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FLEXIBLE, LIGHTWEIGHT STEEL-FOIL SUBSTRATES FOR a-Si:H THIN-FILM TRANSISTORS

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ABSTRACT

For many flat panel display applications, traditional glass substrates for the TFT backplane are not sufficiently rugged. Therefore, we have begun to explore the use of steel foils as TFT substrates for emissive or reflective displays. We report the fabrication of high quality a-Si:H TFTs on lightweight, flexible 75 μm thick stainless steel foils. The electrical characteristics of the TFTs were good and were not significantly affected by either dropping over 15 meters to a concrete floor or being bent to a radius of curvature of 8.25 cm for a period of over 400 hours. Typical device characteristics were: $I_{ON}/I_{OFF} > 10^7$, $I_{OFF} \sim 10^{-12}$ A, $V_T \sim 3.2$ V, and $\mu_{EFF} \sim 0.9$ cm^2/Vs. We also discuss our recent work on the successful integration of organic light-emitting diodes (OLEDs) with TFTs on steel substrates, resulting in a new form of emissive display.

INTRODUCTION

A current subject of interest to the flat-panel display industry is that of alternative substrates to glass for use in the backplane of liquid crystal displays (LCDs). 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 [1]. Although clear plastic substrates would appear to be an ideal alternative to glass [2], efforts to develop an inexpensive, clear plastic capable of withstanding the highest temperatures utilized in traditional PECVD grown TFTs (~350°C) have thus far been unsuccessful. In addition, thermal expansion mismatch between typical plastics and a-Si:H (50:1), and thermally induced, irreversible shrinkage may continue to pose significant obstacles to the use of plastic substrates in conventional FPD manufacturing. One alternative substrate material which is highly stable at the required TFT processing temperatures is steel. Already used for some time as a substrate for flexible, lightweight photovoltaic modules [3], stainless steel foils possess both high chemical and mechanical stability at elevated temperatures and a reasonable thermal expansion match to a-Si:H (5:1).

We have previously demonstrated that high-quality TFTs can be grown on 200 μm and 75 μm thick stainless-steel [4,5]. We have also demonstrated that substrate roughness plays an important role in determining device yield and reliability, with unpolished 75 μm foils having a reduction in yield of ~50% over TFTs grown on the polished 200 μm foils [5]. In the present work, we report an improved process for growth of TFTs on 75 μm foils, in which a spin-on-glass film was used to planarize the foil before TFT growth. This improved process resulted in significant enhancements in both electrical performance and device yields.

Although the opacity of the steel foils prevent their use in standard, backlit FPDs, they are well suited to use in either reflective or emissive displays. As a demonstration of one such possibility, we have successfully integrated the TFTs on steel foil with organic light-emitting diodes (OLEDs). In a simple circuit in which the TFT was used as a current source to drive the OLED, easily visible light was produced under normal room lighting conditions. These integrated devices were also subjected to dropping and bending tests and showed no degradation in device performance. These results clearly illustrate the exciting potential of these devices for use in the development of a new type of lightweight, flexible, highly durable emissive display.

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EXPERIMENT

The substrates used in this experiment are grade 430 stainless steel, 75 μm thick, unpolished, and possess an rms surface roughness of approximately 0.2 μm. The density ratio of grade 430 steel (7.7 g/cm^3) to 7059 glass (2.76 g/cm^3) is 2.8. Consequently, this steel foil thickness is roughly equivalent in weight to 210 μm thick 7059 glass. The large surface roughness arises from the rolling of the stainless steel foil to the desired thickness, and is thus primarily oriented in the direction of rolling. The surface roughness is comprised of both "high" and "low" frequency components, as shown in the surface profile trace of Figure 1a.

