Amorphous Oxide Transistor Electrokinetic Reflective Display on Flexible Glass

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Abstract

Thin flexible glass substrates represent an enabling technology towards high throughput roll-to-roll manufacturing with exceptional surface quality as well as thermal and dimensional stability. This paper describes the integration of a high performance back-channel etch amorphous oxide TFT backplane with an electrokinetic reflective frontplane on 100 micron thick flexible glass.

1. Introduction

Full-color reflective and flexible displays can potentially provide light-weight, robust, low-power displays for a range of applications including e-readers and digital signage. In addition, the development of roll-to-roll (R2R) processes may significantly change the scaling and cost of manufacturing of displays, opening new markets and application space. However, improvements in substrate quality and thin-film transistor (TFT) backplane design are necessary to achieve the optical performance necessary for bright color reflective media. This work integrates advances in substrate, backplane, and front plane technology, enabling a fully integrated reflective display on flexible glass with a pathway to roll-to-roll manufacturing.

2. Flexible Glass

Highly engineered plastic films have been developed for flexible electronics; and significant progress has been made to improve the surface quality, dimensional stability, thermal stability, and optical transparency. However, continued issues with surface quality and long-range dimensional stability have made scaling the technology challenging. Innovative solutions such as self-aligned imprint lithography (SAIL) can mitigate layer-to-layer alignment errors caused by dimensional instability and provide a path to roll-to-roll backplane manufacturing.[1] However, surface quality, upper processing temperatures, and optical transparency still limit the fabrication of high performance R2R backplanes on plastic substrates.

Ultra-thin flexible glass (<50-200 microns) represents a highly promising substrate material for R2R fabrication of high-performance electronics. Flexible glass features exceptional surface quality, temperature stability, dimensional stability, and optical transparency compared to electronic grade plastic substrates. The surface quality of flexible glass is comparable to glass substrates used in current active matrix display manufacturing. AFM found the R(a) and R(peak-valley) surface roughness to be <0.5 nm and <20 nm, respectively. These values are greater than three times lower than high performance PEN and PET films used in flexible electronics. The hardness of glass also makes it considerably less prone to scratches and other surface defects.

In addition, the upper process temperature of flexible glass for device fabrication is >300°C. While it is possible to form high-performance transistors using amorphous silicon or amorphous oxide TFTs at plastic-compatible temperatures (<250 °C), the best performing devices are typically formed at 300 °C or higher. Flexible glass substrates also have a low coefficient of thermal expansion (3-5 ppm/°C) making conventional photolithography processes possible over large area substrates.

Finally, the optical transmission of flexible glass, limited by surface reflection, is >90% over the entire visible spectrum and extends into the UV. This high transmission is essential for optically engineered stacked reflective display technologies. Overall, flexible glass provides an exceptional combination of process and patterning compatibility with the potential to be integrated in roll-to-roll process tools.

3. Amorphous Oxide TFTs

Amorphous oxide TFTs provide improved mobility (>10 $cm^2/V\cdot s$) and stability compared to amorphous silicon TFTs. This is combined with improved uniformity and reduced process complexity compared to poly silicon TFTs, generating significant interest in the integration of amorphous oxide TFTs into large LCD panels, high resolution displays, and AMOLED panels. For bright, stacked reflective displays the high mobility of amorphous oxide TFTs allows the transistor size to be scaled down accordingly, increasing the clear aperture and improving light efficiency.

The back-channel etch (BCE) TFT process requires one less masking step, reducing process cost and complexity and also makes it compatible with R2R patterning processes such as self-aligned imprint lithography. However, back-channel etch processes have been significantly more challenging to develop due to challenges with etch selectivity and damage to the back surface of the oxide semiconductor channel during source drain patterning. As a result, we previously described the process and integration of indium-zinc-oxide (IZO) TFTs using a lift-off process to pattern the source drain metal, avoiding damage induced during source drain etch.[2] However, the lift-off process is not highly scalable or compatible with R2R processes such as self-aligned imprint lithography.

