



A Comparison of Processes and Challenges Between Organic, a-Si:H, and Oxide TFTs for Active Matrix Backplanes on Plastic

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Abstract:

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A comparison of processes and challenges between organic, a-Si:H, and oxide TFTs for active matrix backplanes on plastic

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Processes to produce active-matrix backplanes on plastic substrates have been developed utilizing a-Si:H, multi-component oxide, and organic semiconductor technologies. The suitability of these technologies for future flat panel display applications is discussed. Of these material systems multi-component oxides exhibit highest field-effect mobilities (10 cm²/Vs for zinc tin oxide demonstrated), followed by small molecule organic semiconductors (0.95 cm²/Vs), and a-Si:H (0.5 cm²/Vs). Yet despite higher mobilities, organic TFTs drive less current than a-Si:H because of the low device capacitances required to fabricate such devices. Backplanes made with a-Si:H appear to be the least risky technology, followed by multi-component oxide, and organic semiconductor technologies.

1. Introduction

The need for thinner and lighter displays, different form factors from curved surfaces to very large areas, higher impact resistance, and lower manufacturing costs has driven researchers to investigate the use of plastic as a substrate material for displays.

As one of the largest users of displays, HP has a great interest in developing the state-of-the-art. In particular, HP has invested significant research resources in multi-component oxide (MCO) TFTs such as zinc oxide (ZnO)¹, indium gallium zinc oxide (IGZO), zinc indium oxide (ZIO), and zinc tin oxide (ZTO)²; a roll-to-roll manufacturing processes for amorphous silicon (a-Si:H)³ and MCO⁴ active matrix backplanes by self aligned imprint lithography (SAIL); and low-temperature processes using organic TFTs. These TFT technologies (MCO, a-Si:H, and organic) have enabled the demonstration of flexible electrophoretic displays³, full color electrophoretic displays⁵, flexible OLED displays⁶, and full color-reflective liquid crystal displays⁷.

This paper will summarize recent progress in these various technologies. Due to space limitations, the focus will be kept to a comparative discussion around adapting three technologies –a-Si:H, MCO, and organic TFTs– to plastic. Further details about these technologies may be found in the references.

2. General Considerations

The selection of the plastic substrate is a critical choice and has been extensively covered elsewhere⁸. It is important to note that to date, none of these substrates come close to glass in terms of having in combination good thermal, mechanical, and optical properties. As such, optical properties are sacrificed in order to achieve good thermal and mechanical properties as in the case of polyimide, and the converse is true for plastics that provide good optical qualities which would be needed for use in displays such as LCD or transparent OLED.

The technology with the most widely adopted material system which drives the majority of displays today is a-Si:H. However the low mobility (0.1-1 cm²/Vs) of a-Si:H is insufficient to drive newer technologies such as OLED displays and even large-area LCD 3D TVs with refresh rates at or above 240Hz. Further, the relatively high deposition temperature (150-350°C) limits the possible display substrates that can be used.

With mobilities in the range of 10 – 20 cm²/Vs at plastic compatible temperatures, multi-component oxides such as IGZO and ZTO have the potential for successfully driving OLED displays and large area 3D TVs, and would have sufficient performance to act both as pixel devices as well as drive circuitry

for electrophoretic e-readers where refresh rates are much lower. A further benefit is that MCO tooling is quite similar to that of a-Si:H which largely decreases the cost of adoption of this material and can take advantage of much of the institutional knowledge developed around manufacturing a-Si:H devices. However, processing temperatures for MCO devices, particularly for the dielectrics, are not significantly different than those of a-Si:H and neither of these technologies offer sufficiently low-temperature processes to make them compatible with the most optically transparent plastics such as PET or cyclo-olefins which would be ideal for LC or transparent OLED applications.

Table I. Comparison of parameters and general considerations between a-Si:H, MCO, and organic TFT backplane technologies.

	a-Si:H	MCO	organic
Mobility (cm ² /Vs)	0.1 – 1	10–20 ²⁾	0.1 – 4
Bias stress stability	Good	Good	Good
Parameter variability	Good	Good	Moderate
Off current	Good	Good	Moderate
Chemical inertness	Good	Moderate	Poor
Deposition Temp (°C)	150-350	RoomT	RoomT
Process Temp (°C)	150-350	150+	<150
Process Risk	Low	Med	High
Tooling Risk	Low	Low	High
Moisture resistance	High	Med	Low
Thermal stability	High	High	Low
Light stability	Med	Med	Med
Adhesion	Good	Good	Poor
Hardness	High	High	Low
Flexibility	Med	Med	High

