ORGANIC LIGHT-EMITTING DIODE/THIN FILM TRANSISTOR INTEGRATION FOR FOLDABLE DISPLAYS

Eugene Y. Ma, Steven D. Theiss*, Michael M.H. Lu, Chung-Chih Wu, J.C. Sturm, S. Wagner
Department of Electrical Engineering, Princeton University, Princeton, NJ 08544, USA
*Current address: Lawrence Livermore National Laboratory, Livermore, CA 94550, USA

Abstract

We demonstrate the integration of organic light-emitting diodes (OLEDs) and thin film transistors (TFTs) on 25μm thick, highly flexible stainless steel substrates. Our goal is to develop an active matrix OLED display that can be folded for use in highly rugged and portable applications such as foldable intelligent maps. OLED/TFT structures were fabricated on 38 mm x 38 mm steel foils and subsequently scissor-cut into strips 4 mm wide and 38 mm long. These strips were rolled along their length and tested for topological integrity and electrical/optical performance. The transistors remain operational under convex or concave bending down to 2.5 mm radius of curvature. Our results suggest that foldable displays are feasible.

Introduction

As display applications grow in number, becoming as varied as they are numerous, one area of interest to the flat-panel display industry concerns the use of alternative substrates to glass. 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, such as the TFT/OLED structure, may be limited by the stress E in the thin-film layer that develops when the substrate is bent. For a given radius of curvature r, E is proportional to the thickness d of the substrate and thin-film composite, and is given by

$$E = Y \cdot \frac{d}{2} \cdot \frac{1}{r}$$

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

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-

ISSN1083-1312/97/1701-L078-$1.00 + .00 © 1997 SID

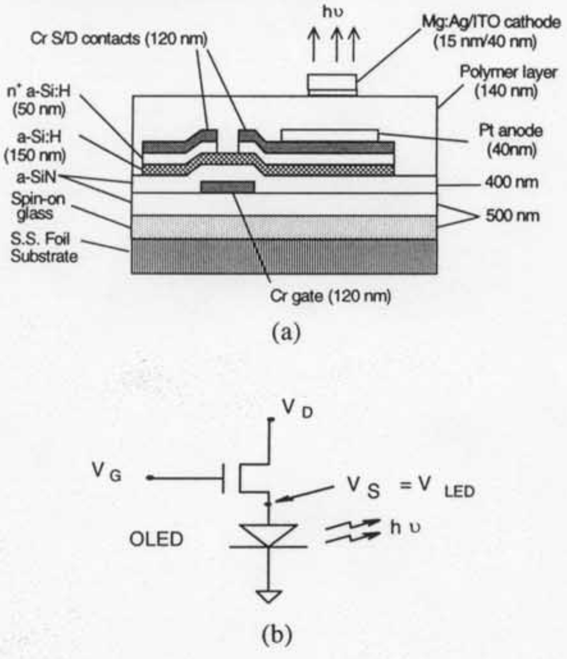


Figure 1 *(a) Schematic cross section of the TFT/OLED on the steel foil, (b) the equivalent circuit.*

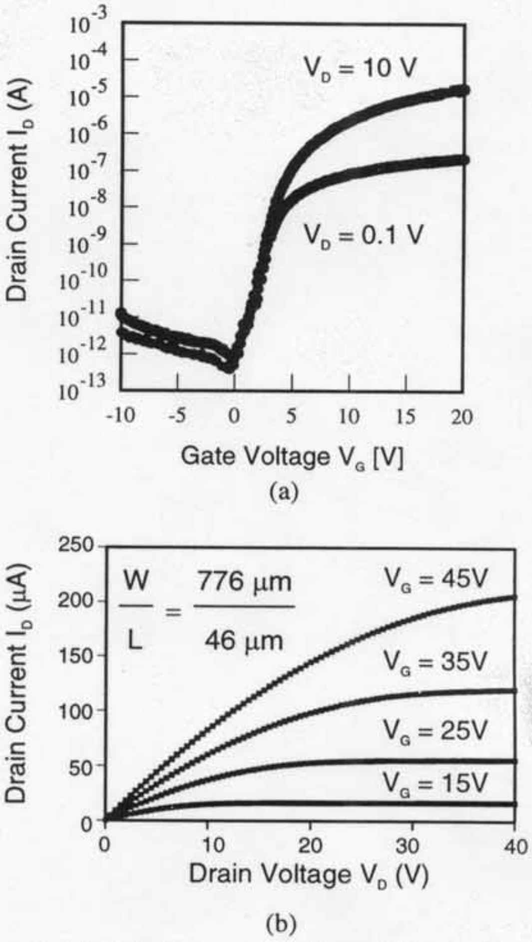


Figure 2 *(a) Output characteristic and (b) transfer characteristic of TFT on 25μm steel foil.*

