

Managing mechanical stress in flexible active-matrix backplanes

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ABSTRACT

Flexible displays will be used first in curved, hand-held and wrist-worn devices, and later in panoramic and surround applications. These displays will be made with thin plastic or metal substrates and encapsulation. The TFT backplanes experience mechanical stress during their fabrication and when they are flexed in displays. Mechanical results obtained with flexible TFT backplanes provide guidelines for the mechanics of flexible displays.

INTRODUCTION

Thin-film transistor (TFT) backplanes experience mechanical stress during manufacture and in use (Wagner et al., in press). During manufacture the stress is managed to keep the TFT films or the substrate from breaking, and to obtain accurate overlay registration in photolithography. Because flexible substrates are more deformable than rigid glass plates they break less easily. But being more deformable, they also are less dimensionally stable. TFT films on flexible substrates break and misalign more easily than on glass plates.

The strain ε is the relative ($\Delta L/L$) extension (defined positive) or shrinkage (negative) under the action of stress σ , which is the force applied to a cross sectional area. ε and σ are related by Young's modulus E , which is a material property.

$$\sigma = E \cdot \varepsilon \quad (1)$$

The goals of TFT backplane mechanics are: (1) to keep the strain ε below a critical, fracture, value, which is typically 0.01 (1%) for TFT materials; and (2) to keep ε constant during fabrication to ensure accurate overlay alignment at successive photolithographic steps.

In today's a-Si TFT backplanes for AM-LCDs the glass plate dominates the mechanical properties, because it is much stronger than the TFT films. The TFTs must comply with any changes in the dimension of the glass plate, for instance by thermal expansion. The TFTs are strained much

more than the plate. The TFTs do not break during fabrication because the coefficient of thermal expansion α of glass is low. The thermal expansion or contraction of the glass during fabrication (possibly added to built-in stress of the TFT films) does not exceed the fracture strain of the TFTs. The TFT layers must be made to adhere well, because they break when they delaminate. The forces ($\sigma \cdot d$) acting per unit length of the cross-sectional areas of the film and of the substrate are opposite and equal. This force balance gives the ratio of the strains in the device film and the substrate, ε_f and ε_s , in function of their Young's moduli and thicknesses, E_f , E_s , d_f and d_s :

$$\varepsilon_f / \varepsilon_s = E_s \cdot d_s / E_f \cdot d_f \quad (2)$$

Table 1 lists examples for the four possible combinations of E . The substrate always is thicker than the device film, $d_s \gg d_f$. Therefore a stiff substrate dominates any device film, and a compliant substrate dominates a compliant device film. In these cases most of the strain will develop in the device films, which will conform to a dimensionally stable substrate. However, a stiff device film on a compliant substrate may make the strengths of the film and the substrate approximately equal:

$$E_f \cdot d_f \cong E_s \cdot d_s \quad (3)$$

(Example: $E_f \cong 200$ GPa, $E_s \cong 5$ GPa, $d_f \cong 1 \mu\text{m}$, $d_s \cong 50 \mu\text{m}$). When the strains in film and substrate become equal, both may change noticeably at many process steps. This is the most complicated situation (Young et al., 2003). We describe its

Table 1 Combinations of device films and flexible substrates

Films \Rightarrow Substrate \Downarrow	Stiff (high E_f)	Compliant (low E_f)
Stiff (large E_s)	ITO / glass	OLED / steel
Compliant (small E_s)	Si TFT / polymer	OTFT / polymer

consequences and show one technique for managing it.

The TFT substrate can be stabilized for processing by bonding it to a stiff, dimensionally stable carrier. Thermoplastics that are resistant to the process chemicals are used as adhesives. At the end of processing the TFT backplane is detached by melting the adhesive, without melting the substrate. Therefore the process temperature for a bonded substrate is lower than for a free-standing substrate.

We have been working with free-standing substrates that are held in a loosely fitting frame and face down for the deposition of a-Si and SiN_x. In this paper we describe experiments and results obtained with such nearly free-standing substrates. These results will be also useful for eventual roll-to-roll fabrication.

STRESS MANAGEMENT

The first goal of stress management is to prevent device or substrate fracture by keeping the strain below a few 0.1%. This goal is easy to attain in display use, if the display is designed properly, and is packaged for mechanical strength and for protection against bending strain. Strain during backplane fabrication is more difficult to control. During some period of deposition at elevated temperature the built-in strain and differential thermal strain may add to exceed the fracture strain.

