

Integration of Organic LED's and Amorphous Si TFT's onto Flexible and Lightweight Metal Foil Substrates

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Abstract—We report the integration of organic light emitting devices (OLED's) and amorphous Si (a-Si) thin-film transistors (TFT's) on both glass, and unbreakable and lightweight thin stainless steel foil substrates. The doped-polymer OLED's were built following fabrication of driver TFT's in a stacked structure. Due to the opacity of the steel substrate, top-emitting OLED structures were developed. It is shown that the a-Si TFT's provide adequate current levels to drive the OLED's at video brightness (~ 100 cd/m²). This work demonstrates that lightweight and rugged TFT backplanes with integrated OLED's are essential elements for robust and highly portable active-matrix emissive flat-panel displays.

I. INTRODUCTION

A long-sought-after goal has been a flat-panel display that is unbreakable, lightweight, flexible, and low cost. Organic light emitting devices (OLED's) based on organic thin films have this potential because of their demonstrated performance, their versatility of colors, their lack of a need for a crystalline substrate, and their potential low cost [1]–[3]. Meanwhile, amorphous Si (a-Si:H) thin-film transistors (TFT's) have been in widespread production for a number of years as the switching elements in high-resolution, active matrix liquid crystal displays (AMLCD's). Both of these thin-film technologies are typically fabricated on fragile glass substrates. In this letter, we report the integration of a-Si TFT's and OLED's onto glass substrates as well as onto rugged and lightweight stainless steel thin foils.

Although there have been successful demonstrations of flexible OLED's fabricated on plastic substrates [3]–[5], the fabrication of a-Si TFT's on plastics has proven difficult due to mechanical and chemical instabilities of such substrates at the processing temperatures typically needed for a-Si TFT's (~ 300 °C) [6]. Therefore, integration of both OLED's and TFT's on a flexible plastic substrate to make an unbreakable display is still problematic. Since OLED's can be made to emit light from the top surface [7]–[8], transparency of substrates is not required for OLED/TFT integration, lending more freedom to our choice of substrates. Thin steel foils, which have

high mechanical strength, flexibility, light weight and thermal stability, have been previously demonstrated by Theiss et al. to be compatible with TFT processing [6], [9]. In this letter, we demonstrate the integration of a-Si TFT's with OLED's on steel foil substrates which may find uses in large-area active matrix displays.

II. EXPERIMENT

OLED's are carrier-injection devices conventionally built on glass substrates precoated with indium tin oxide (ITO) used as the bottom, hole-injecting anode contact. In this configuration, light emits through the transparent ITO layer and the glass substrate. To make the top-emitting OLED's on the opaque steel substrate, the transparent bottom anode contact has been replaced by the high work function metal Pt, which is found to have a hole injection efficiency comparable to ITO. On the other hand, semitransparent cathode contacts needed for top surface emission can be formed by using thin (< 20 nm) layers of low work function metals such as Ag [10]. These thin single-layer metal films, however, cannot provide efficient electron injection and have high sheet resistance, leading to rather low quantum efficiency ($< 0.01\%$) and high drive voltage. In this device, we therefore employ double-layer cathode contacts [8], in which a thin (100–170 Å) semitransparent Mg:Ag layer provides for electron injection, while a transparent and conducting ITO cap layer provides for high conductivity and environmental robustness. A transmittance of $\sim 70\%$ can be achieved using this cathode composition [8].

A schematic cross section of the integrated TFT/OLED is shown in Fig. 1(a), with the circuit shown in Fig. 1(b). The steel foil substrates are 200- μm thick, one-side polished, grade 430 stainless steel, and possess an rms surface roughness of ~ 70 nm. An insulating barrier layer, a-Si_x:H, was first deposited to electrically isolate the active devices. a-Si TFT's with an inverted-staggered structure and a W/L ratio of 776 $\mu\text{m}/42$ μm (~ 18) were then fabricated on top of the barrier layer. All a-Si:H and a-Si_x:H layers were deposited at a pressure of 500 mtorr in a three-chamber plasma enhanced chemical vapor deposition (PECVD) system, in which undoped a-Si:H (at 250 °C), n⁺ a-Si:H (at 260 °C) and a-Si_x:H (at 310 °C) are deposited in separate chambers. Chromium gate and drain/source contacts were deposited by a separate thermal evaporating system. The details of material growth and TFT device fabrication have been previously described