thin substrates of 25 μm thick stainless steel foil. A schematic cross-section of the integrated TFT/OLED structure on ultra-thin steel foils is shown in Figure 1(a), and its equivalent circuit is shown in Figure 1(b) [3]. 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 [4], followed by 120 nm Cr source/drain contacts. 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. The as-processed TFTs have threshold voltages $V_{th} = 4.5$ V, OFF currents $I_{OFF} \approx 10^{-15}$ A/μm, and ON currents $I_{ON} \approx 10^{-8}$ A/μm, as shown in Figure 2(a).

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 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 Figure 1(a), in which the high work function metal Pt functions as the reflective bottom anode and a semitransparent 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 1400 Å active luminescent molecularly doped polymer (MDP), followed by the deposition of double-layer Mg:Ag (10:1, 100-170 Å)/indium tin oxide (ITO, ~400 Å) semitransparent top cathode. The overlap of the anode and cathode contact areas determines the active OLED device area, a 250 μm diameter circle, without the need to separately isolate the organic layers. All OLED fabrication steps were performed at room temperature and are compatible with finished TFTs [3].

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-butylphenyl)-1,3,4-oxadiazole (PBD) and a small amount of fluorescent dye, Coumarin 6, which provides efficient emission centers [3].

Results

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. These strips were rolled along their length under both convex (TFTs facing outward) and concave (TFTs facing inward) bending, and tested for topological integrity and electrical performance. Figure 3 illustrates the flexibility of these substrates. TFT characteristics are shown in Figure 4. The TFT structures began to peel off at radii of curvature between 1.5 and 2.5 mm. The electrical performance of the TFTs was not affected by the rolling until the TFTs peeled off.

Figure 5 shows how the OLED luminance depends on the current through the device.

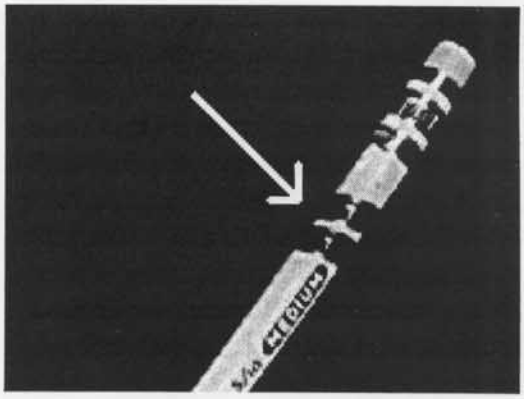


Figure 3. *TFT strip wrapped twice around a pencil.*

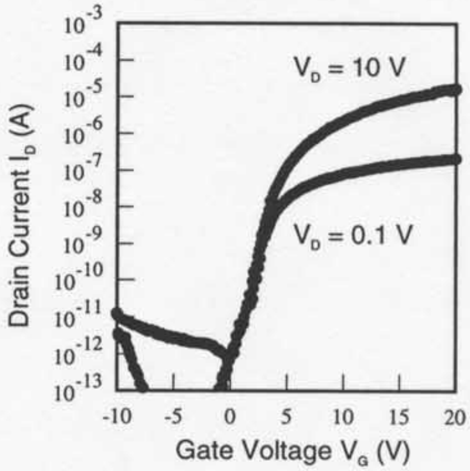


Figure 4. *Output characteristic of TFT after being rolled to a 2.5 mm radius of curvature.*