Any degree of stress caused by mismatch strain will make the TFT backplane curve. Stiff a-Si TFT films can cause compliant polymer substrates to curve very much. When such structures are flattened the TFTs may break. When the curvature changes during fabrication, the size of the flattened substrate will change, too, as seen in Equation (5) below. This change of size causes misalignment in the overlay registration at successive photolithographic mask levels. Short of device fracture, this misalignment is the most serious challenge at present to the fabrication of a-Si TFTs on polymeric substrates. To avoid it the strain in the backplane must be kept constant.

Sources of strain

Mechanical mismatch strain can develop during the fabrication, encapsulation, and use of TFT backplanes. In fabrication strain is (i) built-in during film growth, or is developed by (ii) differential thermal expansion or contraction during heating and cooling, and (iii) differential humidity expansion or contraction:

$$\begin{aligned} \varepsilon_{mismatch} &= \varepsilon_0 + \varepsilon_{thermal} + \varepsilon_{humidity} \\ &= \varepsilon_0 + \Delta\alpha \cdot \Delta T + \Delta\beta \cdot \Delta(\%R.H.) \end{aligned} \quad (4)$$

We assume that the thermal strain is zero at the growth temperature. Once substrate material and

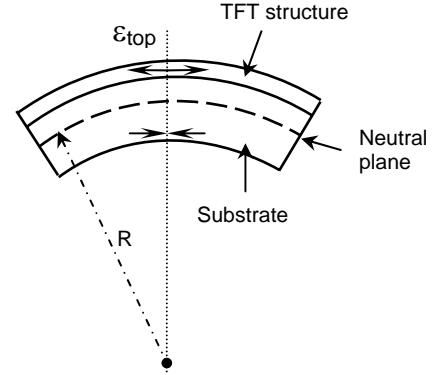


Figure 1 A film-on-foil structure bent to a cylindrical roll. When a TFT backplane of thickness d is rolled to a radius r , the thin film is put into a well defined strain, which is tensile when the film is on the outside of the roll and compressive on the inside.

process temperature have been selected, one has little control over thermal and humidity expansion. Therefore we focus on the control of stress by controlling the stress built in during film growth.

Stress produced by external bending

Bending a substrate strains a film on its surface. This is shown in Figure 1. When bent to a cylinder of radius R of the neutral plane, the strain ε is proportional to the additional radius to the film plane. For a *stiff* film on a *stiff* substrate or a *compliant* film on a *compliant* substrate the neutral plane lies in the middle of the backplane of thickness $d_s + d_f$. The additional radius is $(d_s + d_f) / 2$. The bending strain in the film is given by

$$\varepsilon_{bending} = (d_s + d_f) / 2R \quad (5)$$

Note that strain and radius are reciprocal. For a *stiff* TFT film on a *compliant* substrate $\varepsilon_{bending}$ is less than in Equation (5) (Suo et al., 1999). A display is made flexible by keeping $(d_s + d_f)$ small. It becomes most rugged when its electronics are placed in the neutral plane by meeting the following condition for substrate and encapsulation (Suo et al., 1999):

$$E_s \cdot d_s^2 = E_e \cdot d_e^2 \quad (6)$$

Built-in strain produced by film growth

Device films typically develop built-in strain during growth. Atoms deposited in non-equilibrium positions cause built-in stress. When the films are deposited on a compliant substrate, the resulting built-in strain can produce strong curvature. Figure 2 illustrates the curvature produced by the deposition of a-Si TFT films on a compliant substrate. The stress built into the SiN_x film. depends on the radio frequency power used for

