

## Organic thin-film transistor-driven polymer-dispersed liquid crystal displays on flexible polymeric substrates

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We have fabricated organic thin-film transistor (OTFT)-driven active matrix liquid crystal displays on flexible polymeric substrates. These small displays have  $16 \times 16$  pixel polymer-dispersed liquid crystal arrays addressed by pentacene active layer OTFTs. The displays were fabricated using a low-temperature process ( $< 110^\circ\text{C}$ ) on flexible polyethylene naphthalate film and are operated as reflective active matrix displays. © 2002 American Institute of Physics.

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Organic thin-film transistors (OTFTs) have received considerable attention recently because they can be fabricated at reduced temperature and potentially reduced cost compared to hydrogenated amorphous silicon thin-film transistors. Low fabrication temperature allows a wide range of substrate possibilities and makes OTFTs an attractive technology for many low-cost electronics applications, particularly those that require or may benefit from flexible polymeric substrates such as rf identification tags, smart cards, electronic paper, and flat panel displays. In the case of flat panel displays, the integration of OTFTs on polymeric substrates with liquid crystal materials or organic light emitters allows active matrix liquid crystal displays (AMLCDs) or active matrix organic light emitting diode displays that are flexible, lightweight, inexpensive, and rugged.

OTFT technology continues to advance, with recent reports of organic integrated circuits on rigid<sup>1,2</sup> and polymeric substrates,<sup>3,4</sup> organic “smart pixels” which combine OTFTs with organic light emitting devices,<sup>5–7</sup> a  $64 \times 64$  pixel AMLCD display driven by polymer transistors on a glass substrate,<sup>8</sup> and a  $2 \times 3$  pixel AMLCD display using OTFTs on a polymeric substrate.<sup>9</sup> Here we report  $16 \times 16$  pixel OTFT-based AMLCDs fabricated on flexible polymeric substrates.

OTFTs with a pentacene active layer were used to fabricate  $4 \times 4$  mm pixel array backplanes on polymeric film with a maximum device processing temperature of only  $110^\circ\text{C}$ . The maximum temperature is limited by a photoresist softbake during photolithographic patterning of metal and dielectric layers. Polymer-dispersed liquid crystal (PDLC) was used as the electro-optic element to make active matrix reflective displays. The PDLC is transparent when the liquid crystal domains are aligned by an applied electric field controlled by the OTFTs. In the absence of an electric field,

light is scattered by the nonaligned liquid crystal domains. Polymer-dispersed liquid crystals were chosen for their compatibility with flexible displays since they are not based on polarization and provide wide viewing angle while avoiding problems with polymer substrate birefringence.

The substrate material was  $125\ \mu\text{m}$  thick transparent polyethylene naphthalate (PEN) film. Prior to device processing, the substrates were mounted to glass carriers for mechanical support using vacuum lamination and heated to  $150^\circ\text{C}$  for 2 h to reduce substrate shrinkage during subsequent processing. The polymeric film was held to the glass carriers using a pressure sensitive silicone gel, which allows the glass support to be easily removed after processing. Nickel gate electrodes, silicon dioxide gate dielectric, transparent indium tin oxide (ITO) pixel electrodes, and palladium source and drain contacts were deposited by ion-beam sputtering and patterned using photolithography and liftoff. The pentacene active layer was deposited by thermal evaporation at a rate of  $\sim 0.5\ \text{\AA/s}$  with the display substrate held at  $60^\circ\text{C}$ . Prior to active layer deposition, the gate dielectric surface was vapor treated using octyldecyltrichlorosilane at  $100^\circ\text{C}$ .

Our pentacene thin-film transistors (TFTs) are typically slightly depletion mode and have significant off-state leakage through the pentacene layer. This leakage greatly reduces on/off current ratio, an important device parameter for active matrix displays, and can be eliminated by patterning the pentacene active layer. To pattern the active layer without significantly degrading the pentacene, water-based polyvinyl alcohol (PVA) photosensitized with ammonium dichromate was used. The PVA is applied by spin coating and photolithographically patterned to form an etch mask. The pentacene layer outside the active device regions is then removed with an oxygen plasma.

Figure 1 shows electrical characteristics for a typical pentacene TFT on PEN film with channel width of  $200\ \mu\text{m}$ , channel length of  $10\ \mu\text{m}$ , and oxide thickness of  $450\ \text{nm}$ .

