ON INTEGRITY OF FLEXIBLE DISPLAYS

Piet C.P. Bouten*

1. INTRODUCTION

Nowadays two display types are dominant in the display market: the bulky cathode ray tube (CRT) and liquid crystal displays (LCD). Both types use glass as substrate material. The LCD display is the dominant player for mobile applications, in for instance mobile phones and portable computers. In the development of displays and their applications a clear interest exists to replace the rigid rectangular display cells by free-shaped, curved or even roll-up cells. These types of applications require flexible displays.

Different types of flexible displays have been presented recently.[1] Section 2 gives a short introduction to these display types. To realize the flexible displays, flexible substrate materials such as thin glass,[2] metal foil,[3] and/or polymer are used as substrate materials instead of rigid (rectangular) glass sheets. Requirements for (polymer) substrates, used to realize flexible displays are treated in section 3. To fulfill the requirements, functional brittle layers are applied on the polymer substrates.

Various types of failures encountered in flexible displays are presented in section 4. Dominant failure types are related to the application of thin brittle layers on polymer substrates. An example of such a failure type, the tensile failure of a brittle ITO layer on a polymer substrate, is presented in more detail in section 5. This example shows that formalisms, used in scaling laws and reliability predictions for the (standard) glass displays are not (completely) valid for flexible displays. In the final discussion the need for scaling laws and reliability models for flexible displays is emphasized.

---

* Piet C.P. Bouten, Philips Research Laboratories, 5656AA Eindhoven, The Netherlands.

2. TYPES OF FLEXIBLE DISPLAYS

Slikkerveer[1] defines a flexible display as "a flat panel display made using thin, flexible substrates, where the substrate can be bent to a radius of curvature of some centimetres without loss of functionality." An example of a flexible display is given in figure 1. This display, a flexible CTLC (Cholesteric Texture Liquid Crystal) cell, is only 250 μm thick and can be bent down to a radius of two centimeter while operating.[4] The size of the presently shown display cell is 150*125 mm^2.

Four application areas are recognized for flexible displays:

1. Flat displays. In this area the main points are the ruggedness of the cell, the low weight and the freedom to use non-rectangular devices.
2. Curved displays. The display is used at a constant, predefined, curvature, for instance on a (curved) surface of a handheld device.
3. Displays on flexible devices. The display bends as the substrate bends. An example is a display in a smartcard.
4. Roll-up displays. These displays are frequently rolled and unrolled during application.

In application areas 2–4 the display cells are mechanical loaded on purpose. In the second application area it is loaded once when bending the cell in its final shape. Areas 3 and 4 require more loading cycles. Not only functional requirements on the display performance (the image quality), but also structural requirements on the display construction and the materials are needed.

Many presently used flat panel displays with glass substrates, such as LCD cells in a mobile phone, are used in constructions that prevent loading of the display cell. Excessive loading of these cells leads to glass failure. In mobile phones, for instance, display cells are always incorporated at a certain depth in the body to prevent glass fracture in a drop test. At this point the flexible displays differ clearly from the

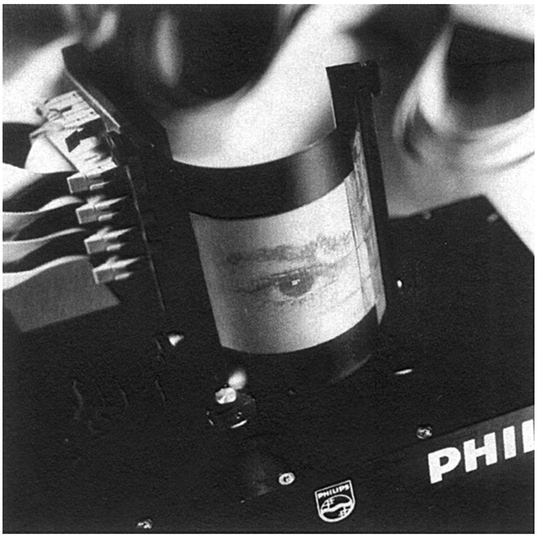

Figure 1. A flexible liquid crystal display.

presently used glass-based flat panel displays. To bend the display, a mechanical load has to be applied on the cell. This load leads to a stress distribution in the display. Upon bending the inner surface is loaded in compression and the outer surface in tension. Knowledge about the acceptable stresses and/or strains of the various display parts is required for reliability modeling.