Organic semiconductors are routinely processed at temperatures below 150°C (often as low as 100°C) which make them ideal candidates for use in applications where transparent substrates must be used. The performance of this class of materials has continuously been improving and can now easily achieve mobilities in the 0.1-0.5 cm²/Vs range for polymers⁹⁾ and 1-4 cm²/Vs range¹⁰⁾ for small molecules (SMO) and SMO/polymer blends with much improved ambient stability. This makes the higher mobility materials interesting candidates for OLED applications where concerns for ambient stability can be further ameliorated by the fact that OLED encapsulation requirements are sufficiently stringent to ensure good stability of the drive device. However, the true cost of these solution processes has yet to be proven, and further, they have yet to be established in manufacturing. Because of this, organic semiconductor based technologies seem to pose the highest risk for success and longest time to market. Yet the rate at which this materials advance and the vast amount of possibilities afforded by organic chemistry means these materials should not be readily

discounted.

3. Process reliability

Process yield is also an important factor for evaluating display technologies. The transition from glass to plastic substrates adds a variety of challenges that reduce process reliability, thus affecting yield.

CTE mismatch between plastic substrates and most deposited materials induces stress which can lead to stress related etch non-uniformity and at worst can cause gross mechanical failure and cracking such as seen on the right of Fig. 1. While, this problem is common to oxides, a-Si:H, and organic TFT systems with regard to deposited metals, inorganic dielectrics used in a-Si:H and oxide TFTs are particularly susceptible to stress failures because of their high deposition temperatures and their relative brittleness.

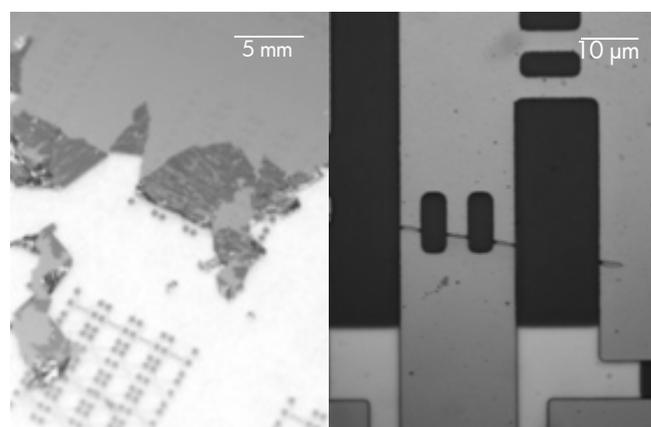


Fig. 1. Gate delamination during develop step in organic TFT process (left), and a data line crack due to poor stress control in an a-Si:H process (right).

Adhesion to the substrate and between films of the TFT stack must also be carefully considered. Most deposited metals have poor adhesion to plastic so adhesion layers must be deposited between the plastic and first metal layer to ensure a good mechanical foundation. Adhesion between layers is also very important as built in stresses discussed above can result in separation of the thin films. Many organic semiconductor systems suffer from this problem as these systems have to resort to low surface-energy and low polarizability dielectrics to obtain maximum electrical performance¹¹⁾. Fluoropolymer dielectrics and fluorinated surface treatments make it extremely difficult to maintain stack integrity through a process flow. Processes as benign as developer spin coating can impart sufficient force to separate films from these dielectrics as can be seen on the left of Fig. 1. While thin film stress issues may be mitigated through

design such as countering stress on opposite sides of the substrate or setting the critical layers at the center of the displays bending plane; and delamination due to poor adhesion can be reduced by creating strap-down structures; it still unclear whether yields can be made as high as those on glass.

Process chemistries must also be adjusted to ensure substrate compatibility. Resist strippers used in most photolithography processes are inherently designed to swell and damage most polymers. This necessitates the use of aqueous strips or dry etching of photoresist which may be corrosive to other metals, or leave a lot of polymer and carbon residues.

In the case of self-aligned imprint lithography, it is critical to maintain a wide etch rate margin and orthogonality between etch chemistries for the various metal layers, dielectrics and semiconductor. Fortunately, a-Si:H, silicon dioxide, and silicon nitride are fairly inert to wet chemistries used to etch metals. However, metal oxides are much less so and metal choices must be made carefully. Organic semiconductors are perhaps the most susceptible to process chemistries as they are easily damaged by plasma bombardment and become more conductive on exposure to oxygen and water. Modern organic semiconductors have made great strides in improving their stability through molecular design^{9,12} yet the rigors of extreme pH, pressures, and temperatures while exposed oxygen and water, make it difficult to maintain electrical performance through a typical display manufacturing process.

