Flexible electrophoretic display driven by solution-processed organic thin-film transistors

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Abstract — An organic thin-film-transistor (OTFT) backplane has been fabricated by using a solution-processed organic semiconductor (OSC) and organic insulators. The OSC, a peri-xanthenoxanthene derivative, provides a mobility of 0.5 cm^2/V-sec. These organic materials enhance the mechanical flexibility of the backplane. The developed backplane successfully drives a 13.3-in. flexible UXGA electrophoretic display that can operate when bent at a radius of 5 mm.

Keywords — *Organic TFT, solution-processed, electrophoretic display, flexible display, flexible substrate.*

DOI # 10.1889/JSID20.3.143

1 Introduction

Organic thin-film-transistors (OTFTs) have been attracting much interest as switching devices for active-matrix flexible displays because they are inherently flexible, robust, and lightweight.[1–8] Both organic semiconductors (OSCs) and organic insulators have been used in OTFTs because these organic components have many advantages over conventional inorganic components. One significant advantage is that organic materials are soluble in many organic solvents, which allows many types of functional inks to be used in device fabrication. Consequently, OTFTs can be fabricated by printing and/or coating processes using such inks at a low temperature. These processes are considered to use less energy and materials than conventional processes such as high-temperature vacuum deposition.[4–9]

Much effort has been expended to fabricate OTFTs by using such solution-based methods, and some OTFTs have been used to produce flexible electrophoretic displays (EPDs). For example, Burns *et al.* developed a 10.1-in. EPD with a resolution of 100 dpi using an OTFT backplane having a mobility of 0.03 cm^2/V-sec,[6] while Maeda *et al.* fabricated a 10-in. EPD with a resolution of 80 dpi in which printed OTFTs with a mobility of 0.05 cm^2/V-sec were used.[7] Efforts are currently under way to increase the display size and resolution of EPDs driven by OTFTs (OTFT-EPD), which requires improving the OTFT performances and the fabrication method. The alignment accuracy of each layer is also important when increasing the display size and/or resolution.

In this study, we developed an OTFT with an enhanced mobility of 0.5 cm^2/V-sec by using a solution-processed OSC, a peri-xanthenoxanthene (PXX) derivative.[9] A flexible backplane is fabricated by integrating these OTFTs by using the developed fabrication method, which has an alignment accuracy of less than 0.5 μm to drive a 13.3-in. flexible EPD with a resolution of 150 dpi. The display can operate when it is bent with a radius of 5 mm because the backplane is fabricated from mechanically soft organic materials and ductile metals. We compared the properties of the developed OTFT with a conventional OTFT that has a vacuum-deposited OSC and found that the solution-processed PXX derivative has a better performance than the vacuum-deposited conventional semiconductor (pentacene).

2 Structure of the OTFT-EPD and fabrication of the OTFT backplane

Figure 1(a) shows a schematic cross section of a pixel in the developed OTFT-EPD. The display is 13.3 in. on the diagonal has a resolution of 1600×1200 pixels with a pixel size of 169×169 μm. Each pixel consists of an OTFT and a storage capacitor; its equivalent circuit is illustrated in Fig. 1(b). The OTFT has a bottom-gate top-contact structure with a channel length of 5 μm. All the layers are patterned by conventional photolithography.

This backplane consists of three metal layers, one OSC layer, and three insulating layers. The OSC and all the insulating layers are formed by spin-coating functional inks because such solution-based methods can reduce the tact time and material and energy consumption during backplane fabrication.

Although conventional solution-processed organic insulators have been applied to the passivation and interlayer dielectrics, we used self-developed inks to form the gate insulating layer and OSC layer. The gate insulator is formed by spin-coating an ink that consists of poly(4-vinyl-

