Wide-QQVGA Flexible Full-Color Active-Matrix OLED Display with an Organic TFT Backplane

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Abstract

A 5.8-inch wide-QQVGA flexible full-color active-matrix OLED display was fabricated on a plastic substrate. Low-voltage-operation organic TFTs and high-efficiency phosphorescent OLEDs were used as the backplane and emissive pixels, respectively. The fabricated display clearly showed color moving images when the driving voltage was below 15 V.

1. Introduction

Ultra-thin, lightweight flexible displays would be very suitable for the portable terminals of advanced digital mobile broadcasting services. An active matrix (AM) displays consisting of organic thin film transistors (OTFTs) and organic light emitting diodes (OLEDs) has advantages of having a low-temperature and low-cost fabrication process, mechanical flexibility, and the ability to be incorporated in thin film devices. Recently, flexible AM-OLED displays on a plastic substrate driven by OTFTs have been reported[1, 2].

Previously, we demonstrated low-voltage-operation OTFTs using a Ta_2O_5 layer with a high dielectric constant of 24 as a gate insulator and pentacene as an organic semiconductor layer on a plastic substrate[3]. These OTFTs can control the drain current at a low gate voltage (under 15 V). Flexible displays with 16×16 pixels incorporating these OTFTs and phosphorescent OLEDs have been reported[4]. Monochromatic moving images were clearly displayed at a low operation voltage.

The previously reported displays on a plastic film had a screen size less than 3-inch. In the future, digital mobile broadcasting services will likely use flexible displays with larger screens and high resolution. These will also need to be operated at low voltage and power.

As part of our ongoing research into flexible displays, we fabricated a 5.8-inch wide-QQVGA flexible full-color AM-OLED display with an OTFT backplane. In this paper, we explain the pixel circuit for the AM-OLED. Second, we describe the fabrication process of the OTFT arrays and phosphorescent OLED layers on a plastic film. After that, we discuss the electrical properties of the OTFTs. Finally, we describe the performance of the fabricated display.

2. Pixel circuit

The OTFT backplane has 213 (data lines) × RGB × 120 (scan lines) pixels. The resolution of the display is 42 ppi and corresponds to a main pixel size of 600 μm × 600 μm.

As shown in figure 1, a conventional pixel circuit is employed for the backplane; it consists of two OTFTs (Sw-OTFT and Dr -OTFT), an emissive pixel (OLED), and a storage capacitor (C_s). The Sw-OTFTs are used to select a pixel, and the Dr-OTFTs are used to drive OLEDs. The scanning voltage of V_{scan}, data voltage of V_{data}, and constant voltages of V_{dd} and V_{cath} are supplied for driving the flexible display.

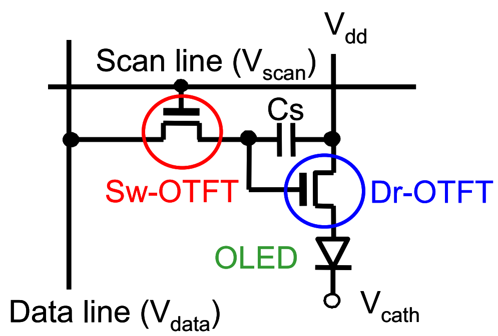

Fig. 1: Schematic diagram of the pixel circuit of AM-OLED display.

3. Fabrication procedure

3.1 OTFT backplane

Figure 2 shows the process of fabricating the low-voltage-operation OTFT backplane. We used poly ethylene naphthalate (PEN) film with a thickness of 125 μm as a transparent flexible substrate. After cleaning the PEN film, we annealed it at over 100 °C for 2 hours to remove water.