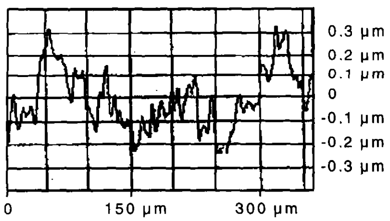

Figure 1a. *Surface profile of as-rolled 75 μm foil.*

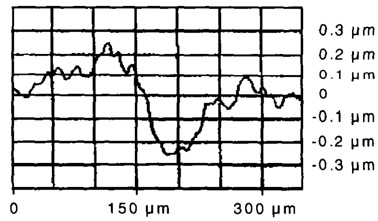

Figure 1b. *Surface profile of "planarized" 75 μm foil.*

Previous experiments had shown that the as-rolled roughness seriously reduced the yield of functioning TFTs, as well as reducing their ability to withstand bending stresses [5]. Rather than polishing the substrates, we attempted to reduce the roughness by planarizing them with a spin-on glass (SOG) film, a process which could prove to be much less expensive industrially than polishing. Also, the SOG layer would ideally save a step in the TFT fabrication process by acting as the insulating layer between the substrate and the TFTs. The SOG used here was methylsiloxane 500F glass (Filmtronics), which is normally used in the planarization of IC metal levels with tall features. One spin-coating leaves a nominal film thickness of ~ 0.5 μm. This was cured in flowing N_2 at a temperature of ~ 425°C. A surface profile trace of a planarized steel foil is shown in Figure 1b. Note the elimination of the "high" frequency roughness. In our earlier work with TFTs on steel, a thick (~ 1 μm) layer of SiN_x was deposited directly on the steel before beginning the gate metallization, to act as an electrically insulating layer between the substrate and the TFTs. Although the ultimate goal is to replace this SiN_x layer with the single SOG layer, concerns about the resistivity of the SOG led to a 0.5 μm thick SiN_x layer being deposited on top of the SOG layer before gate metallization.

The TFT was fabricated in the inverted-staggered configuration with a back-channel etch. A 4-level mask process with specially designed masks was used to define the TFTs. These masks were designed to have large feature sizes to enable ease of probing during bending experiments as well as to simplify their integration with the organic light-emitting diodes. The TFT semiconductor and dielectric layers were deposited at 500 mTorr in a three chamber plasma enhanced chemical vapor deposition (PECVD) system using RF power at 13.56 MHz. Metal layers were deposited via thermal evaporation of chromium in a separate system. The process parameters for the different TFT layers are summarized in Table 1. The metal patterning was done using a wet-etch process, while the amorphous silicon and silicon nitride layers were defined using reactive-ion etching (RIE) with a CF_4/O_2 gas mixture. Following the back-channel etch, the TFTs were annealed for 30 minutes at 200°C in vacuum to remove plasma damage. Figure 2 shows a schematic cross-section of the current TFT structure.

Layer	Gas Flows (sccm)	T (°C)	Power (mW/cm^2)
a-SiN_x:H	13 : SiH_4 130 : NH_3	350	22
a-Si:H	50 : SiH_4	250	20
n^+ a-Si:H	44 : SiH_4 6 : PH_3	260	16

Table 1. *PECVD Process Parameters.*

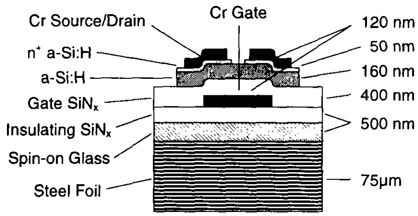

Figure 2. *Schematic cross-section of TFT on 75 μm steel foil.*

RESULTS

The electrical characteristics of the TFTs on the planarized steel foil are shown in Figures 3 and 4. They demonstrate excellent transistor behavior. We obtain from these figures an ON/OFF current ratio of greater than 10^7, Off currents of 10^{-12} A, a subthreshold slope of 0.5 V/decade and a threshold voltage of 3.2 V in the linear current regime. The field effect mobility in the linear current regime is approximately 0.9 $cm^2/V \cdot sec$. All measurements listed here were done with the source electrode grounded. Planarization of the rough steel foils with the SOG layer was very effective in bringing the yield of functioning TFTs back up to approximately 100%, which was similar to the yield attained for TFTs grown on the 200 μm thick polished foils. Although the topology of the "planarized" foils is still significant, as seen in Fig. 1b, this "low frequency" roughness does not appear to affect the device performance.