Based on a paper presented at the 2011 SID Symposium held May 17–20, 2011, in Los Angeles, California, USA.
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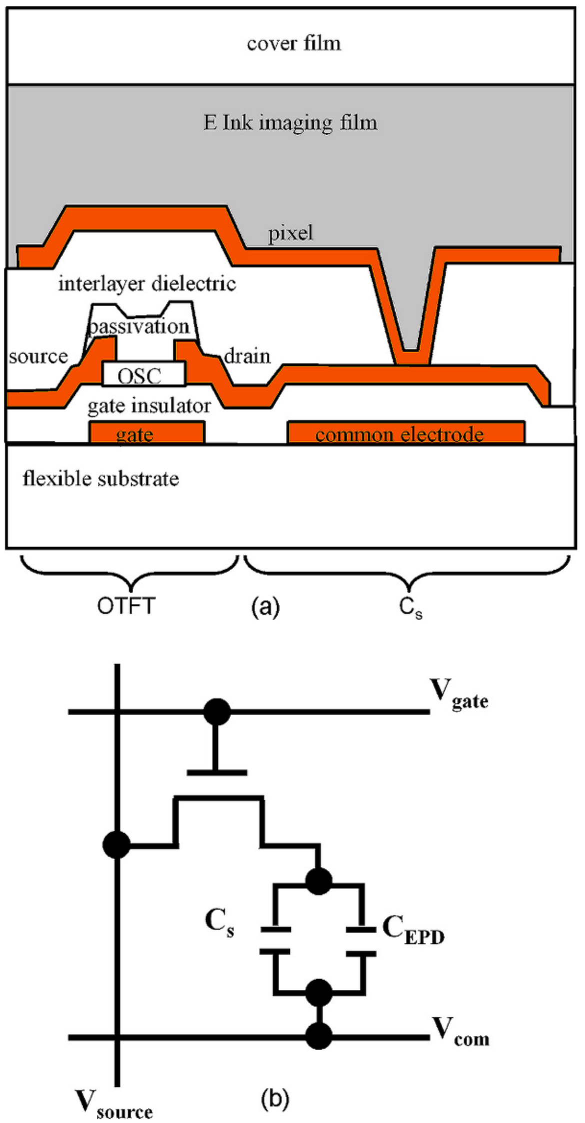

FIGURE 1 — (a) Schematic cross section of the OTFT backplane. (b) Equivalent-circuit diagram of a pixel of the EPD.

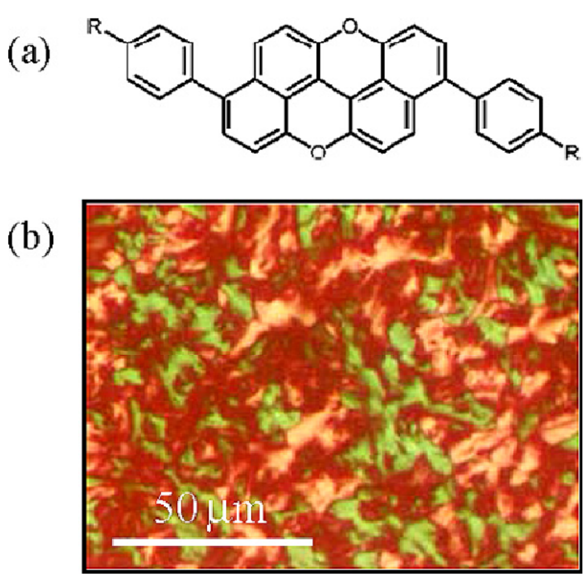

FIGURE 2 — (a) Molecular structure of PXX derivative. (b) Polarized optical microscopy image of PXX-derivative film.

phenol), octadecyltrichlorosilane, a cross-linking agent, and an organic solvent.[1,10] A soluble semiconductor, a PXX-derivative, was chosen and applied to develop the OSC ink [see Fig. 2(a)]. To form the semiconducting layer, the OSC ink is spin-coated on the gate insulator. After baking on a hot plate, we obtained the highly crystalline OSC layer as shown in the polarized optical microscopy image [see Fig. 2(b)].