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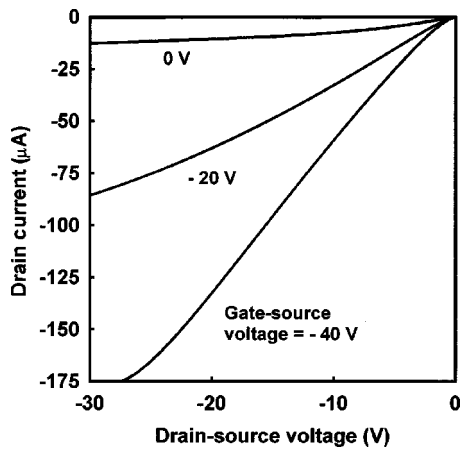


FIG. 1. Drain current as a function of drain–source voltage for a discrete pentacene TFT on flexible PEN film with  $L = 10 \mu\text{m}$ ,  $W = 200 \mu\text{m}$ , and gate oxide thickness of 450 nm.

This device has a saturation carrier field-effect mobility of  $1.2 \text{ cm}^2/\text{V s}$  and on/off current ratio of  $10^8$ . We found that direct exposure of pentacene to PDLC materials severely degrades TFT performance. To avoid this degradation, an additional layer of PVA was deposited as a protective barrier. Some pentacene TFT degradation was still observed after PDLC assembly; the cause of this degradation is still under investigation. OTFT on currents dropped by a factor of  $3\text{--}8\times$  after PDLC assembly, due to a reduction in mobility and shift in threshold voltage. Even with this degradation, device performance was sufficient to obtain functioning pixel arrays. The display was completed by depositing a 4:1 mixture of Merck TL205 liquid crystal and PN393 polymer precursor directly onto the passivated OTFT backplane and then laminating a Mylar® cover sheet onto the sample. The PDLC cell was then created from the mixture by photoinduced phase separation<sup>10</sup> using illumination from an ultraviolet lamp ( $10 \text{ mW}/\text{cm}^2$  intensity) for  $\sim 20$  minutes. PDLC

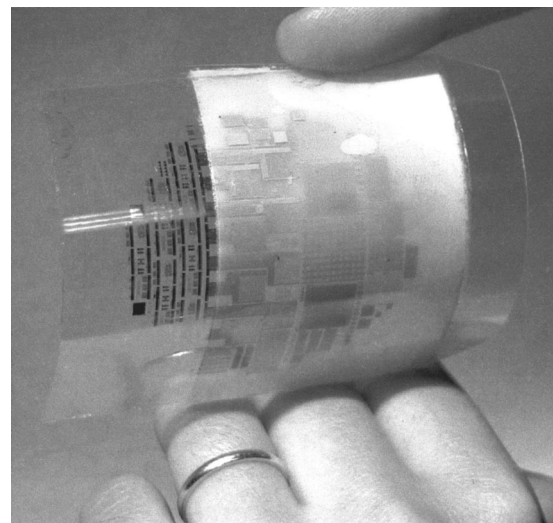


FIG. 3. Photograph of a test chip containing pentacene TFTs, circuits, and pixel arrays on flexible PEN film removed from glass carrier after PDLC assembly.

thickness was set by  $16 \mu\text{m}$  plastic spacers. The Mylar® sheet was coated on one side with ITO to act as the common electrode for the display. Figure 2(a) shows a schematic cross section and Fig. 2 (b) an optical micrograph of a single pentacene TFT pixel on PEN film. Figure 3 shows a photograph of a test chip containing pentacene TFTs, circuits, and pixel arrays on flexible PEN film removed from the glass carrier after PDLC assembly.

Four different types of  $250 \mu\text{m}$ -pitch,  $16\times 16$  pixel arrays were fabricated with clear aperture between 38% and 58%, and varying OTFT design. All arrays showed reasonable electro-optic response to 1/4-VGA wave forms with the best performance for arrays with the largest OTFT width to length ratio. Each array was operated using data voltage =  $\pm 20 \text{ V}$ , select voltage =  $-30 \text{ V}$ , and deselect voltage =  $+25 \text{ V}$  with  $69 \mu\text{s}$  line time and 60 Hz refresh rate. Because of the PDLC-degradation-related reduced OTFT on currents, the pixels were not able to fully converge at the  $\pm 20 \text{ V}$  data voltage in the  $69 \mu\text{s}$  line time. However, even with degraded on currents and their resulting pixel convergence errors, the pixel arrays were able to respond well to