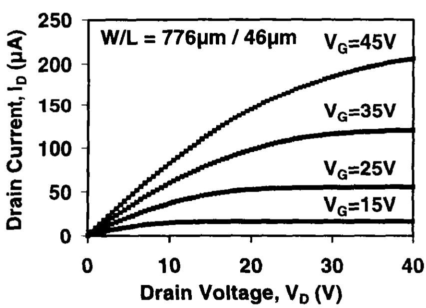

Figure 3. *Transfer characteristics of TFT on 75 μm steel foil.*

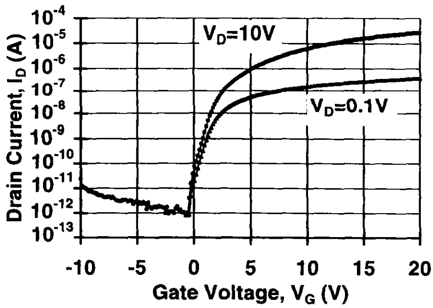

Figure 4. *Output characteristics of TFT on 75 μm steel foil.*

To demonstrate the enhanced durability of TFTs deposited on steel foils, we subjected the sample to impact and bending tests. The impact test consisted of dropping the sample down a stairwell from a height of 4 floors (~15m) onto a concrete surface. The TFTs were then remeasured to check for any changes in electrical characteristics. As with those grown on 200 μm thick steel, the TFTs grown on 75 μm thick planarized steel showed no change in their characteristics after this test. It should be noted that 1 mm thick glass substrates subjected to this same test were completely destroyed. To test the effect of bending stress, the sample was bent around a cylindrical section with a radius of curvature (ROC) of 8.25 cm and then clamped at both ends. The electrical characteristics were measured repeatedly over a period of time to identify any time-dependent shifts in the properties. Figure 5 shows the TFT in the bent configuration. No consistent shifts in either the OFF current or the threshold voltage have been observed in a sample bent at this ROC for over 400 hours. Although more tests are needed before conclusions may be drawn, our results clearly suggest that TFTs may be safely bent for long periods of time without degradation in their electrical performance. We are currently designing apparatus that will allow these tests to be performed at elevated temperatures and a variable radius of curvature.

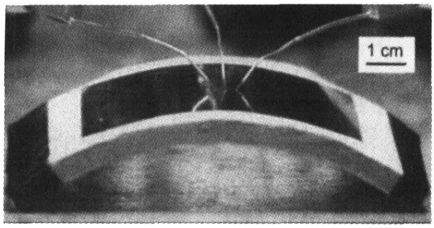

Figure 5. *Electrical testing of TFT during bending around cylinder with R=8.25cm.*

To demonstrate the viability of a-Si:H TFTs on metal foils for display applications, we have begun to integrate the TFTs on steel with organic light emitting diodes (OLEDs). OLEDs are an emerging thin-film LED technology and have shown great potential for use in FPD development because of their demonstrated performance, versatility in colors, wide choice of substrates and potential low cost [6,7]. Furthermore, top-emitting and flexible OLEDs have also been demonstrated [8,9], which establishes their clear compatibility with TFTs on metal foils. Conventional OLEDs are fabricated on glass substrates coated with a transparent hole-injecting anode contact such as indium tin oxide (ITO), and an opaque electron-injecting metal cathode, with the light being emitted through the glass. A schematic cross-section of our integrated TFT/OLED structure is shown in Figure 6, along with its equivalent circuit.

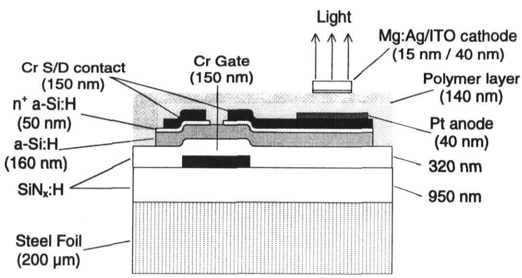

Figure 6a. *Schematic cross section of integrated TFT/OLED.*

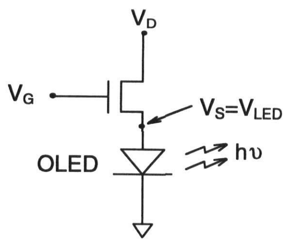

Figure 6b. *Equivalent circuit for TFT/OLED.*

The OLEDs were fabricated on the source/drain contact pads of the completed TFTs. Because of the opacity of the steel foil, it was necessary to develop the top-emitting structure as shown in Figure 6a. In this structure the high work function metal Pt served as the reflective bottom anode. After depositing and patterning the Pt anode, a continuous layer of luminescent polymer was applied to the substrate via spin-coating. Finally, a semi-transparent cathode contact consisting of a double-layer of Mg:Ag (10:1) and indium tin oxide (ITO) was deposited through a shadow mask. In the double-layer Mg:Ag/ITO cathode contacts, invented by Gu *et al.* [8], the thin Mg:Ag layer provides the capability of electron injection and yet is still relatively transparent. The transparent and conducting ITO cap layer provides both protection and robustness to the underlying Mg:Ag layer. A transmittance of ~70% could be achieved with this cathode structure. The overlap of the anode and cathode contact areas determines the active OLED device area without the need to separately isolate the organic layers. In the present devices, the overlap of the contact areas defined a 250 μm diameter circle. All OLED fabrication steps were performed at room temperature and are compatible with finished TFTs. The active organic materials used in the OLEDs are single-layer molecularly doped polymer (MDP) thin films [10]. They consist of a blend of a hole-transport matrix polymer, dispersed electron-transport molecules, and small amounts of fluorescent dyes as efficient emission centers. Our OLEDs contained the organic dye Coumarin 6 (C6), which emits green light. C. C. Wu *et al.* have fabricated efficient blue, green and orange devices on conventional ITO coated glass substrates, integrating them on a single substrate [9], demonstrating the potential for full color displays. Further details of the OLED fabrication can be found elsewhere [11].