Fabricating the backplane on a plastic film requires an overlay accuracy of less than 1 μm for each layer on the entire area of the 13.3-in. display. We bonded the plastic

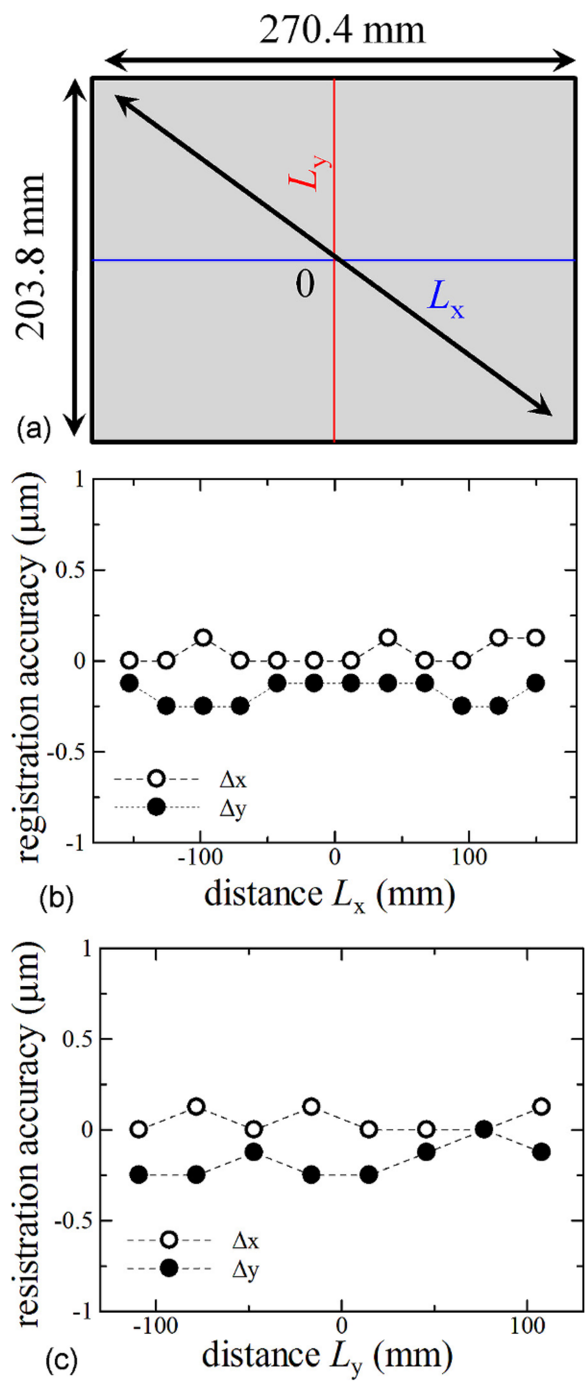

FIGURE 3 — (a) Dimensions of the display. L_x and L_y are, respectively, the distances in the (a) *x* and (b) *y* directions from the center of the display.

film onto a glass substrate using an adhesive in order to achieve this overlay accuracy during the integration process of the OTFT. The overlay accuracy was estimated to be less than 0.5 μm (see Fig. 3). This result suggests that the plastic film can be handled in the same manner as a conventional glass substrate. The estimated registration accuracy was independent of both the position and the direction, indicating that this method is scalable.

3 Performances of solution-processed OTFTs

There are two methods that can be used to form OSC films: thermal evaporation and solution process. In this section, we compare the performances of the developed solution-processed OTFT and the OTFT fabricated using a thermally evaporated OSC. The active layer materials of the developed and conventional OTFTs are a solution-processed PXX-derivative and thermally evaporated pentacene (the most commonly used OSC material),[11] respectively. Except for the active layers, the same materials were used for both OTFTs and they both have the same structure and dimensions as those shown in Fig. 1. For a pentacene TFT, a pentacene layer was formed by thermal evaporation at a substrate temperature of 60°C. During the deposition, the deposition rate was 0.05 nm/sec and the final thickness of pentacene film was 50 nm.

Comparison of their transfer curves reveals that the PXX-TFT has a four times higher mobility than the pentacene TFT (see Fig. 4). The PXX-TFT has a mobility of 0.5 cm^2/V-sec, a subthreshold swing of 0.3 V/dec, and its off current is the same as that of the pentacene TFT. Consequently, the PXX-TFT has a higher on/off current ratio than the pentacene TFT.

