Amorphous Silicon TFT-Based Active-Matrix Organic Polymer LEDs

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***Abstract*—We report active-matrix organic polymer light-emitting displays (LEDs) based on a three hydrogenated amorphous silicon (a-Si:H) thin-film transistor (TFT) pixel electrode circuit that supplies a continuous output current to organic polymer light-emitting devices. The output current level drift induced by either process variations or device aging can be reduced in this design by adjusting the driver TFT operating point with the active resistor. Our first green light-emitting engineering prototype had a brightness of 120 cd/m^2 and fill factor of about 45%.**

***Index Terms*—Active-matrix, amorphous silicon thin-film transistor, light-emitting diode.**

I. Introduction

ACTIVE-MATRIX organic light-emitting displays (AM-OLEDs) are emerging as new flat panel display technology that one day could replace active-matrix liquid-crystal displays (AM-LCDs). This new flat panel display technology has attributes such as high brightness, high contrast ratio, paper-like viewing angle, low power consumption, light weight, low fabrication cost, and the possibility of being integrated with flexible substrates.

In recent years, organic-light emitting devices (OLEDs) have been combined with low-temperature polycrystalline silicon (poly-Si) thin-film transistors (TFTs) active-matrix arrays to produce AM-OLEDs [1]–[5].

Recently amorphous silicon (a-Si:H) TFT based AM-OLEDs [6]–[13] have started to challenge poly-Si TFT AM-OLEDs due to a mature a-Si:H TFT AM-LCD technology base that can produce active-matrix arrays over large areas at low cost on both glass and flexible plastic substrates.

The challenge for a-Si:H TFTs lies in their low current output and large device parameter shifts over time (bias stress induced effect) [16], under PLED illumination (light induced effect) and with operating temperature (thermal effect).

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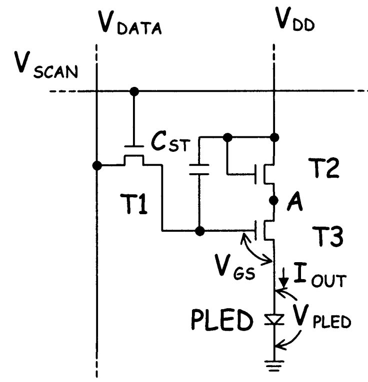


Fig. 1. Schematic diagram of three a-Si:H TFT pixel electrode circuit.

The improved PLED efficiency [13], [14] combined with a high field-effect mobility a-Si:H TFT [15], and proper pixel electrode circuits design and driving schemes could allow for a-Si:H technology to overcome its limitations with respect to AM-OLEDs. Two-a-Si:H TFTs pixel circuits have been already demonstrated for AM-OLEDs [8].

In this paper, we describe 3-a-Si:H TFT AM-PLED with an operating point, which can be adjusted by an active resistor.

II. Pixel Circuit Schematic and Operation

The three a-Si:H TFT pixel electrode circuit shown in Fig. 1 has five components: $\mathrm{C_{ST}}$, a storage capacitor; T1, a switching TFT; T2, an active resistor (AR); T3, a constant current driver TFT; and a PLED, an organic polymer light-emitting device. The pixel is selected through the switching transistor while the scan voltage $(\mathrm{V_{SCAN}})$ is "high". The driver TFT is used to provide continuous current $(\mathrm{I_{out}})$ to the PLED. The $\mathrm{I_{out}}$ at anode (ITO—positively biased) electrode will establish an electrical potential difference between ITO and cathode electrode (Ca/Al—negatively biased). Established electrical field will induce electron injection into and extraction from cathode and anode into lowest unoccupied molecular orbital (LUMO) and highest occupied molecular orbital (HOMO) levels of the polymer, respectively. The process of removal of a negative charge (electron) from HOMO leaves a positive charge (or hole) in the band. This process can be referred to as a "hole injection" into polymer HOMO levels. Under the influence of an electrical field, the oppositely charged radicals (anions and cations) will drift toward each other from polymer chain to polymer chain. Eventually, they will combine on a single conjugated segment, where singlet and triplet excitonic