Flexible displays require not only thin, flexible substrates, but also thin display effects. In most flat panel display the display effect is sandwiched between two substrates. Patterned electrodes on both substrates are used for localized addressing. Three thin display effects are mentioned here:

(3) The liquid crystalline material in a LCD display acts as a light switch. The thickness of this layer is 1–10 μm. LCD displays require accurate cell gap control. This can be achieved with flexible substrates (fig. 1).[4]

(3) The OLED (organic light emitting) displays use light emitting organic molecules. They are incorporated in a very thin (< 1 μm) functional stack. The functional display layer is extremely sensitive to water and oxygen. This sets tough requirements to water and oxygen permeation rates of the substrates.[5]

(3) Electrophoretic displays, for instance an E-ink display,[3] use colored charged particles and a colored liquid. They are encapsulated in an about 50 μm thick polymer film.

High performance displays, such as color displays on mobile phones and computer screens, require high image refresh rate in combination with high display brightness. The patterned electrode structures in these "active matrix" devices[4] contain electronic switches in the display area. High performance active matrix devices are silicon-based.

3. SUBSTRATES

Various types of flexible displays sets different requirement to the substrates. In general, the display substrates need to be transparent and of good optical quality. During display processing, they must withstand a number of chemicals, such as organic solvents and/or strong acids/bases. Although frequently the process temperature can be lowered relative to that of glass, the substrates should be able to withstand temperatures between 150°C and 300°C. The maximum temperature determines to a large extend the selection of the base substrate material. To give an example: the deposition of polycrystalline silicon for high performance active matrix displays requires a maximum process temperature of about 275°C.[6] This temperature requirement limits the substrate selection seriously.

Properties of base polymer films are often not appropriate for display production processes and display applications. Important parameters, like permeability and solvent resistance are inferior to those of glass. To improve the performance of the polymer sheets, several coatings are applied on a base polymer film (fig. 2). Functional coatings like a solvent-resistant and/or scratch resistant coating are either polymer-based or a combined organic/inorganic system. These layers are a few microns thick. Other functional coatings are thin (< 150 nm) fully inorganic layers. So is the transparent conductor ITO (Indium Tin Oxide) used as electrode material. A hermetic transparent permeation barrier is required to guarantee sufficient lifetime

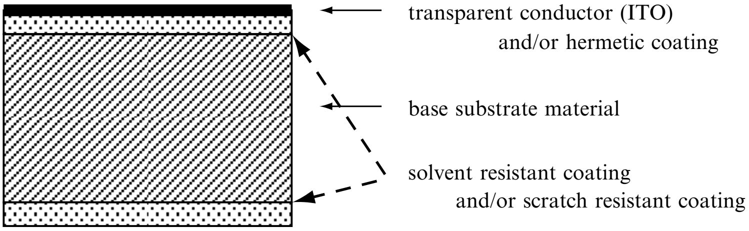

Figure 2. A schematic representation of the cross section of a flexible display substrate.

for the OLED cells. The low water permeation rate ($< 10^{-6}\,\mathrm{gr/m^2/day}$) can only be realized when (transparent) inorganic layers are applied on the polymer substrate.

To achieve sufficient flexibility for the device, the selected substrate thickness is in the 50–200 μm range. Due to thermal expansion differences of the layers, a stress distribution will be present over the thickness of the multi-layer substrate. This leads to warping of the freestanding film. Processing of strongly warped films is not preferred.

