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THIN FILM TRANSISTORS FOR FOLDABLE DISPLAYS

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Abstract

We report the first amorphous silicon thin film transistors (TFTs) on flexible, ultra-thin substrates of 25 μm thick stainless steel foil. The transistors remain operational under convex or concave bending down to 2.5 mm radius of curvature. The goal of our work is a transistor backplane circuit that can be folded, for use in active matrices in highly rugged and portable applications such as foldable intelligent maps. Our results suggest that such foldable backplane circuits are feasible.

Introduction

The use of alternative substrates to glass is one area of increasing interest to the flat-panel display industry. The primary issues which alternative substrates are meant to address are a reduction in the weight of the display and an alleviation of the problem of display breakage during manufacturing and use. Many products, such as cellular telephones, personal digital assistants, hand-held electronic games, and countless other portable electronic devices which currently use glass as a substrate material may benefit from a lighter, more durable substrate. When this substrate material is flexible, in addition to being lightweight and rugged, displays may find new applications in areas which have traditionally been considered too harsh and severe. The use of a flexible, even foldable, substrate material such as thin stainless-steel foil, which is lightweight and rugged, opens up the possibility for new display products such as foldable intelligent maps. The use of this flexible but opaque substrate would necessarily eliminate the use of backlighting. Emissive or reflective displays, however, remain viable options for such backplanes. The goal of our work is to demonstrate the feasibility of such a display.

The foldability of thin-film displays may be limited by the stress E in the thin-film layer that develops when the substrate is bent. Fig. 1 shows the substrate and thin film composite of total thickness d wrapped around a radius of curvature r. When r >> d, the stress E is given by

$$E = \frac{Y}{2} \cdot \frac{d}{r}$$

where Y is Young's modulus (1). With the stress being proportional to the d/r ratio, very thin foil substrates become highly desirable if a flexible display is the goal. Because the substrate also provides mechanical integrity to the display, strong materials are best. For these reasons, we have chosen stainless steel foil.

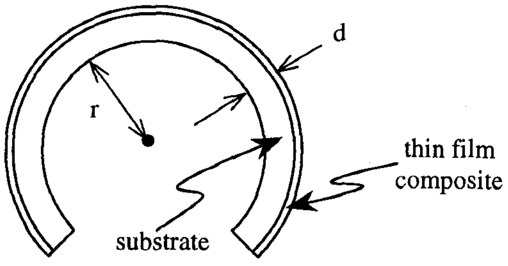

Figure 1. Schematic of a display backplane of thickness d bent around a radius of curvature r.

Experiment

An active-matrix thin film display requires the integration of a light-emitting device with a switch (2). In our experiment, we integrate organic light-emitting diodes with amorphous silicon thin film transistors on flexible, ultra-thin substrates of 25 μm thick stainless steel foil. A schematic cross-section of the integrated TFT/OLED structure on the steel foil is shown in Fig. 2(a), and its equivalent circuit is shown in Fig. 2(b). As-rolled 304 stainless steel foil serves as the substrate. Planarization with 0.5 μm thick spin-on glass removes the short-wavelength roughness of 0.3μm rms. This planarization, necessary for high transistor yield, functions as primary insulation. Further insulation is provided by a 0.5 μm thick plasma-enhanced CVD SiN layer. The TFTs are made in the inverted-staggered, back-channel etch configuration with 120 nm thick Cr gates, 400 nm PECVD gate SiN dielectric, 150 nm a-Si:H channel, and 50 nm n^+ a-Si contacts, followed by 120 nm Cr source/drain contacts (3). The channel length and width are 42 μm and 776 μm, respectively. We employ such large TFTs, and also large contact pads, to ease probing and diagnosis on bent or rolled substrates.