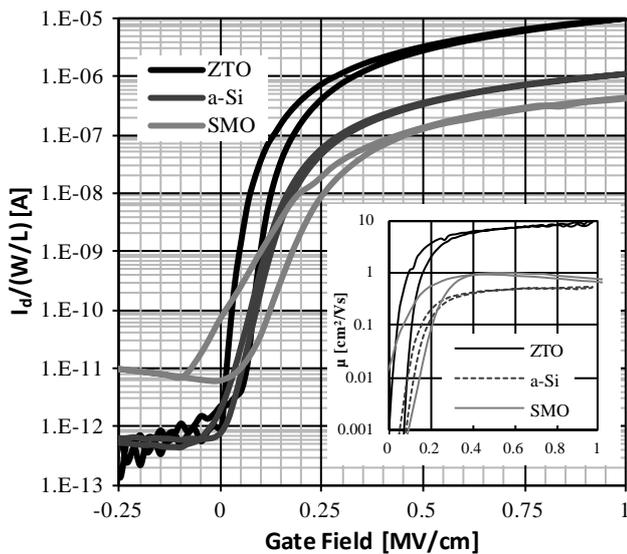


Fig. 2. Transfer curves scaled by W/L in current and by gate field for a Zinc Tin Oxide, a-Si:H and small molecule organic. Inset shows linear mobility for these devices as a function of gate field. All devices have a channel length of 10 μm and are measured at $V_{\text{ds}}=5\text{V}$. The SMO device is

showing negative current and negative gate field to allow for comparison.

4. Electrical behavior

Fig. 2 shows the normalized transfer curves for three thin film transistors. The zinc tin oxide device and a-Si:H device are both bottom gate back-channel etch TFTs made on a polyimide substrate using the SAIL process while the small molecule organic TFT is a p-type top gate device which has been made via photolithography on a polymer coated glass wafer. As can be seen, for a similar sized device, the oxide semiconductor can drive over 10 times more current than either a-Si:H or organic device and exhibits electron mobility very near $10\text{cm}^2/\text{Vs}$ (see inset of Fig. 2). Interestingly, the a-Si:H device can drive more current than the SMO device, despite having about $1/2$ the mobility ($0.5\text{cm}^2/\text{Vs}$ vs. $0.95\text{cm}^2/\text{Vs}$, respectively). This is primarily due to the fact that the a-Si:H device has a 300nm SiN ($k=7$) dielectric with over 5 times the gate capacitance of the SMO device which is made with a 430nm fluoropolymer with a dielectric constant of 2. As mentioned above, the choice of dielectric for the SMO device is crucial to achieving high mobility yet as a device it would require more area on the backplane to perform as well as the a-Si:H device. Further, organic devices require thicker dielectrics than the inorganic devices as they are susceptible to damage from the sputtering process of the gate metal deposition and thus require a significantly higher gate voltage. This in turn could potentially require special drive electronics, cause more cross-talk, and consume more power.

TFT stability is equally important as performance, especially for demanding applications such as OLED. Ideally, all device parameters should remain constant during the lifetime of the display. In practice these materials suffer the most from threshold voltage variation due to bias stress which is generally caused by either defects generated in the bottom half of the semiconductor gap (in which the V_t shift is accompanied by a deterioration in the subthreshold slope) or by creation of states in the dielectric or semiconductor/dielectric interface (exhibited by purely parallel shifts in the I-V curves). Fig. 3 shows how the threshold voltage changes for three devices, similar to those above. Here the a-Si:H and SMO device show low threshold voltage shift ($< 2\text{V}$ at 5000 seconds) while the ZTO device has over 4 volts of shift, none showing any significant subthreshold slope degradation. Oxide TFTs have been known in general to suffer from poor negative bias stress¹³ but this can be reduced by using etch stop process and/or back channel passivation¹⁴ yielding very stable devices.

For back-channel etch devices some form of passivation seems to be required regardless of stability problems. Adsorbates, primarily moisture on the exposed side of the semiconductor¹⁵ can

create trap states that in turn induce conductive back-channels which, because of their poor capacitive coupling to the gate, can be slow to discharge and cause considerable hysteresis as can be seen in Fig. 4. After being generated, the conducting back-channel takes on the order of 10's of seconds to minutes to be turned off depending on how negative the gate bias is. If the device is rapidly switched on and off such as it would in a display and the positive field is stronger than the negative field, the back-channel has a tendency to become increasingly conductive, overwhelming the off-state behavior of the device. In this respect, it seems requirements to protect the semiconductor from the environment are similar for both inorganic and organic semiconductors.