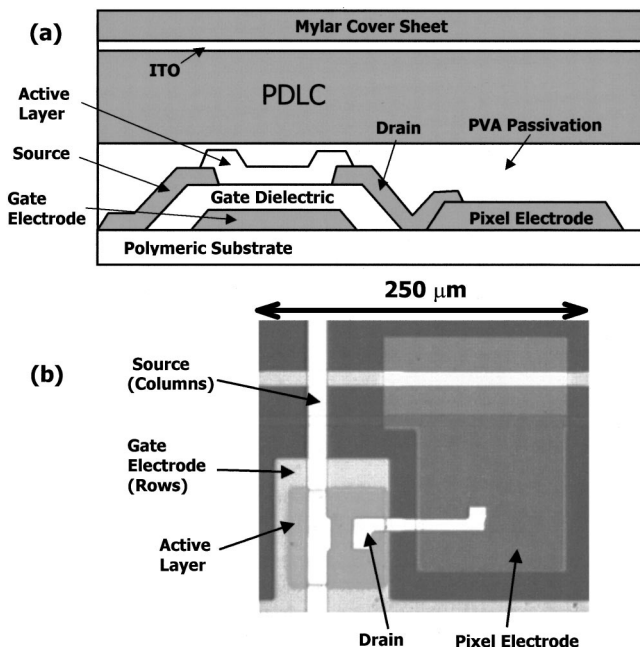


FIG. 2. (a) Schematic cross section and (b) optical micrograph of a single pentacene OTFT-AMLCD pixel on flexible PEN film.

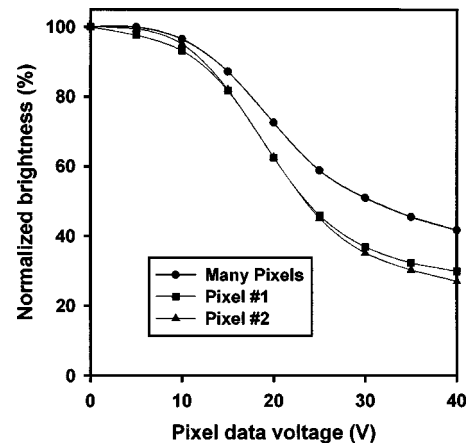


FIG. 4. Reflective electro-optic characteristics for a OTFT-AMLCD pixel array. Brightness as a function of pixel data voltage was measured over an area containing many pixels and for two individual pixels. Each curve is normalized to the brightness at a pixel data voltage of zero.

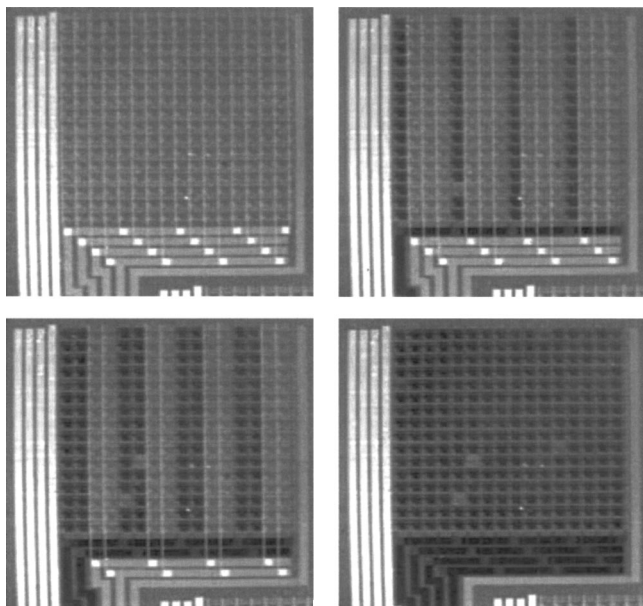


FIG. 5. Optical micrographs showing different patterns on a pentacene OTFT-driven  $16 \times 16$  reflective active matrix PDLC display on flexible PEN film. Each array is 4 mm on a side.

changing data and gave good visual performance. Pixel yield was high ( $\geq 98\%$ ) considering that the substrates were not fabricated in a clean room environment. Illumination conditions consisted of a standard incandescent lamp approximately  $45^\circ$  off axis with a black absorber placed behind the display. Figure 4 gives reflective electro-optic characteristics for a pixel array showing relative brightness as a function of pixel data voltage for three different cases. For the first case, brightness was measured by averaging the reflected light over a large area containing many pixels. In the other two cases, measurements were taken at the center of the pixel electrode for two individual pixels. Each curve is normalized to the brightness at a pixel data voltage of zero volts. The measured contrast ratio is relatively small ( $>2:1$  for many pixels and  $>3:1$  for single pixels) due to the reflection from

the metal lines and other areas outside the pixel electrode which is evident from the improved brightness curves and contrast ratio for the individual pixels. The contrast ratio could easily be improved by using a black matrix layer to reduce reflections outside the pixel electrode. Figure 5 shows optical micrographs of a functioning pixel array displaying four different patterns.

Active matrix PDLC displays driven by pentacene organic thin-film transistors on flexible polymeric substrates have been fabricated and show good response to 1/4-VGA waveforms. Our results confirm that flexible active matrix displays can be made on polymeric substrates using a low-temperature organic thin-film transistor process. These prototype pixel arrays demonstrate the usefulness of OTFTs for low-cost electronics and are a step toward the realization of cheap, light-weight, and flexible applications such as flat panel displays.

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