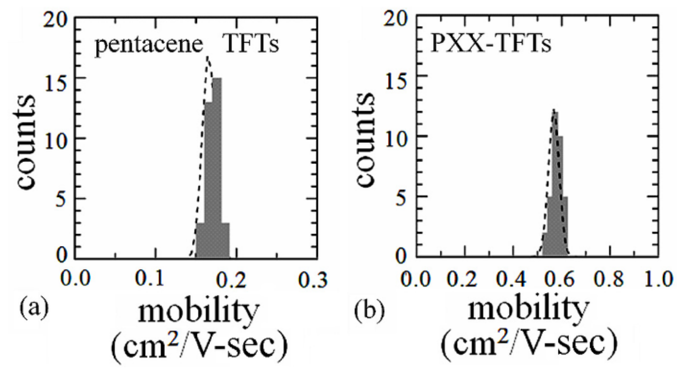

FIGURE 5 — Mobility distribution of (a) pentacene and (b) PXX TFTs. Data measured over the entire area of a 3-in. wafer.

Figure 5 shows the uniformity test results, in which 34 OTFTs were measured for both types of devices. The PXX-TFTs clearly have a higher average mobility (⟨μ⟩) than the pentacene TFTs. We calculated the statistical dispersion from the ⟨μ⟩ and the standard deviation ⟨1σ⟩. The relative variation of the mobility (1σ/⟨μ⟩) is estimated to be 5.5% for the PXX-TFTs and 6.6% for the pentacene TFTs. These results indicate the PXX TFTs not only have a higher average mobility, but also a narrower variation of the mobility compared to that of pentacene TFTs.

The PXX-TFT also has an improved temperature dependence of the mobility. Figure 6 shows Arrhenius plots of the mobilities of these OTFTs; it shows that the PXX-TFT has a smaller temperature dependence than the pentacene TFT. The data are fitted by the Arrhenius function based on the multiple trap and release model[12]:

$$\mu = \mu_0 \exp(-E_a / k_B T), \tag{1}$$

where μ is the measured mobility, k_B is the Boltzmann constant, T is the absolute temperature, μ_0 is the free-carrier

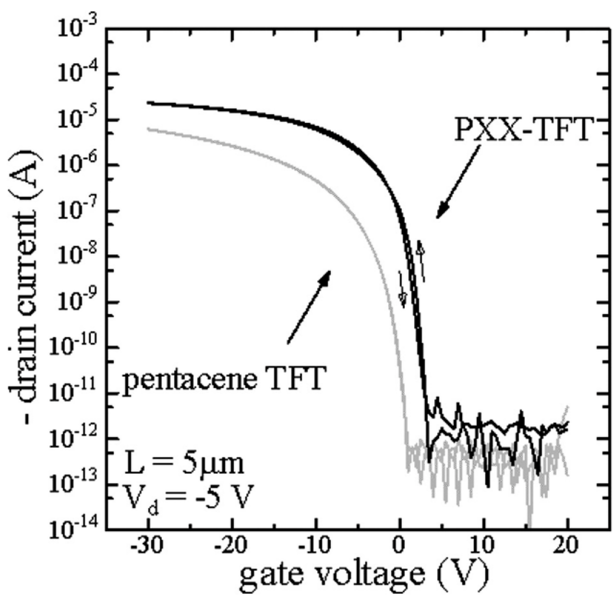

FIGURE 4 — Transfer characteristics of OTFTs with a PXX derivative and a pentacene (L = 5 μm).

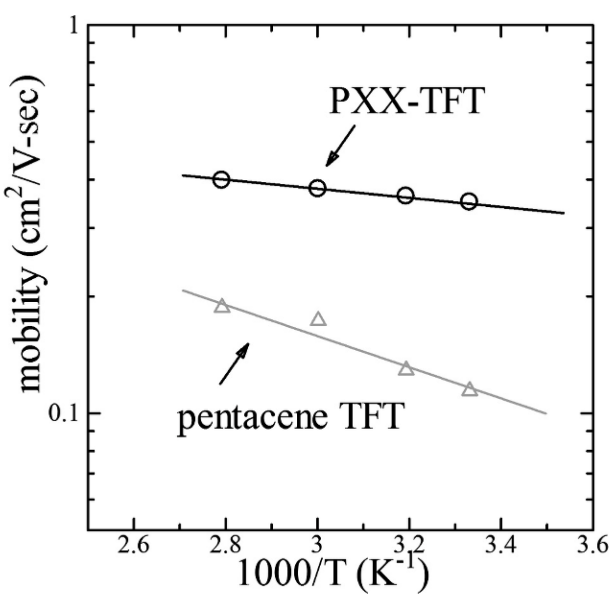

FIGURE 6 — Temperature dependence of the measured mobilities of PXX-TFTs and pentacene TFTs.