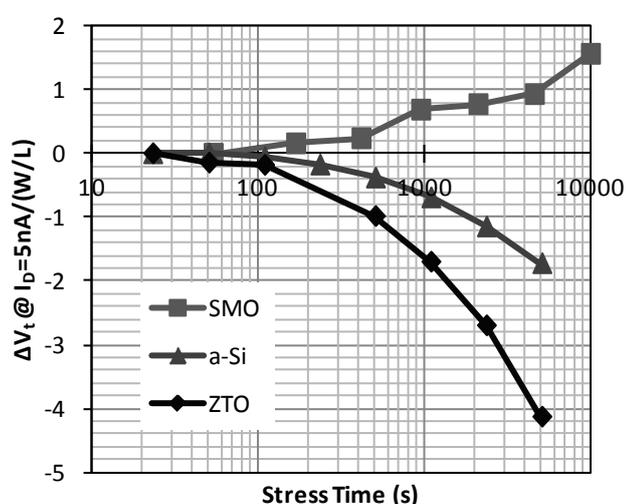


Fig. 3. Threshold voltage shift caused by negative bias stress. a-Si:H and ZTO devices are stressed at -20V V_g s and 0V V_d s, while SMO devices are biased at -60V V_g s and -20V V_d s (in the ON state).

5. Summary and Conclusions

Transitioning active matrix backplanes to plastic substrates promises greatly improving the form factor and robustness of flat panel displays along with potentially opening totally new classes of products. Yet, a number of technical challenges must be overcome in order to see plastic flat-panels begin to displace glass ones. Of the three main candidate material systems, a-Si:H, MCO, and organic semiconductors, it seems that a-Si:H has the lowest technical risk, lowest financial barrier to entry, and best industrial infrastructure. However, its electrical performance is unlikely to satisfy the requirements needed to drive many of the advanced display technologies for which plastic is intended to be used. Here organic semiconductors and multi-component oxides promise to deliver. However, the dielectrics required to drive organic semiconductors, and the necessity to mature a large number of new processes, make organics a risky technology.

Plastic displays driven by multi-component oxides, will likely be introduced soon after a-Si:H based products are established, as long as material stability can be obtained.

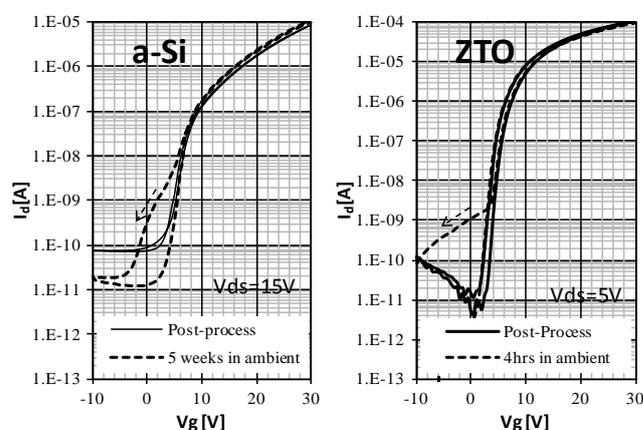


Fig. 4. Transfer curves for a-Si:H and ZTO devices showing the effects of extended exposure to ambient moisture. Back-channel conduction is generated during high positive gate bias, and is exhibited by poor turn-off when the gate is swept negative.

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References

- 1) R.L. Hoffman, B.J. Norris, and J.F. Wager, *Applied Physics Letters* **82**, 733 (2003).
- 2) R.L. Hoffman, *Solid-State Electronics* **50**, 784 (2006).
- 3) H.-J. Kim, et. al., *Journal of the Society for Information Display* **17**, 963 (2009).
- 4) W.B. Jackson, et; al., *Journal of Non-Crystalline Solids* **352**, 1753 (2006).
- 5) T. Koch, J.-S. Yeo, Z.-L. Zhou, Q. Liu, J. Mabeck, G Combs, V. Korhuis, R. Hoffman, B. Benson, and D. Henze, *Journal of Information Display* **12**, 5 (2011).
- 6) L. Zhao, H. Luo, et. al., *Hewlett Packard Technical Reports HPL-2011*, (2011).
- 7) S. Kitson, A. Geisow, J. Rudin, and T. Taphouse, *Optics Express* **19**, 15404 (2011).
- 8) W.A. MACDONALD, *Journal of Material Chemistry* **14**, 4 (n.d.).
- 9) M. Heaney and I. McCulloch, *Flexible Electronics* 261 (2009).
- 10) J. Smith, R. Hamilton, et. al., *Synthetic Metals* (2009).
- 11) J. Veres, S.D. Ogier, et. al., *Advanced Functional Materials* **13**, 199 (2003).
- 12) S. Kola, et. al., *Journal of Polymer Science Part B*: DOI:10.1002/polb.23054
- 13) J.-H. Shin, J.-S. Lee, C.-S. et. al., *ETRI Journal* **31**, 62 (2009).
- 14) K.-H. Lee, J.S. Jung, et. al., *Applied Physics Letters* **95**, 232106 (2009).
- 15) M. Tanielian, *Philosophical Magazine Part B* **45**, 435 (1982).