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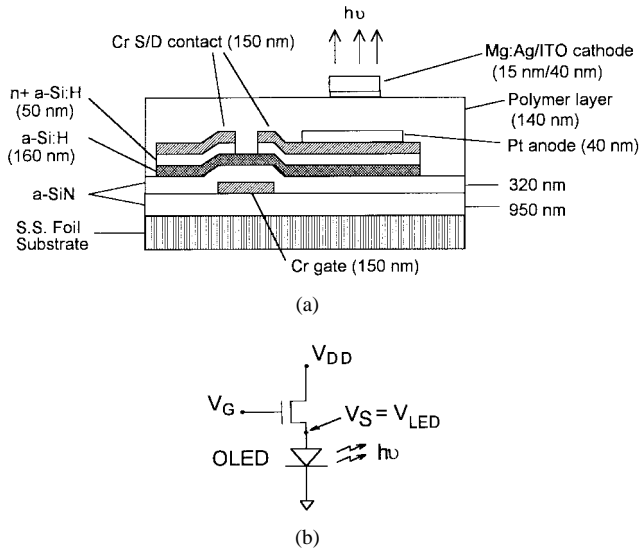


Fig. 1. (a) Schematic cross section of the integrated TFT/OLED on the steel foil substrate. The active area of the OLED is determined by the size of the Mg:Ag/ITO cathode contact, which is a circle with a diameter of $250 \mu\text{m}$. (b) The circuit of the integrated OLED/TFT structure.

[6], [9]. A similar OLED/TFT structure without the first a-SiN_x:H barrier layer was also grown on 7059 glass substrates for comparison.

After fabrication of the TFT's, top-emitting OLED's were then deposited on the surface of the $2 \text{ mm} \times 2 \text{ mm}$ Cr source/drain contact pads. OLED's were fabricated by sequential *e*-beam deposition of 400 \AA thick Pt anode contacts through a shadow mask, spin-coating of a continuous layer of $1400\text{--}1700 \text{ \AA}$ active luminescent polymer, followed by the deposition of semitransparent double-layer Mg:Ag (10:1)/ITO top cathode contacts through a shadow mask. The OLED's consisted of single-layer molecularly doped polymer thin films, in which 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 the fluorescent green dye coumarin 6 (C6) as efficient emission centers [11]–[15]. The PVK:PBD:C6 ratio is 100:40:0.3 by weight. Mg:Ag was deposited by thermal co-evaporation from two separate sources. ITO was deposited from a mixed $\text{In}_2\text{O}_3\text{:SnO}_2$ (90:10 wt%) target by RF magnetron sputtering in an Ar:O₂ (2000:1) ambient [8]. A low RF power of 5 W, resulting in a deposition rate of $\sim 200 \text{ \AA/h}$, was used to minimize the damage in the organic film caused by the sputtering process [8]. The overlap of the anode and cathode contact areas gives a $250\text{-}\mu\text{m}$ -diameter circular OLED, without the need to separately isolate the organic layers. All OLED fabrication steps were performed at room temperature.

III. RESULTS AND DISCUSSIONS

Results on both steel foils and glass substrates are similar, except that the yield of OLED's on steel foils is lower due to the surface roughness resulting from the currently unplanarized steel surface. Fig. 2 shows typical current–voltage (I – V) characteristics for the isolated TFT's and the isolated OLED's

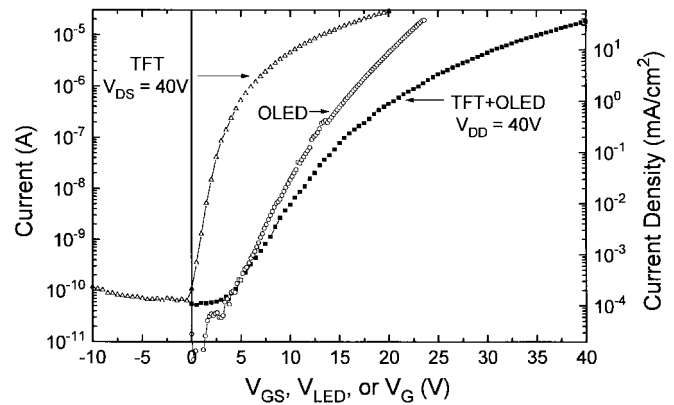


Fig. 2. Current–voltage characteristics of the TFT (versus the gate-to-source voltage, V_{GS}), the OLED (versus the OLED voltage, V_{LED}), and the integrated OLED/TFT structure (versus the gate voltage, V_G). The left ordinate is for all three curves, and the right ordinate is for the OLED and the integrated TFT/OLED.

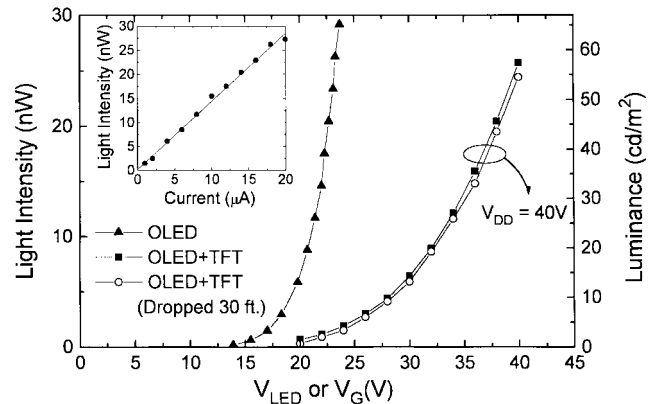


Fig. 3. Light intensity versus the OLED voltage V_{LED} for the OLED, and versus the gate voltage V_G for the integrated TFT/OLED. The right ordinate shows the corresponding luminance unit. The inset shows the light intensity versus the OLED current.