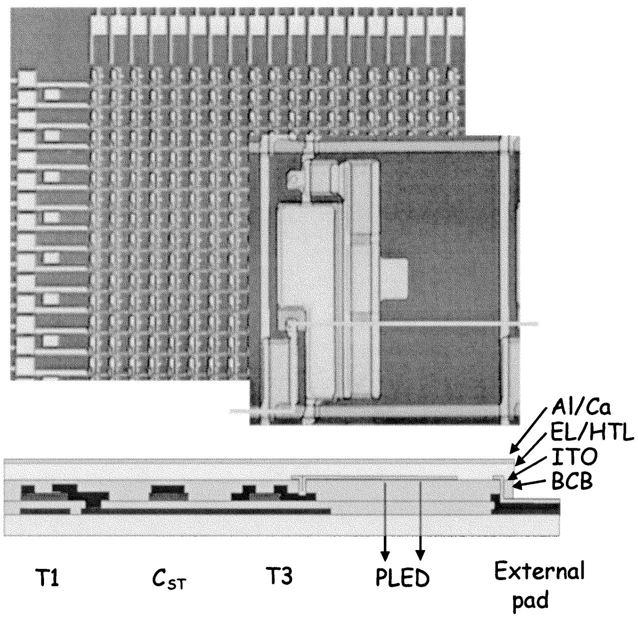


Fig. 2. Top view of 200 dpi AM-PLED back plane is shown. Inset shows single pixel circuit and the cross-section schematics.

states are formed, of which the singlets can radiatively decay with the emission of visible green light.

In this pixel circuit an active resistor forces the a-Si:H TFT (T3) driver to operate in linear regime for V_{DATA} larger than 5 V [14]. Hence, the output current level drifts associated with the a-Si:H TFT (T3) driver and PLED characteristics shifts can be reduced in comparison with the 2-a-Si:H TFT driver operating in saturation regime [8], [9], [17]. Indeed it has been shown that the changes in a-Si:H TFT output current are larger when device operates in saturation regime [17]. Therefore, a better display uniformity is expected for 3-TFT AM-PLED. But 3-TFT pixel circuits power consumption and aperture ratio will increase and decrease, respectively in comparison with the 2-TFT circuits. In our design simulated output current drifts were 6, 14, and 28% for V_{DATA} of 5, 10, and 15 V, respectively. The operating point (and output current level drift) of the 3-TFT pixel electrode circuits can be further optimized through control of the active resistor dimensions (W/L) [10], [11], [14]. To evaluate merits and limitations of this circuit in comparison with the 2-TFT circuits more careful evaluation of both displays performances is needed.

III. AM-PLED

A. Design and Fabrication

To demonstrate an application of the above pixel circuit in an AM-PLED, we have fabricated a small size display as an engineering demonstration unit, Fig. 2. In this 200 dpi AM-PLED the active-resistor had a channel width of 15 μm, and the driving and switching TFTs had channel widths of 105 and 30 μm, respectively, with the same channel length of 10 μm. The storage capacitance was 0.4 pF. The top- and cross-section views of the AM-PLED backplane are shown in Fig. 2. The inset shows a blow-up of single pixel electrode circuit and its cross-section

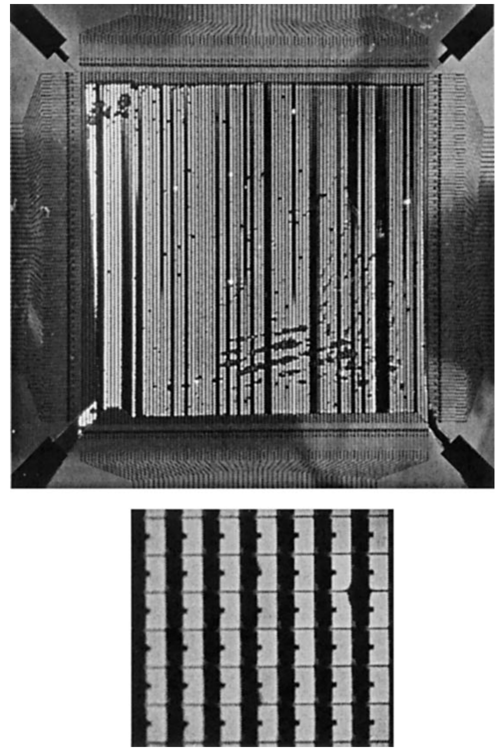


Fig. 3. Top view and blow-up of illuminated AM-PLED is shown. The bright area on the left is glare from the light. The PLED was about 120 μm $\times$ 62.5 μm for pixel size of 127 μm $\times$ 127 μm. The fill factor was about 45%.

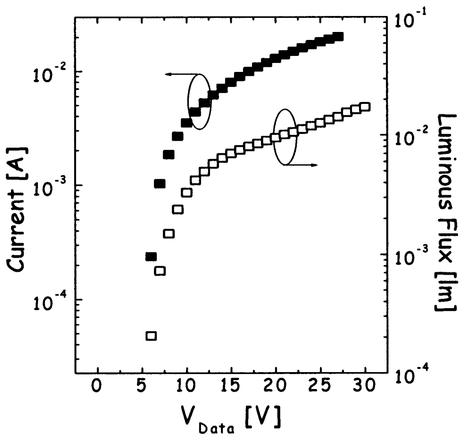
view. The green light is emitted from the back side of the display through the glass substrate. The top surface of the active-matrix arrays was planarized with a spin-cast benzocyclobutene (BCB) layer. The typical thickness of each layer was 3000 Å for Cr, 3000 Å for a-SiNx:H, 1500 Å for a-Si:H, 300 Å for n^+ a-Si:H, 1000 Å for Mo, 3000 Å for BCB, and 1000 Å for ITO.