Following the fabrication of TFTs, OLEDs were made on the surface of the Cr source/drain contact pads of 2 mm × 2mm. Conventional OLEDs are built on transparent substrates

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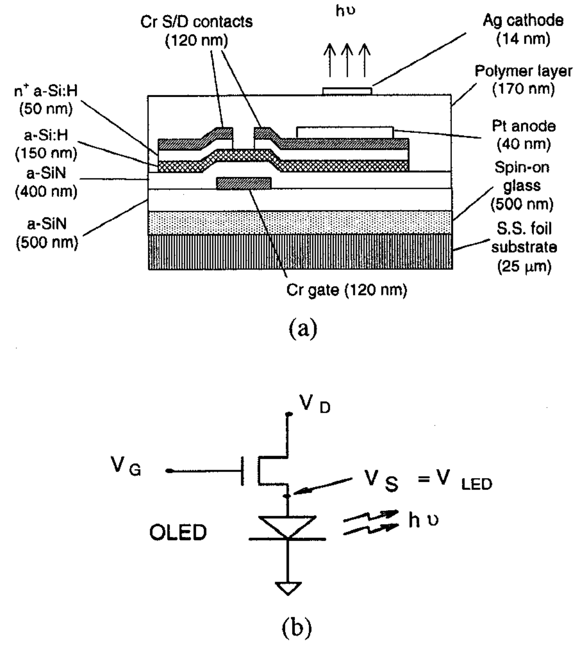


(a)

(b)

Figure 2. (a) Schematic cross-section of the TFT/OLED on steel foil, (b) the equivalent circuit.

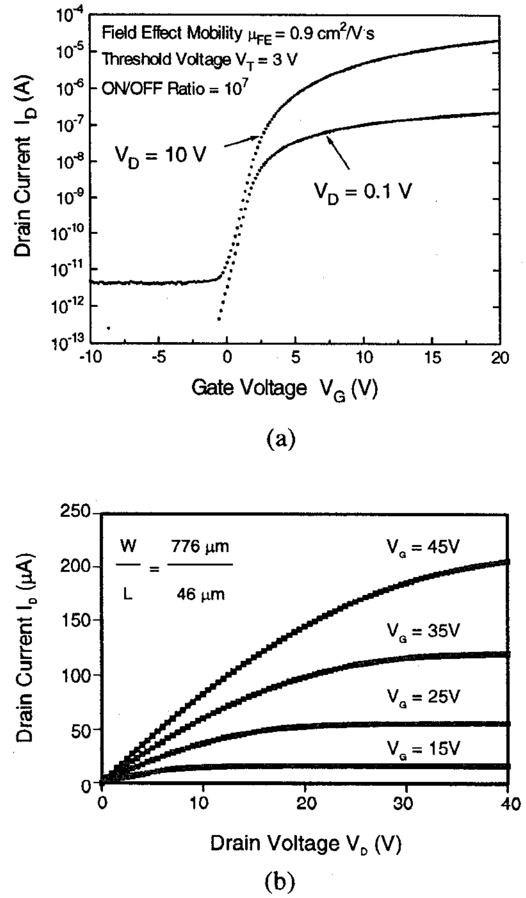
coated with a transparent hole-injecting anode contact such as indium tin oxide (ITO), so that light can be emitted through the substrate, because the top contact is an opaque electron-injecting metal cathode. Because of the opacity of the steel substrate, we developed the top-emitting structure as shown in Fig. 2(a), in which the high work function metal Pt functions as the reflective bottom anode and a semi-transparent cathode is applied on top. OLEDs were fabricated by sequential e-beam deposition and patterning of 400 Å Pt anode contacts, spin-coating of a continuous layer of 1700 Å active luminescent molecularly doped polymer (MDP), followed by the e-beam deposition of a 140 Å semi-transparent Ag top cathode. The overlap of the anode and cathode contact areas determines the active OLED device area, a 250 μm diameter dot, without the need to separately isolate the organic layers. All OLED fabrication steps were performed at room temperature and are compatible with finished TFTs (4).