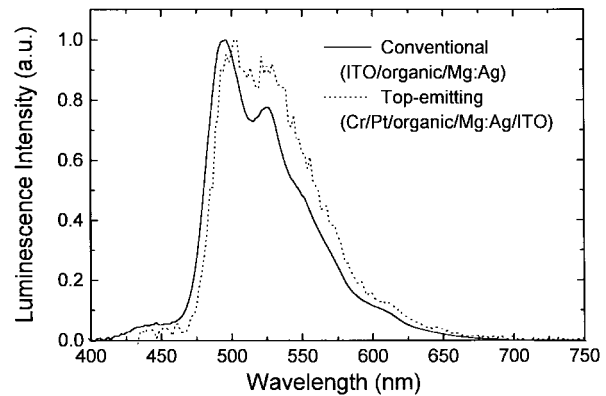


Fig. 4. Electroluminescence spectra for the Cr/Pt/polymer/thin Mg:Ag/ITO top-emitting structure and the conventional ITO/polymer/opaque Mg:Ag bottom-emitting structure.

in the integrated TFT/OLED on steel foil substrates, and the integrated TFT/OLED itself. The on/off characteristics of TFT's measured as a function of the gate-to-source voltage V_{GS} at the drain-to-source voltage $V_{DS} = 40 \text{ V}$ are shown. These TFT's fabricated on steel foils typically have a threshold

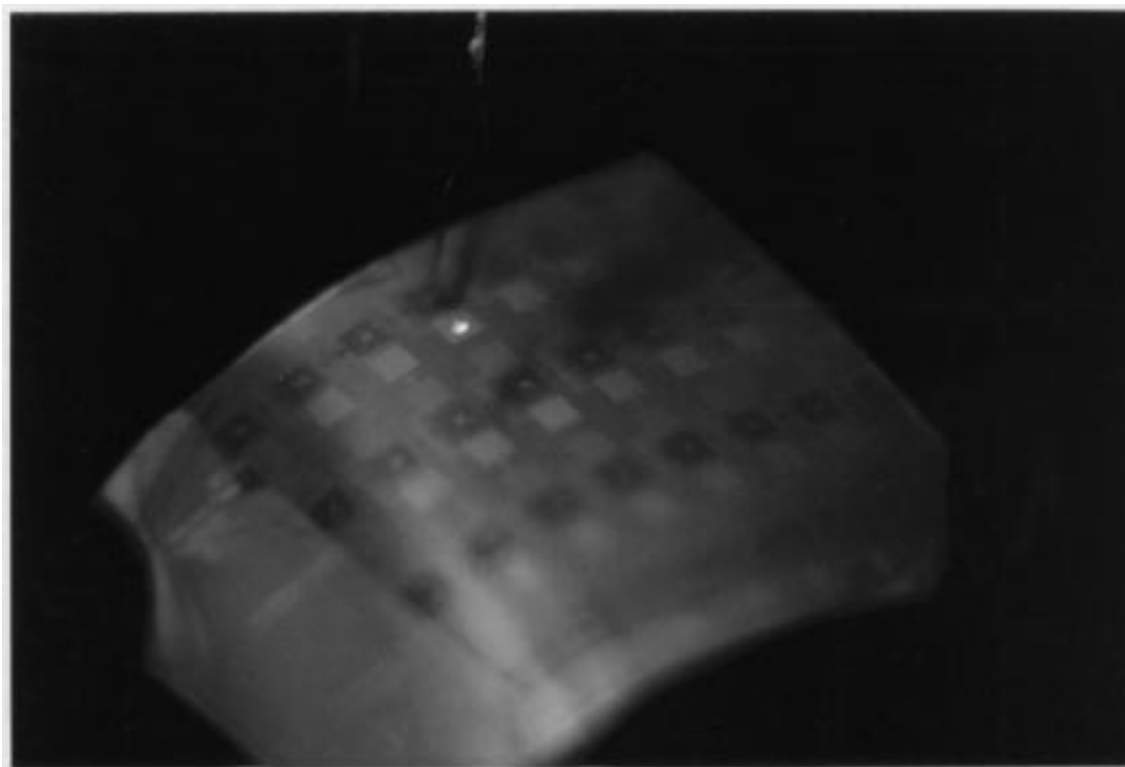


Fig. 5. Photograph of a TFT driving an OLED on a steel foil flexed to a radius of curvature of ~ 9 cm, with probes on the drain, gate, and the cathode of the OLED.