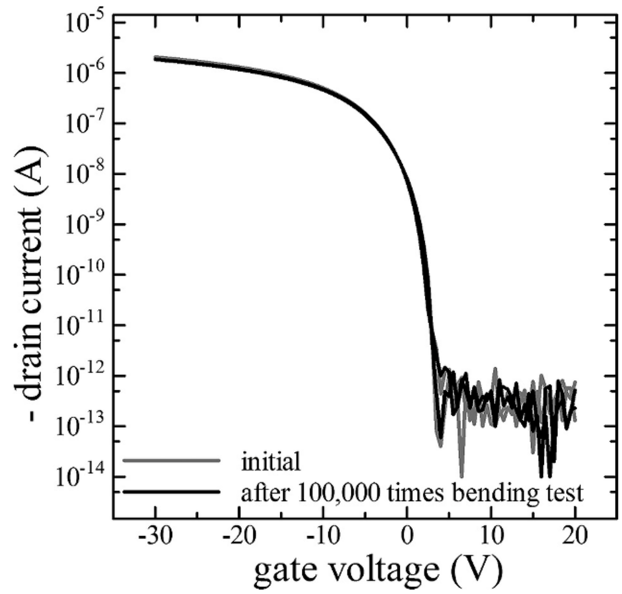

FIGURE 7 — Transfer characteristics of a pixel OTFT measured before (gray) and after (black) performing a bend test for 100,000 times to r = 5 mm.

mobility, and E_a is the activation energy of the trap state. E_a is estimated to be 20 and 77 meV for the PXX-TFT and pentacene TFT, respectively, which implies that the PXX-TFT has a lower hole trap energy than the pentacene TFT.

These results indicate that the solution-processed PXX-derivative not only simplifies backplane fabrication but also improves the OTFT performance, demonstrating the potential of solution-processed OSCs.

4 Flexibility of the backplane

The flexibility of the developed backplane was tested by performing a bending test in which the backplane is bent to a radius of 5 mm and released 100,000 times. For this test, we stacked 60-μm-thick cover film on the test device. Figure 7 shows the transfer characteristics of the OTFT measured before and after the test. No significant degradation was observable after the test. This flexibility is due to the OTFT backplane being mainly composed of mechanically soft organic materials.

TABLE 1 — Specifications of the OTFT-EPD on a plastic substrate.

Display Size	13.3 in.
Resolution	UXGA (1600 x 1200 pixels) 150 dpi
Aperture Ratio	94%
Gray Scale Level	16
Bending Radius	<5 mm
Thickness	120 μm