The active organic material used is a single-layer MDP thin film. The hole-transport matrix polymer poly(N-vinylcarbazole) (PVK) contains dispersed electron-transport molecules 2(-4-biphenyl)-5-(4-tert-butyl-phenyl)-1,3,4-oxadiazole (PBD) and a small amount of green fluorescent dye, Coumarin 6 (C6), which provides efficient emission centers (4).

Results

A. Characterization of TFTs

The TFT/OLED structures were fabricated on 38 mm x 38 mm steel foils. To test the mechanical resiliency of the TFTs alone (before OLED integration), one of these foils was scissor-cut into strips 4 mm wide and 38 mm long. The as-processed TFTs had threshold voltages V_T = 3.5 V, field effect mobilities μ_{FE} = 0.9 cm^2/V·s, OFF currents $I_{OFF} \approx 10^{-15}$ A/μm, and ON currents $I_{ON} \approx 10^{-8}$ A/μm, as shown below in Figure 3(a). These strips were later rolled along their length and held for one minute under both convex (TFTs facing outward) and concave (TFTs facing inward) bending, and tested for topological integrity and electrical performance.



(a)

(b)

Figure 3 (a) Output characteristic and (b) transfer characteristic of TFT on 25 μm steel foil.

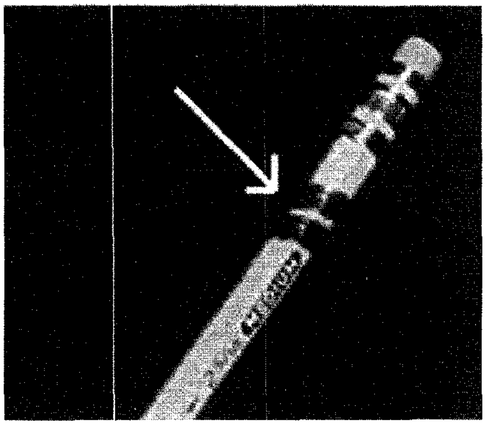


Figure 4. TFT strip wrapped twice around a pencil.

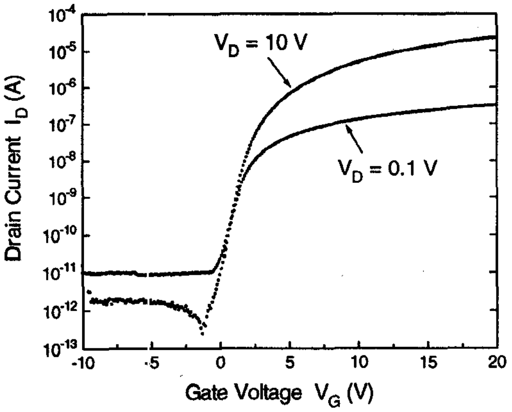


Figure 5. Output characteristic of TFT after bending around a 2.5 mm radius of curvature.

Fig. 4 illustrates the flexibility of these substrates. TFT characteristics after bending around a 2.5 mm radius of curvature are shown in Fig. 5. The TFT structures began to peel off at radii of curvature between 1.5 and 2.5 mm. In all cases, separation occurs between the SiN and spin-on glass layers. Table 1 shows that the electrical performance of the TFTs was not affected by the rolling until the TFTs peeled off.

TABLE 1
Electrical Characteristics of TFTs after Bending

Radius of Curvature	Device Orientation	ΔV_T	ΔI_{OFF}	ΔI_{ON}
2.5 mm	facing out	+0.1 V	none	none
1.5 mm	facing out	-0.1 V	x 200	none
2.5 mm	facing in	-1.0 V	none	none
1.5 mm	facing in	n/a	n/a	n/a

B. Characterization of OLEDs

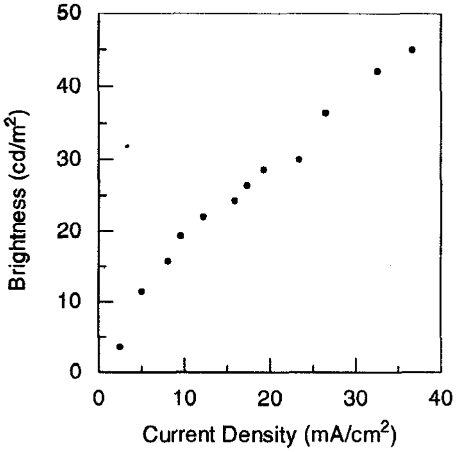


Figure 6. OLED luminance as a function of current through the device.