Once the active-matrix array was fabricated, a hole injection layer (HIL) and a light emissive layer (LEL) were spin-coated. Poly(3,4-ethylene dioxythiophene) (PEDOT) doped with poly(styrenesulfonate) (PSS) and a green light-emitting poly (fluorene) copolymer were used for HIL and LEL materials, respectively. Finally, a calcium/aluminum bi-layer cathode was thermally evaporated through a shadow mask without breaking vacuum under $\sim 10^{-6}$ torr.

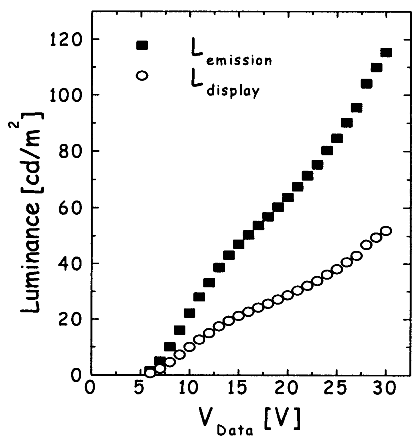
B. Optoelectronic Properties

The test unit was operated to illuminate the whole display without packaging and driver electronics, Fig. 3. The display size is 0.7 in diagonal with 100 $\times$ 100 pixels. Uniform light intensity among pixels across the display was observed under the microscope, Fig. 3(inset). However, several line defects of the V_{DD} or data signal bus lines and some pixel defects with bright spots were observed.

The optoelectrical characteristics of the AM-PLED were measured using an integrating sphere and a calibrated photo-detector connected to a radiometer to measure the total luminous flux. To light up the display we continuously applied a DC signal (30 V) to all the scan lines and the V_{DATA} signal was varied from 0 to 30 V for different grey scales. All the measurements were performed in the air at room temperature.



(a)



(b)

Fig. 4. (a) Measured current and luminous flux and (b) luminance of our AM-PLED display.

Fig. 4(a) shows the current and luminous flux versus data voltage characteristics. The initial light emission is observed when V_{DATA} is about 4–5 V. This data voltage is being considered as a turn-on data voltage closely related to the green PLED turn-on voltage and the V_{DS} of the switching TFT (T1) and the V_{GS} of the driving TFT (T3) during selection time. We obtained up to 2×10^{-2} lumen at $V_{\mathrm{DATA}} = 30\mathrm{V}$. The display luminance was estimated from the optical flux, assuming that the AM-PLED has Lambertian emission (it was checked experimentally that PLED luminance was constant over the whole angular domain). The total display area of $1.27\ \mathrm{cm} \times 1.27\ \mathrm{cm} = 1.62 \times 10^{-4}\mathrm{m}^2$ results in the display luminance:

$$L_{\mathrm{display}} = \frac{\Phi}{\pi \times 1.6 \times 10^{-4}} \quad (1)$$

However, we also need to consider the actual light-emitting area to calculate the effective luminance of the light-emitting areas (L_{emission}), which can be expressed as $A_{\mathrm{emission}} = (\text{total\#of pixels}) \times (\text{yield of emitting pixels}) \times (\text{PLED area in each pixel})$. For our 200 dpi AM-PLED, this area is $\mathrm{A}_{\mathrm{emission}} = 4.74 \times 10^{-5}\mathrm{m}^2$, where the yield of emitting pixels ($\sim$65%) was estimated from Fig. 3.

Fig. 4(b) shows the evolution of the luminances with the data voltage. The estimated luminance values ($\mathrm{L}_{\mathrm{display}}$ and $\mathrm{L}_{\mathrm{emission}}$) at maximum luminous flux are about 50 and 120 cd/m^2, respectively. These values can be increased through optimization of the AM-PLED.

IV. Conclusion

We have fabricated a small size engineering 200 dpi AM-PLED based on a 3- a-Si:H TFT pixel electrode circuit. Furthermore, we have shown that a-Si:H TFTs can provide sufficient out current for a AM-PLED. The brightness of our display increases almost linearly up to 120 cd/m^2 with $\mathrm{V}_{\mathrm{DATA}}$ ranging from 0 V to 30 V.

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