The thin (< 150 nm) inorganic (brittle) layers have in general a significantly smaller failure strain than the base substrate material. They limit seriously the allowed deformations of the substrates and the cells. Failure of these brittle layers is a serious point of concern in the discussion on integrity of flexible displays. In the next section attention will be paid to several failure mechanisms, observed in flexible display cells and substrates. In section 5, some aspects on the failure of an ITO layer are described in more detail.

4. FAILURE TYPES

A complex interplay between residual stress distribution, cohesive and adhesive properties of the various layers in the stack, and the location of a critical defect determine how a crack proceeds in a product. Some examples of evolving cracks will be given.

In the previous section it is indicated that the basic substrates require processing at temperatures above 150°C. The substrates therefore should have a high glass transition temperature. The highly transparent substrates are amorphous or semi-crystalline. At ambient temperatures, they are in the glassy state. This can also be seen from the failure behavior. Figure 3 shows a strongly bent flexible LCD display. In the LCD display a cell gap between the two substrates is filled with the liquid crystalline material. A crack has started at the lower cutting edge of the upper substrate and runs in the strongly curved substrate, loaded in tension. Around the crack the gap between the substrates increased, and the LC material is withdrawn. The crack was initiated at an edge defect. This mechanism is similar to that observed in glass sheets. The quality of the cutting edge determines the failure strain. The sample shows a dominant brittle failure behavior for the polymer substrate.

At ambient conditions usually a biaxial compressive stress is present in the brittle top layer of the substrate. At high biaxial stresses a characteristic delamination pattern, the “telephone cord” structure is frequently observed.[7] Figure 4 shows an AFM image of this structure, observed for an ITO layer on a polymer substrate. From the characteristic sizes an estimate for the adhesion quality can be obtained.

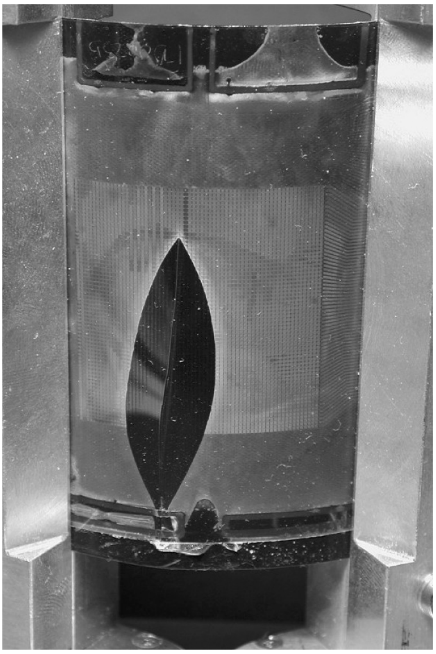

Figure 3. Edge failure of the upper substrate of a flexible LCD cell upon bending.

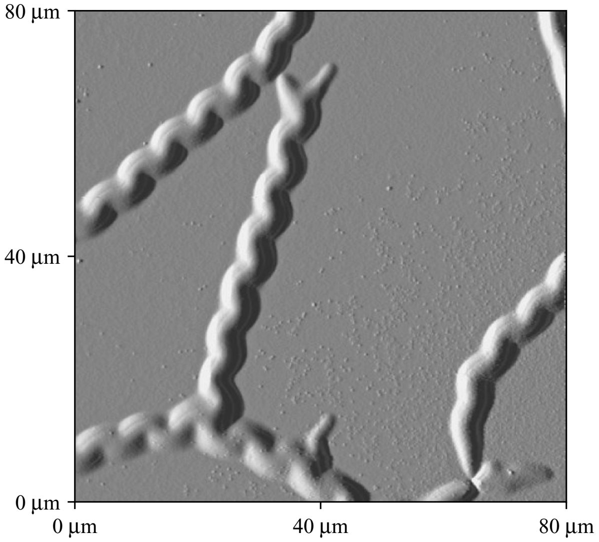

Figure 4. "Telephone cord" type delamination pattern due to biaxial compressive stress in the top layer.