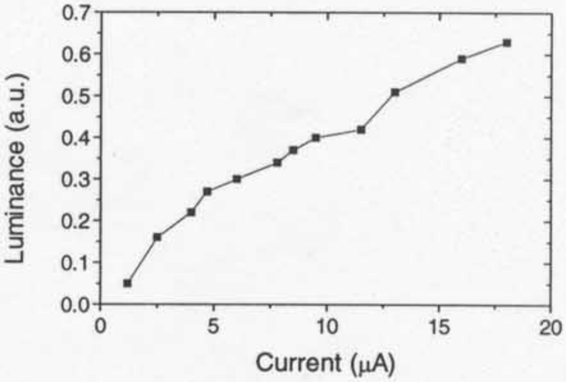
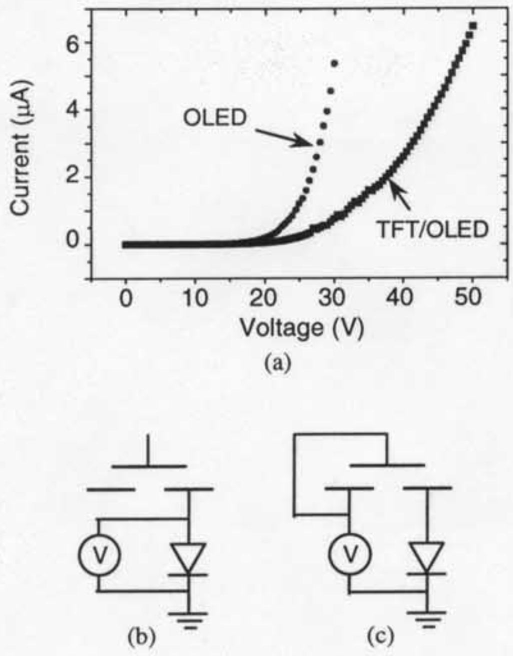


Figure 5. *OLED luminance as a function of current through the device.*



(a)

(b)

(c)

Figure 6 *(a) I-V characteristics, and circuit schematics for (b)OLED and (c) TFT/OLED measurements.*

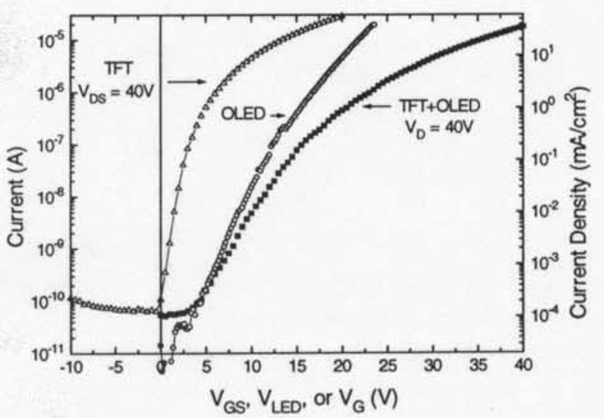


Figure 7. *I-V characteristics of the TFT, the OLED and the integrated TFT/OLED.*

As expected, the behavior is linear once the OLED begins to luminesce. Figure 6(a) shows the I-V characteristics of the integrated TFT/OLED device on a linear current scale. Figures 6(b) and (c) illustrate how the voltage is applied to obtain the OLED and TFT/OLED curves, respectively.

The I-V characteristics of the individual TFT, the individual OLEDs, and of the integrated TFT/OLED structure, are shown in Figure 7, with the current density through the OLED indicated on the right axis. The typical ON/OFF characteristics of TFTs measured as a function of V_{GS} at V_{DS} = 40V are shown.

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. Our results suggest that foldable displays are feasible.

Acknowledgments

We thank Dr. Xudong Jiang for information on thin foil mechanics. This research is supported by EPRI and by DARPA under Air Force grant number F33615-94-1-1464, managed by WPAFB.

References

[1] J.M. Gere and S.P. Timoshenko, *Mechanics of Materials*, PWS-Kent Publ. Co., Boston, 1990, p.252.

[2] J.C. Sturm and C.C. Wu, "Integrated Organic Light Emitting Diode Structures Using Doped Polymers," this proceedings volume.

[3] C.C. Wu, S.D. Theiss, G. Gu, M.H. Lu, J.C. Sturm, S. Wagner and S.R. Forrest, "Organic LEDs Integrated with a-Si TFTs on Lightweight Metal Substrates," SID Tech. Dig., vol. 28, pp. 67-70, May 1997.

[4] S.D. Theiss and S. Wagner, "Flexible Lightweight Steel-Foil Substrates for Amorphous Silicon Thin–Film Transistors," AM-LCD '96 Tech. Dig., 1996, pp. 365-368.