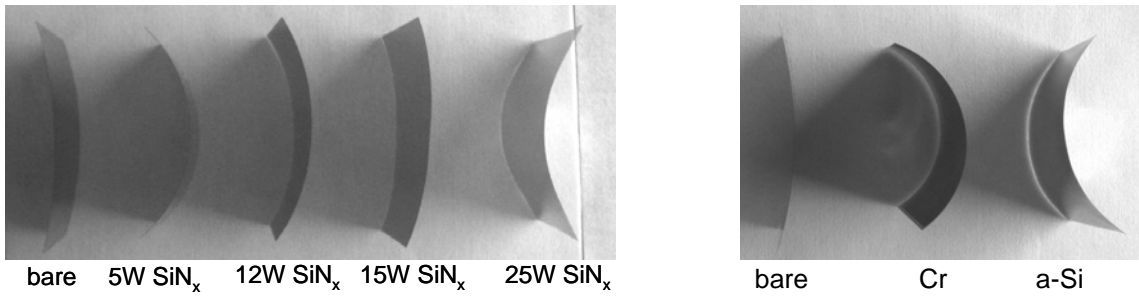


Figure 2 Stress-induced curvatures by films of (a) SiN_x deposited at five deposition powers and of (b) Cr and a-Si, all on $51\text{-}\mu\text{m}$ thick Kapton® E polyimide substrates. The 300-nm (5W) to 500-nm (25W) thick SiN_x and the 250-nm a-Si films were deposited at 150°C ; the thermally evaporated Cr film is 80 nm thick. The built-in stresses of Cr and a-Si films are tensile and compressive, respectively. The films are on the left side of the substrates (Cheng, 2004).

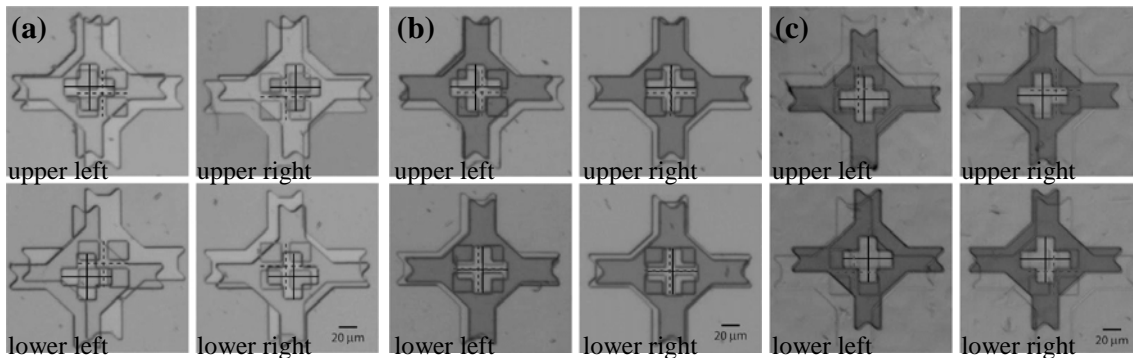


Figure 3 Overlay misalignment between the first, bottom-gate, and second, source/drain, photolithography levels in back-channel etched a-Si TFT process with (a) 5W gate SiN_x , (b) 12W gate SiN_x , and (c) 25W gate SiN_x . The frames lie 52 mm apart near the corners of the 70-mm square substrate. The dashed crosses mark the center at the gate mask level and the solid crosses the centers at the source/drain mask levels. The sample is seen to shrink substantially with 5W SiN_x , slightly with 12W SiN_x , and expand substantially with 25W SiN_x (Cheng, 2004).

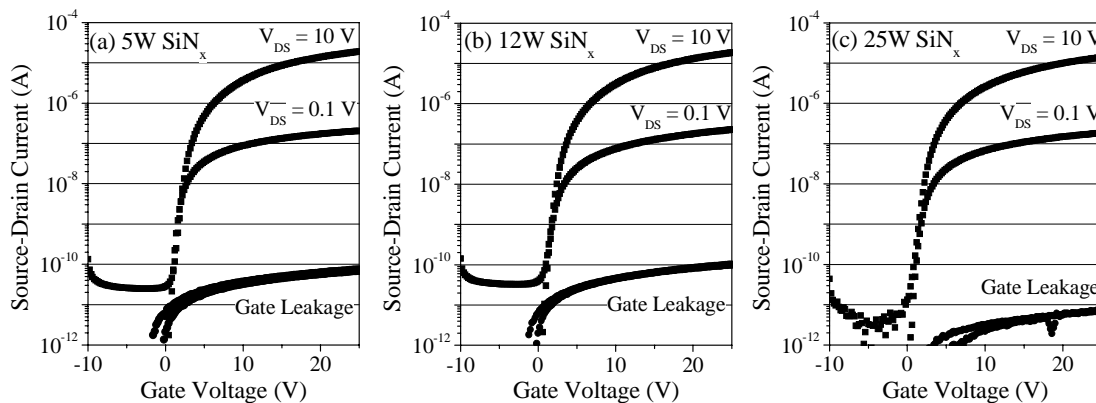


Figure 4 Transfer characteristics of TFTs of Figure 3(a), (b), and (c). The TFT gates are $80\text{ }\mu\text{m}$ wide and $10\text{ }\mu\text{m}$ long. The OFF and leakage currents are instrument-limited shunt values. The ON current at $V_G = 25\text{ V}$ is seen to drop slightly with decreasing tensile strain in the TFT. This drop results from the reduction of tensile strain in the TFTs (Cheng, 2004).