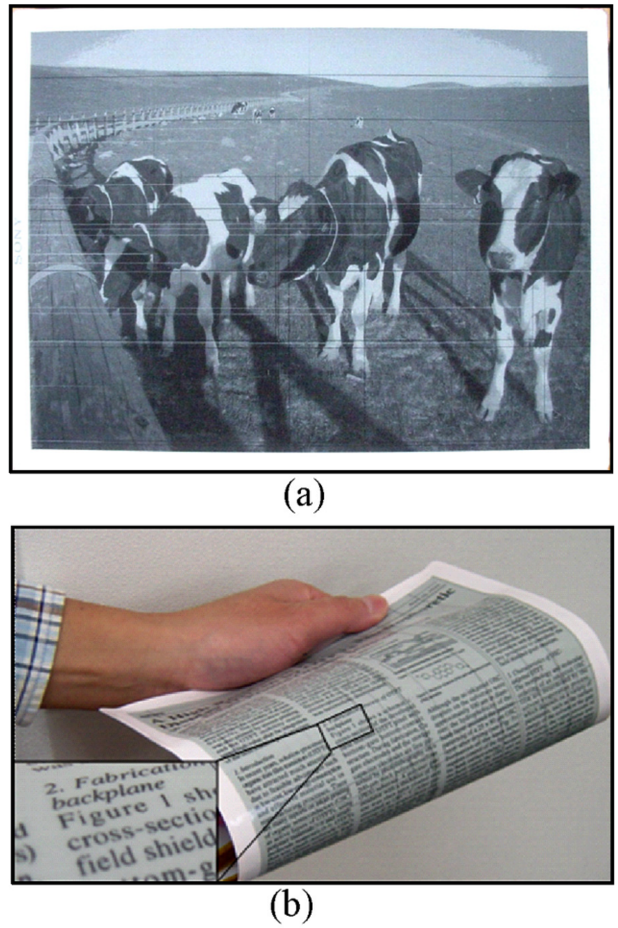

FIGURE 8 — Photographs of a 13.3-in. UXGA OTFT-driven EPD on a plastic substrate in (a) flat and (b) bent states.

5 13.3-in. bendable OTFT-EPD display

The developed OTFT backplane successfully drives a 13.3-in.-UXGA EPD with a resolution of 150 dpi (see Fig. 8). We use E Ink imaging film supplied by E Ink Corp. as an electrophoretic device. The specifications of the OTFT-EPD are summarized in Table 1. The UXGA display achieves 16 gray scales at a scan rate of 50 Hz. This result is due to the performance of the OTFT backplane. The flexibility of the backplane is reflected in the display. Consequently, the display can operate even when it is bent at a radius of 5 mm.

Figure 9 shows the storage test results for the display. The fabricated displays were stored in ambient conditions for 8 months, and the contrast ratio, which was determined from the measured luminosity, was used to evaluate the stability of the displays. No degradation was observed in this test.

6 Conclusions

We have developed a flexible OTFT backplane that has a mobility of 0.5 cm^2/V-sec using a solution-processed organic semiconductor, a PXX-derivative. A scalable method for handling a plastic substrate has been developed. This

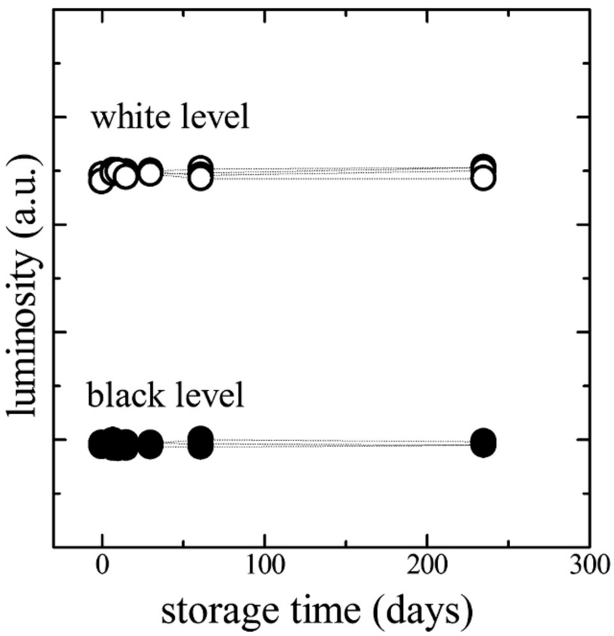

FIGURE 9 — Storage-time dependence of the luminosities of three OTFT-EPDs.

method gives an overlay accuracy of less than 0.5 μm during the integration process of an OTFT backplane, and it enabled us to fabricate a 13.3-in. EPD with a resolution of 150 dpi on a plastic substrate. The display can operate when bent with a radius of 5 mm because the backplane was fabricated from mechanically soft organic materials and metals.

Acknowledgments

The authors would like to thank E Ink Corporation for technical support regarding the E Ink imaging film. We would also like to thank H. Igari, T. Miyata, R. Yasuda, K. Akamatsu, S. Akasaka, A. Nishiike, S. Kumon, and T. Kamei for experimental support and valuable discussions.

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