First, a silicon dioxide (SiO_2) layer (100-300 nm) was formed on the PEN film by sputtering. Second, tantalum (Ta) for the gate electrode was deposited by sputtering and patterned by reactive ion etching. The gate insulator of tantalum oxide (Ta_2O_5) was formed by anodizing Ta in ammonium borate solutions[5]. Electrochemical oxidation enables high-dielectric-constant insulators to be fabricated at room temperature. The anodization conditions were optimized to increase the breakdown voltage of the Ta_2O_5 layer. A thickness of the layer was about 170 nm. Several dry etching processes were conducted to fabricate the contact pads for the gate electrode of Dr-OTFTs. The pixel electrode of ITO (60 nm) and source/drain electrodes of Au/Cr (70/3 nm) were deposited and patterned by using a photolithographic lift-off process.

Next, the organic semiconductor layer of pentacene (100 nm) was deposited by vacuum evaporation. Before this deposition, the surface of the Ta_2O_5 layer was cleaned by oxygen plasma and UV irradiation to remove organic contamination. Furthermore, the surface was treated with 1,1,1,3,3,3-hexamethyldisilazane (HMDS) to form a self-assembled monolayer (SAM). Through this treatment, the surface energy of the Ta_2O_5 layer decreased[6]. The pentacene layer was patterned by a photolithographic process using two protection layers. The first layer of poly *p*-xylylene (parylene) film was deposited by chemical vapor deposition (CVD) on the pentacene layer without significant damage, and then the second layer of thin SiO_2 was formed to protect against the photoresist. The pentacene layer except for the channel region was etched by oxygen plasma. Figure 3 shows an optical micrograph of the fabricated pixels. This flexible display employed a bottom-emission structure in which the two OTFTs, C_s, and the OLEDs are arranged side-by-side.

The channel width (W) and length (L) of the Dr-OTFTs is 300 and 5 μm, and the W/L of the Sw-OTFTs is 200/5 μm, respectively.

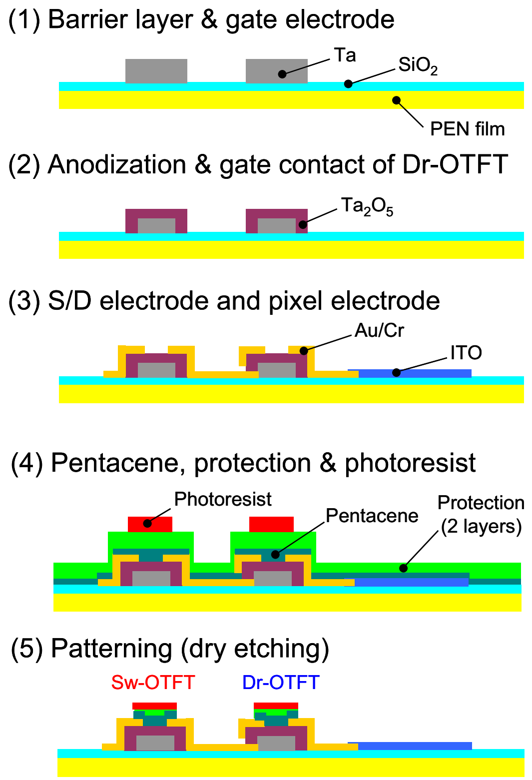

Fig. 2: Process flow of the flexible OTFT backplane.

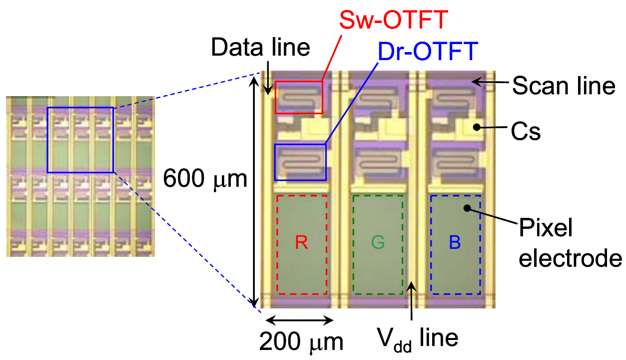

Fig. 3: Optical micrograph of the pixel on the OTFT backplane.