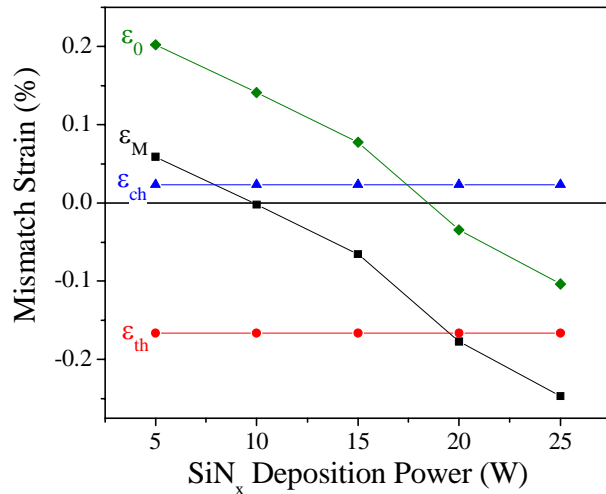


Figure 5 Mismatch strain ε_M extracted from the radius of curvature, and its components for samples of SiN_x deposited on 50- μm thick Kapton® E foil. The horizontal line denotes zero strain. The film is in tension at positive strain and in compression at negative strain. (Cheng, 2004).

plasma-enhanced chemical vapor deposition. The strain in the film can be extracted from the radius of curvature using a modified Stoney equation (Suo et al., 1999). By varying the RF power we can dial a stress value into the SiN_x film, and can adjust the total stress in the entire TFT backplane so that it becomes flat (Cheng, 2004).

Adjusting the strain of the SiN_x gate dielectric enables accurate overlay alignment of photolithographic masks. Figure 3 shows how the alignment between the bottom gate and the top source/drain levels changes with varying RF plasma power in the deposition of the SiN_x gate dielectric. In the TFT transfer characteristics of Figure 4 it can be seen that the SiN_x strain has only a minor effect on the TFT performance. Adjusting the built-in strain in the SiN_x is a useful tool for obtaining mask alignment in a-Si TFT fabrication on free-standing polymer substrates.

The mismatch strain $\varepsilon_{\text{mismatch}}$ (or ε_M) in a sample can be evaluated from radius of curvature data like those shown in Figure 2. The built-in strain ε_0 can be calculated from literature values for α and β , and measured values of ΔT and $\Delta(\%R.H.)$, using Equation (4). $\varepsilon_{\text{mismatch}}$ and its components for a group of SiN_x / polyimide foil samples are shown in Figure 5.

DISCUSSION

During fabrication a-Si TFTs may break more easily on polymer substrates than on glass, because the differential thermal strain $\Delta\alpha \cdot \Delta T$ can

be large. For TFT performance it is desirable to keep the same high process temperature on polymer substrates as on plate glass substrates. Therefore polymer substrates with low coefficients of thermal expansion are of advantage. Cutting the TFT circuits into mechanically isolated islands is also known to relieve stress on the TFTs and keep them intact. The next important issue becomes accurate mask overlay alignment. The backplane must have identical dimensions at each photolithographic step. Various techniques are under study to keep dimensions stable. One is to bond the substrate to a rigid temporary carrier. Another, described in this paper, is to adjust the stress in a device layer such that the backplane dimension remains constant. Local patterning also has an effect on the local dimensions of the backplane. The effects of local patterning have yet to be studied.

CONCLUSION

A stiff device film on a compliant polymer substrate makes the most demanding TFT backplane in terms of stress control. The foremost goal of stress management in TFT backplanes is to keep them from breaking. While this goal is easily met for bending by external force, it is more challenging during the temperature cycles associated with TFT fabrication. The second goal is to keep the film/substrate package dimensionally stable. Dimensional stability can be achieved by adjusting the stress in the SiN_x gate dielectric layer. This mechanical adjustment is found to have little effect on the electrical characteristics of the TFTs. Other layers, for example those used for substrate passivation, may be used for the same purpose.

Acknowledgements

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