A seal line is used to connect both substrates in the construction of flexible display cells, for instance at the circumference of the cell. Upon bending serious stress concentrations occur at the mechanically loaded seal line. This may lead to preferential failure near this seal line. of the some layers on the substrate. Figure 5 shows crack patterns in the ITO layer on top of a substrate at a location where the seal line is removed. The ITO layer is partly removed with the seal line.

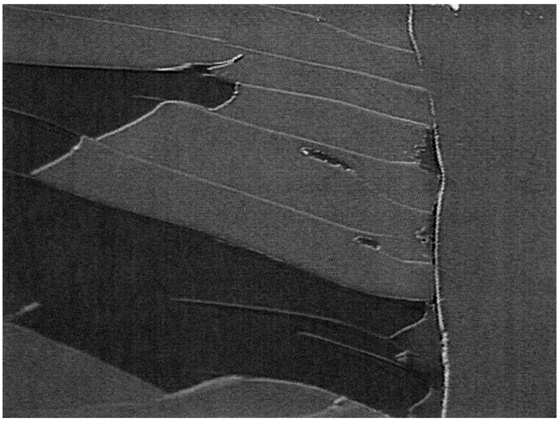

Figure 5. Crack patterns in the ITO layer at the location of the removed seal line (left).

A more detailed experimental study on the propagation of cracks in the multilayer structure of model substrates for flexible displays[8] clearly shows an interaction of the cracks in the brittle layer and cracks in a polymer hard-coat layer.

5. ITO TESTING

We will now focus on the failure of the transparent conductor (ITO). A tensile test is used in combination with resistance measurements[9, 10] to determine the critical failure strain of the brittle transparent conductor (ITO) on the polymer substrate. The strain, determined directly from the displacement of the clamps[9] is systemically too high. To circumvent this problem the displacement can be measured on the sample.[10]

The two point bending test,[11] schematically represented in figure 6, has no clamping problems. A rectangular sample of the film (length 80 mm, width 15 mm) is placed between two parallel plates. At the location with the lowest curvature radius,

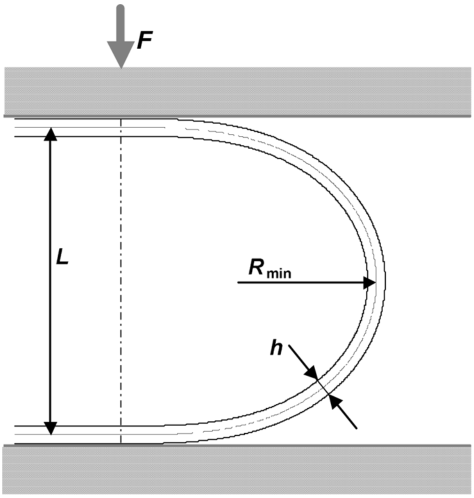

Figure 6. Geometry of the two point bending test.

R_{min}, the largest tensile strain is present at the outer surface. For a symmetrical sample the strain at this location is $\varepsilon_{max} = 1.198\, h/L$, where h is the sample thickness and L the distance between the neutral lines. The faces of the clamps isolate the sample electrically from the machine frame. In the test the resistance of the ITO layer is determined as a function of the distance L_o between the plates ($L_o = L + h$). The crosshead velocity of the universal testing machine (Instron 5566) during the test is 10 mm/min. The relative resistance increase $\Delta R/R$ is represented as a function of maximum tensile strain ε_{max} in figure 7. The curves, represented in this figure are measured on samples of the same width (15 mm). One sample has a uniform ITO layer over the full width. On the other samples a single ITO line of a defined width is etched.

Up to a certain strain level the resistance is constant. Above this strain an increase in the resistance is observed. The strain corresponding to a 10% resistance increase is used as a critical strain. The significant increase of the resistance is due to the development of cracks in the ITO layer normal to the conductive path. The shape of the curve in figure 7 depends on the ITO line width. A sudden resistance increase is observed for narrow lines, a more gradual increase for the wider lines.

