta V_{th}=0}$ and $I_{\Delta V_{th}=\pm 0.5}$ denote the OLED current when V_{th} is shifted $0\,V$ and $\pm 0.5\,V$, respectively. As shown in the figure, the error rate of the pixel is less than 2% even under the 20% strain is applied, which shows that the V_{th} compensation ability is maintained even when the display is stretched.

Fig. 8 shows the luminance of the display as the function of data voltage with and without strain effect compensation. In both cases, V_{th} is fixed for the clear observation of strain effect compensation ability. The luminance variation due to strain appears $83\ \mathrm{cd/m^2}$ without compensation, which is significantly reduced to $16\ \mathrm{cd/m^2}$ after compensation. Thus, it is proved that the proposed circuit can successfully compensate for the luminance reduction caused by display stretching.

4. Conclusions

We have proposed the stretchable display pixel circuits which can compensate for not only the TFT V_{th} variation but also the luminance reduction due to display stretching. The circuit was designed based on the equation, and the compensation ability was verified by simulation. We could find that both the threshold voltage and the luminance reduction of the stretchable display can be effectively compensated by using the proposed circuit.

Acknowledgments

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