Figure 7 shows the electrical characteristics of the isolated TFT (source grounded), the isolated OLED (source at V_{LED}), and the integrated TFT/OLED structure (source at V_{LED}), with the current density through the OLED indicated on the right axis. The TFTs fabricated for this phase of the experiment preceded the development of the optimized TFTs on planarized substrates and thus have slightly poorer electrical properties than those shown previously. The TFT was held at, or near, saturation throughout these measurements by keeping V_{DS}=40V. For the integrated TFT/OLED circuit, V_G is the sum of the V_{GS} and V_{LED} required to maintain that current through the OLED. As the figure demonstrates, the TFT can successfully switch the OLED on and off through the gate voltage V_G.

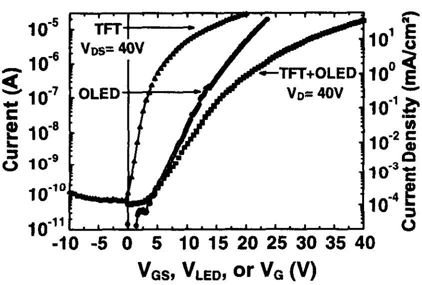

Figure 7. *I-V characteristics of the TFT, the OLED and the integrated TFT/OLED.*

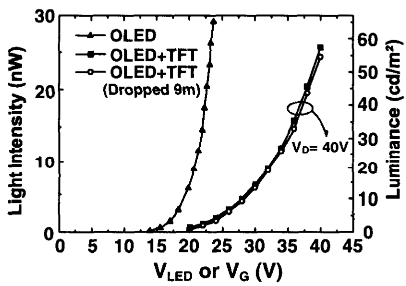

Figure 8. *Light intensity vs. voltage.*

Light intensity vs. forward bias voltage of the OLED, and vs. V_G (V_D = 40V) in the integrated TFT/OLED structure are shown in Fig. 8. In both cases, the light emission increases with the forward current through the OLED. This OLED emits green light similar to conventional devices. Because the external quantum efficiency of these devices (~0.06%) is lower than that of conventional devices on ITO (~1%), it is clear that they are not inherently limited by the organic materials. This reduction in efficiency is most likely due to the non-optimized nature of the current top-emitting structure, which will be improved in future work. With proper device optimization, it is projected that a brightness close to a practical video brightness of ~100 cd/m^2 could be attained with a voltage drop across the TFT of less than 10V.

To demonstrate the durability of the integrated TFT/OLED on steel structure, we subjected the sample to impact and bending tests similar to those described earlier for the TFTs. The impact test consisted of dropping the sample ~ 9 meters onto concrete. As shown in Fig. 8, the impact test had no significant effect on the characteristics of devices. The picture in Fig. 9 shows a TFT driving an OLED on a steel foil flexed to a radius of curvature of ~ 9 cm, with no significant degradation. This clearly shows that the integrated structure is capable of withstanding significant mechanical stresses, and thus shows great promise as a new type of lightweight, flexible, highly durable form of display.

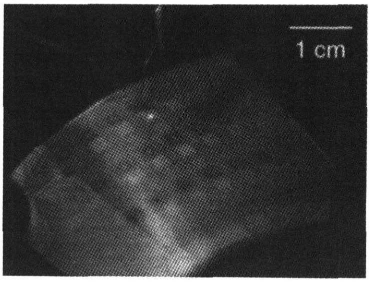

Figure 9. *The operation of the integrated TFT/OLED (bright spot) on the steel foil in the bent configuration.*

SUMMARY and CONCLUSIONS

We have successfully fabricated high quality a-Si:H TFTs on lightweight, flexible steel foil substrates. These TFTs have been shown to be very robust, continuing to function after being both bent to a small radius of curvature and dropped from significant height onto concrete. We have also successfully integrated these TFTs with OLEDs to produce visible light, using the TFT as a current source for the OLED. The integrated TFT/OLED demonstrates good electrical properties and is also very robust, showing great promise as a new type of lightweight, unbreakable emissive display.

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