Here we describe a robust low-mask count single metallization back-channel etch process used to fabricated fully integrated TFTs using both indium-gallium-zinc oxide (IGZO) and zinc-tin oxide (ZTO). In these devices PECVD SiO_2 is used for the gate insulator and molybdenum source and drain electrodes are dry etched and stopped on the back channel. The devices are then passivated using a zinc-tin-silicon oxide (ZTSO) interface layer and then PECVD SiO_2. The 25 nm ZTSO layer is used to minimize the threshold voltage shifts observed during the subsequent PECVD process. A schematic cross-section of these devices can be seen in Figure 1. Figure 2 and Figure 3 show transfer characteristics for BCE ZTO and IGZO devices with mobility of 6 $cm^2/V\cdot s$ and 10 $cm^2/V\cdot s$, respectively. These single metallization back-channel etch and passivation processes are compatible with both ZTO and IGZO channel materials and are simpler than bimetal back channel etch processes previously described.[3]

4. Electrokinetic Reflective Display Technology

In addition to amorphous oxide TFT technologies, HP also has developed a R2R compatible electronic reflective media. This novel front-plane technology utilizes layered subtractive colorants (CMY) to achieve bright colors and overcome inherent limitations associated with side-by-side color filter approaches. Using this approach we demonstrated color exceeding Specifications for Newsprint Advertising Production (SNAP) standards for stacked color. The details of the architecture and operation of this front-plane technology have been previously described.[4]

While this technology has demonstrated exceptional color, the optical performance can be further improved by engineering the stacked architecture. For example, color shifts and shadowing due to parallax impact the device viewing angle and become small when the distance between the high contrast light modulating layers are less than the pixel size and close to the reflector. Therefore, approaches which reduce the total stack thickness are important to optimal performance. The electronic front-plane is made using a roll-to-roll process on plastic substrates and can be made very thin. However, most conventional active matrix backplanes are fabricated on >0.5 mm thick glass which are the thickest layer in the device stack and increase the impact of parallax. The integration of 100 micron thin flexible glass provides a roll-to-roll compatible substrate for high performance electronic backplanes while simultaneously optimizing the optical performance of stacked reflective color displays.

5. Integration

The entire set of materials described – flexible glass substrates, amorphous oxide TFTs, and electrokinetic reflective media – are all compatible with roll-to-roll processes. In a first step towards full roll-to-roll integration, a bond-debond process was utilized to enable fabrication of the amorphous oxide backplane on flexible glass. For these demonstrators, ZTO TFTs similar to the devices described above were fabricated; these devices utilized a 150 nm ALD Al_2O_3 or a 300 nm PECVD SiO_2 gate dielectric and had an upper process temperature of 225 °C (limited by the bond-debond process). Figure 4 and Figure 5 illustrate a cross-section schematic and transfer characteristics for a typical device on flexible glass. Figure 6 shows the two single TFT pixel architectures employed in this work with a minimum size storage capacitor to optimize optical transmission (clear aperture of 85% and 95%) and improve stacked reflective color. After fabrication the backplanes were released from their carrier substrates and the electronic ink based electrokinetic frontplane technology was laminated to the glass. Figure 7 shows operational images of a 1.4" diagonal 35 x 35 ZTO TFT pixel array with 750 x 750 micron pixels as shown in Figure 6a. These arrays have been integrated with both cyan and magenta ink. Figure 8 shows operational images of a 3.5" diagonal 128x128 array with 500 x 500 micron pixels as shown in Figure 6b.

6. Conclusions

We have developed a robust back-channel etch process for both IGZO and ZTO and integrated a zinc-tin-silicon oxide passivation interface layer to minimize device changes induced during PECVD passivation. This oxide TFT process has been integrated with ultra-thin flexible glass and combined with a color electrokinetic reflective media. To the best of our knowledge this is the first demonstration of a display with a high performance amorphous oxide TFT backplane fabricated directly on a flexible glass substrate. The amorphous oxide TFT technology and thin, high optical transparency glass substrates are enabling technologies for high performance stacked reflective displays. The extension of both technologies to R2R manufacturing may revolutionize the infrastructure, cost, and scaling associated with fabricating displays.