3.2 Phosphorescent OLED layers on the OTFT backplane

Figure 4 shows a schematic cross-section of the display. After fabrication of the flexible OTFT array, parylene film was deposited by CVD on the backplane as a passivation layer. The parylene film on the pixel electrode was removed by photolithography and dry etching. The phosphorescent OLED layers were formed by using either vacuum evaporation or ink-jet printing[7, 8].

In the case of vacuum evaporation, the structure of the phosphorescent OLED layer consists of a hole transport layer, RGB emission layers using iridium (Ir) complexes, a hole blocking layer, and an electron transport layer. The phosphorescent materials for the RGB emission layers were deposited on the pixel electrodes through shadow masks.

In the case of ink-jet printing, first, a hole injection layer was printed once the surface treatment of the pixel electrode had been completed. Second, the phosphorescent polymers for the RGB emission layers were printed. The phosphorescent polymers were copolymers consisting of phosphorescent units, hole-transport units, and electron-transport units[9]. After printing, each layer was baked in a vacuum to remove solvents. The hole blocking and the electron transport layer were deposited on the emitting layers by vacuum evaporation.

In both OLED formation methods, a cathode made of Al (200 nm) and LiF (0.5 nm) was deposited.

After the formation of OLED pixels, parylene film and a barrier layer were deposited as an encapsulation layer by CVD and sputtering, respectively. This encapsulation layer, consisting of organic and inorganic materials, acts as an effective gas barrier for the lifetime of the OLED devices[10]. Finally, a PEN film with the barrier layer was laminated on the fabricated panel.

4. Results and discussion

4.1 Characteristics of the OTFTs

Figure 5 shows typical transfer and output characteristics of the Dr-OTFT in the fabricated OTFT array on a plastic film. The drain current was modulated at a low gate voltage of 15 V. The output characteristics also exhibited a good current saturation behavior when the drain voltage was -15 V. We estimated the field-effect mobility to be about 0.1 cm^2/Vs, the threshold voltage (V_{th}) to be about 12 V, and the current ON/OFF ratio to be over 10^6. Before patterning the pentacene layer, the drain off-current was very high (about 10^{-7} A). However, after patterning it became low enough to turn off the OLED pixel. These results show that the organic semiconductors were successfully patterned with the conventional photolithographic process.

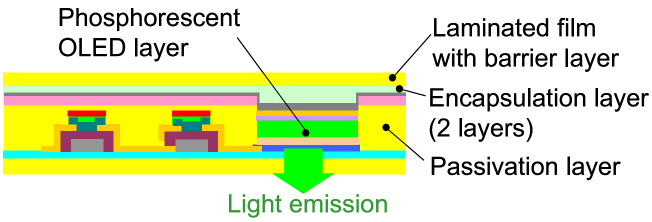

Fig. 4: Schematic cross-section of the flexible AM-OLED display.