voltage of ~ 3 – 4 V, a subthreshold slope of 0.5 – 1 V/decade, an electron mobility of 0.5 – 0.7 $\text{cm}^2/\text{V}\cdot\text{s}$, and an on/off current ratio of $>10^5$. The characteristics of TFT's with or without OLED's are also similar to those of TFT's grown directly on glass substrates. The forward current of the OLED versus the OLED voltage V_{LED} are also shown in Fig. 2, and are similar to previous results for devices built on ITO-coated glass substrates and capped with opaque Mg:Ag contacts [11]–[13], except for a higher ($\sim 50\%$) drive voltage. The higher voltage is partly due to the thicker polymer layers (1400 Å versus 1000 Å) used to compensate for the roughness of the steel surface, and is probably also due to the additional resistance at the Mg:Ag/ITO interface resulting from the oxidization of Mg:Ag during the ITO deposition [8]. For the integrated TFT/OLED circuit, the drain current measured as a function of the gate voltage V_G at $V_{\text{DD}} = 40$ V is also shown in Fig. 2. At a given current level, $V_G = V_{\text{GS}} + V_{\text{LED}}$ required to maintain that current. Clearly, the TFT can successfully switch the OLED on and off through the voltage V_G .

The electroluminescence spectrum of the top-emitting OLED is shown in Fig. 3, and is compared with that of a conventional bottom-emitting OLED made on an ITO-coated glass substrate. Both spectra are similar, except for a slight red shift in the spectrum of the top-emitting structure due to the semitransparent cathode contact [8]. Light intensity versus forward bias voltage of the OLED and versus V_G ($V_{\text{DD}} = 40$ V) in the integrated OLED/TFT structure are shown in Fig. 4. Light emission is proportional to the current (inset of Fig. 4). This Pt/PVK:PBD:C6/thin Mg:Ag/ITO device has an external electroluminescence quantum efficiency

$\eta_e \sim 0.06\%$ photon/electron, with the emitted light originating from exciton recombination in C6 doped into the polymer thin-film [11]–[13]. The efficiency is lower than our conventional ITO/organic/opaque Mg:Ag devices (typically with $\eta_e \sim 1\%$ at 17 to 18 V and 25 mA/cm^2 for ~ 1400 Å thick organic thin films) [11]–[13], indicating that the present devices are not inherently limited by the organic materials. In an OLED using the ITO anode on glass and the thin Mg:Ag/ITO cathode, the external efficiency drops from 1% for the conventional OLED to 0.15% and the drive voltage increases. Further replacing the ITO anode with Pt, the I – V characteristics remain unchanged while the efficiency further drops to 0.06% . We attribute the reduction of the efficiency to the lower optical transparency of the thin Mg:Ag/ITO cathode contacts than the ITO anode and the low reflectivity of Pt bottom anode contacts ($\sim 60\%$) to visible light. Since the drive voltages are increased when the opaque Mg:Ag cathode is replaced with the semitransparent Mg:Ag/ITO cathode, the electron injection ability in these devices may also be reduced by the oxidation of the thin Mg:Ag layer during the ITO sputtering. The reduction of the electron injection ability surely could contribute to the drop of efficiency. This is, however, not well understood yet. Due to the nature of the steel foil substrate, dropping the finished foil (4 cm \times 4 cm) over 30 feet onto concrete had no significant effect on the substrate or on the characteristics of the devices, as shown in Fig. 4. The photograph in Fig. 5 shows a TFT driving an OLED on a steel foil flexed to a radius of curvature of ~ 9 cm.

Because of the lower efficiency of the present top-emitting OLED ($\sim 0.06\%$, 0.22 cd/A), a high OLED current density

of ~ 40 mA/cm², corresponding to the drain-to-source current $I_{DS} = 20$ μ A, has to be applied to achieve a brightness close to that used in video displays (~ 100 cd/m²). However, an OLED with $\eta_e = 1\%$ (3.6 cd/A) only requires a current density as low as ~ 3 mA/cm², corresponding to $I_{DS} = 2$ μ A. If such a top emitter structure were achieved, this current requirement could easily be met with V_{GS} and V_{DS} below 10 V by matching the W/L ratio, as is apparent from Fig. 2.

IV. SUMMARY

In summary, we have demonstrated the integration of polymeric OLED's and a-Si TFT drivers onto lightweight, rugged and flexible steel foil substrates. The simple doped-polymer OLED process is compatible with the TFT fabrication process. By matching the W/L ratio of the a-Si TFT's to the OLED drive current requirement, the a-Si TFT's can provide adequate current to drive OLED's.

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