7. References

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[3] S. M. Lee, et al. "Control of Threshold Voltage in Back Channel Etch Type Amorphous Indium Gallium Zinc Oxide Thin Film Transistors." *Society for Information Display Digest 2011,* p. 104.

[4] T. Koch, et al. "Novel flexible reflective color media with electronic inks." *Journal of Information Display*, v. 12,no. 1, p. 5-10, 2011.

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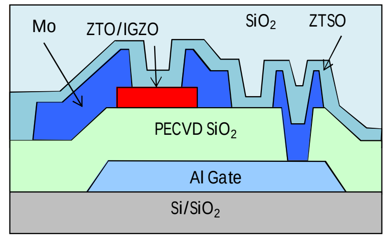


Fig. 1 Schematic cross section of discrete amorphous oxide TFTs
100 nm Al gate, 200 nm PECVD SiO_2 (ε_r ~4) gate insulator, 50 nm oxide semiconductor, 100 nm sputtered Mo source and drain, 25 nm ZTSO/200 nm PECVD SiO_2 passivation.

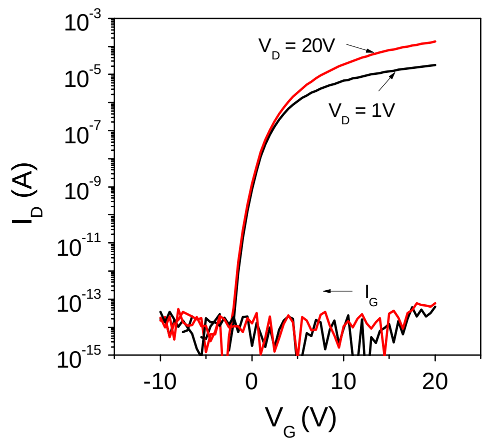


Fig. 2 Passivated BCE ZTO TFT
Linear and saturation transfer characteristics for ZTO BCE TFTs (W/L = 110/10 μm).

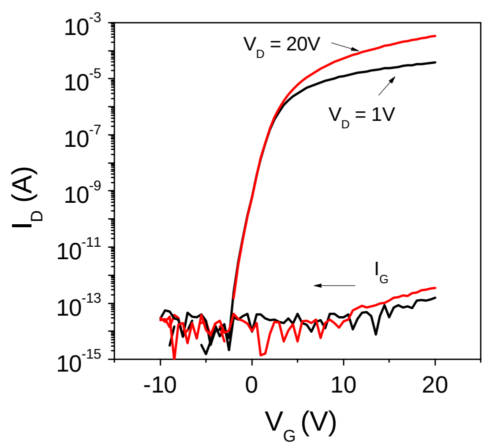


Fig. 3 Passivated BCE IGZO TFT

Linear and saturation transfer characteristics for ZTO BCE TFTs (W/L = 110/10 μm).

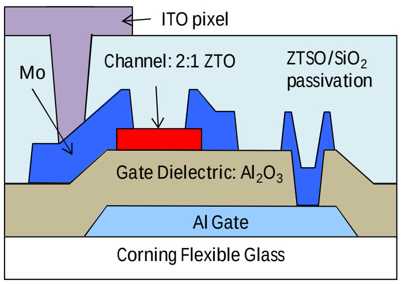


Fig. 4 Schematic cross section of active matrix oxide TFT integrated on flexible glass