Fig. 6 shows how the OLED luminance depends on the current through the device. As expected, the behavior is linear once the OLED begins to luminesce. It should be noted that the factor limiting the luminance in this device is not the polymer material itself, but the semi-transparent top-contact. Here, we obtain 50 cd/m^2 at 40 mA/cm^2 (20μA) with V_G=V_D= 40 V. Previous experiments using this polymer on oxygen plasma treated ITO have demonstrated that brightness as high as 1000 cd/m^2 at 40 mA/cm^2 can be achieved (2). Fig. 7(a) shows the I-V characteristics of the integrated TFT/OLED device on a linear current scale. Fig. 7(b) and (c)

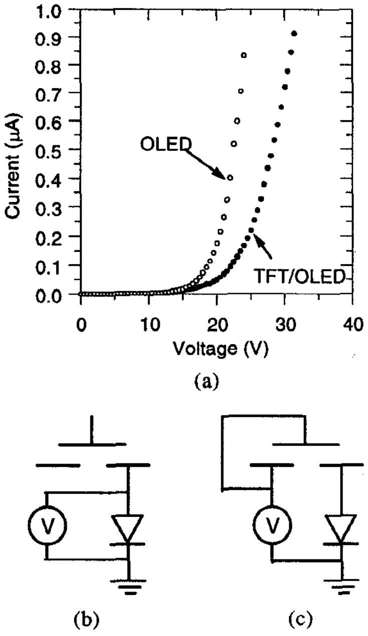


Figure 7 (a) I-V characteristics, and circuit schematics for (b) OLED and (c) TFT/OLED measurements.

illustrate how the voltage is applied to obtain the OLED and TFT/OLED curves, respectively. The shift in turn-on voltage results from the additional 3.5 volts required to turn on the TFT. The output characteristics of the individual OLEDs, and of the integrated TFT/OLED structure, are shown in Fig. 8, with the current density through the OLED indicated on the right axis.

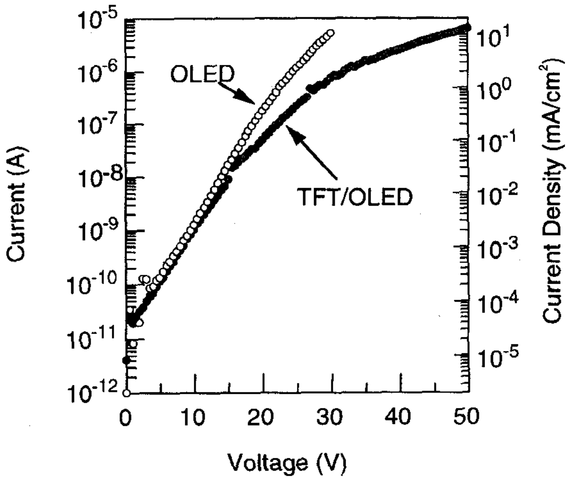


Figure 8. Output characteristics of the OLED and integrated TFT/OLED.

Summary and Conclusions

We have successfully integrated high-quality a-Si:H TFTs with OLEDs on ultra-thin, flexible stainless steel foil substrates. Electrical and optical characterization of these devices show that the TFTs provide sufficient current levels to drive OLEDs. The transistors remain operational under convex or concave bending down to 2.5 mm radius of curvature with no degradation in electrical performance. Our results therefore suggest that foldable displays are indeed feasible.

Acknowledgments

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