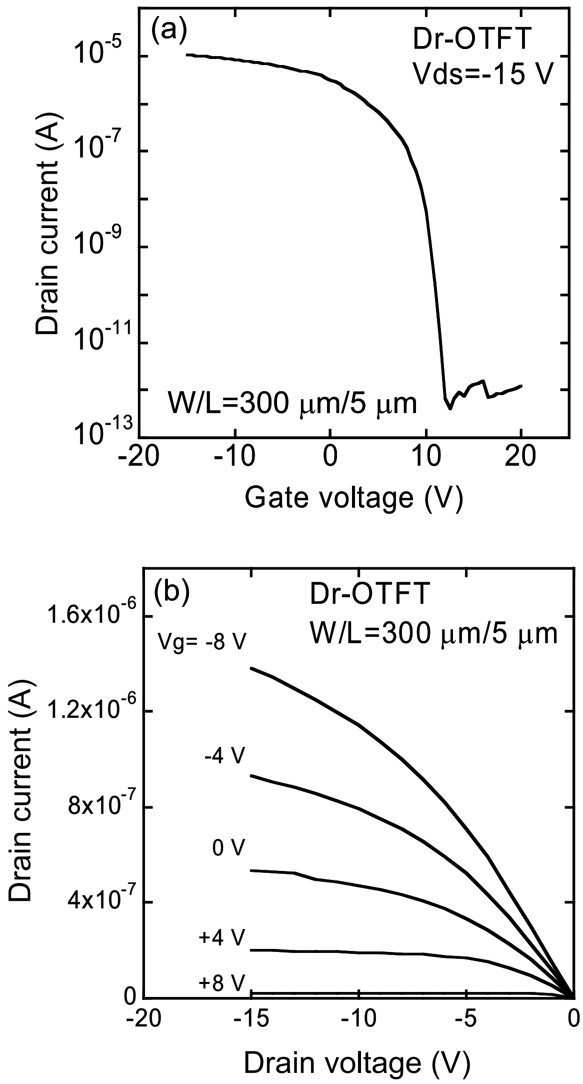

Fig. 5: (a) Transfer and (b) output characteristics of the low-voltage-operation OTFT.

The characteristics of the Sw-OTFT were similar to those of the Dr-OTFT. This indicates that a photolithographic process is an effective way to integrate OTFTs on a plastic film at low temperature.

4.2 Display performance

The specifications and driving conditions of the flexible display are listed in Table 1. The fabricated display could be operated at a frame rate of 60 Hz and at all supply voltages below 15 V.

Figure 6 shows a photograph of the fabricated display in operation. Color moving images were clearly displayed at a low operation voltage. The emitted light was uniform over the whole area of the display. Average brightness was 20-30 cd/m^2. The color moving images were stable even when the flexible display was bent.

5. Summary

We fabricated a wide-QQVGA full-color flexible AM-OLED display with a screen size of 5.8-inch that is driven by low-voltage-operation OTFTs. The OTFT array was created by photolithographic patterning of organic semiconductor on a plastic film. Phosphorescent materials were used for the emitting layers of the OLEDs that were formed by either vacuum evaporation or ink-jet printing. Color moving images were clearly displayed at a low operation voltage (below 15 V) and the display could show moving images even when it was bent. These results indicate that the combination of OTFTs and OLEDs on a plastic substrate is a promising way of making large full-color flexible displays.

Table 1: Specifications and driving conditions of flexible AM-OLED display driven by OTFTs.

Display size	5.8-inch diagonal
Number of pixels	213 x RGB x 120 (Wide-QQVGA)
Main pixel size	600 μm x 600 μm
Resolution	42 ppi
Operation scheme	2T-1C
Frame rate	60 Hz
Scan voltage (V_{scan})	15 V
Signal voltage (V_{data})	0～10 V
V_{dd}-V_{cath}	<15 V

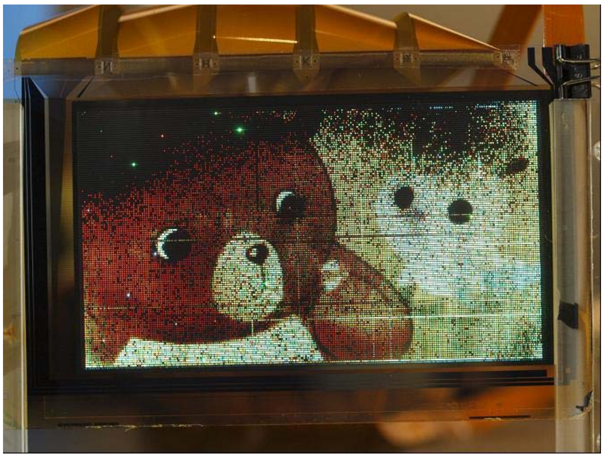

Fig. 6: Photograph of the fabricated flexible AM-OLED display driven by OTFTs.

6. References

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