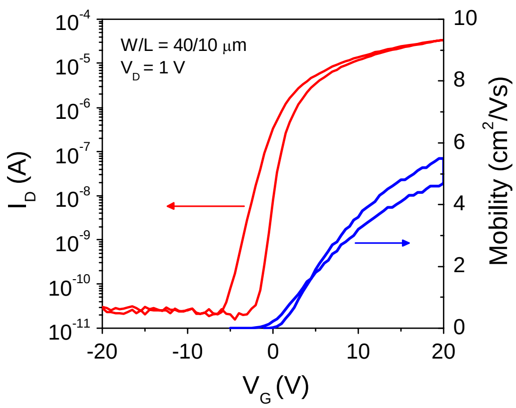
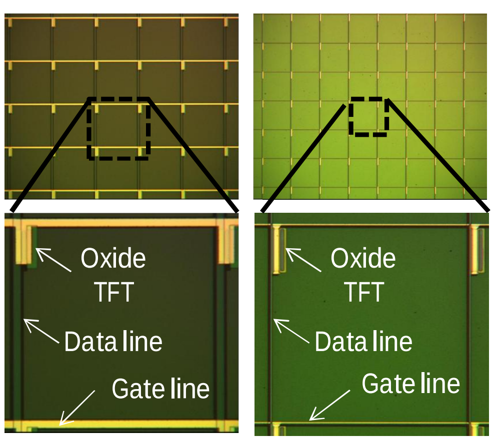


Fig. 5 Integrated ZTO TFT on flexible glass
Transfer characteristics for ZTO TFTs on flexible glass substrate with Al gate, 150 nm Al2O3 (ε_r ~ 8) gate insulator, 50 nm ZTO, Mo source and drain, ZTSO/SiO2 passivation.



(a) (b)

Fig. 6 Optical micrographs of backplane

Two high clear aperture (CA) backplanes used in this work (a) 750 micron pixels, 85% CA (b) 500 micron pixels, 95% CA.

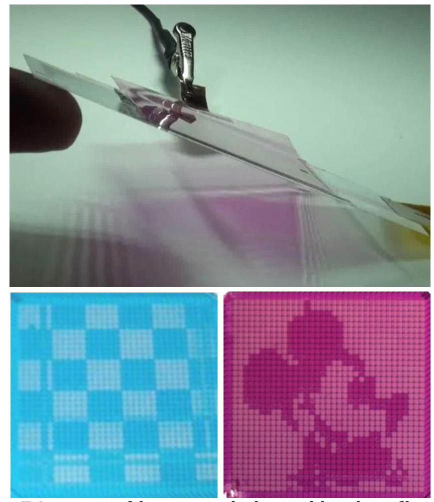


Fig. 7 Images of integrated electrokinetic reflective display on flexible glass backplane. 35x35 pixel 1.4" diagonal display using 750 micron pixels and 85% clear aperture with (bottom left) cyan ink and (bottom right) magenta ink.

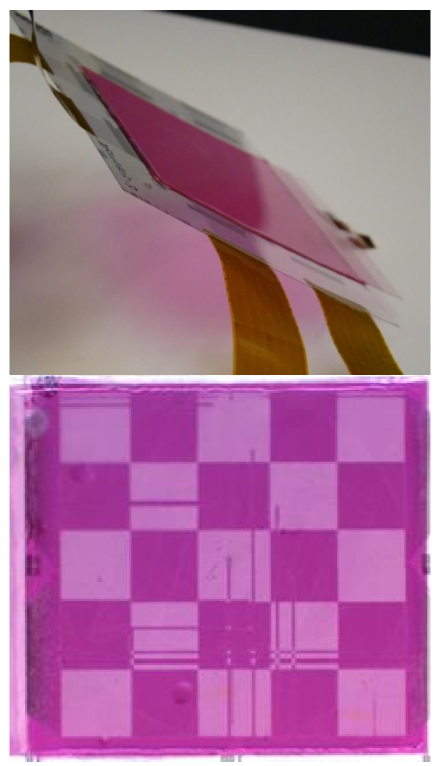


Fig. 8 Images of integrated electrokinetic reflective display on flexible glass backplane 128x128 pixel 1.4" diagonal display using 500 micron pixels and 95% clear aperture with magenta ink.