Figure 8 shows the edges of the ITO layer. The cracks, visible in the upper sample surface (uniform ITO layer on top), are due to the cutting process. The cracks are present in a zone near the sample edges that is approximately 200 μm wide. The

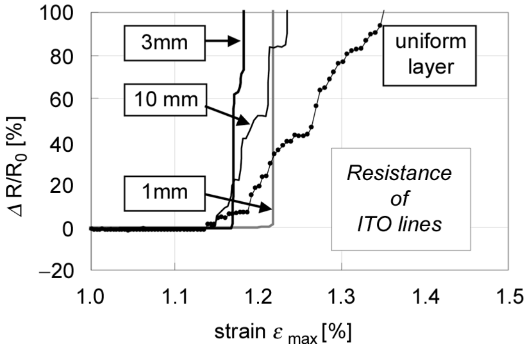

Figure 7. The increase in resistance of ITO layers as a function of the maximum applied strain. ITO lines of different width are tested.

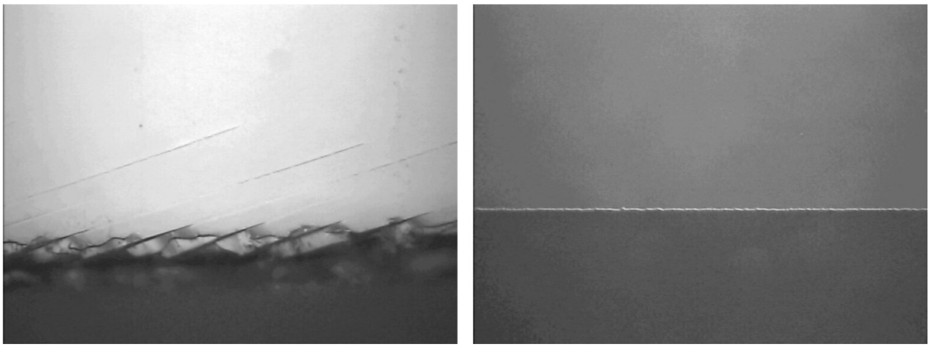

Figure 8. ITO edge of cut sample (left) and etched ITO line (right).

etched ITO layer shows no edge cracks. The crack onset strain for the etched lines and the sample with the uniform ITO layer is nearly similar, about 1.2% for the tested samples. The presence of the edge cracks has no significant effect on the on the critical failure strain of the thin layers.

To get information on the failure strain distribution, larger series of samples are tested in three batches. For one substrate type, samples with a uniform ITO layer and samples with etched narrow ITO lines are measured. For a second sample type only a uniform ITO layer is investigated. Details of the tests are given in table 1.

Experiments on narrow single ITO lines show at a critical failure strain a sudden increase of the resistance, in most cases to infinity. This effect is used to reduce the number of tested samples: Six samples with ten parallel 0.75 mm wide ITO lines at 1.0 mm pitch are etched. The resistance of these ten parallel lines is measured as a function of the plate distance L_o. Failure of a single ITO line is recorded as a step in the resistance-strain curve. From the six samples 60 line failures are recorded.

The data are represented in a two parameter Weibull distribution: $P = 1\text{-}\exp(\varepsilon/\varepsilon_o)^m$. Figure 9 shows the experimental data of substrate II in a Weibull graph. The experimental failure strain ε_{max} and the failure probability P are represented on the axes. The slope m and the characteristic strain ε_o (at 63 % failure probability) are obtained from a fit on the experimental data. The fit constants for the 3 tests are included in table 1.

Table 1. Characteristic failure strains obtained from a Weibull analysis on 3 sets of samples.

Sample type	h [μm]	ITO layer	# samples	Weibull	
				ε_o [%]	m
I	130	Lines, 0.75 mm	60	1.17 ± 0.02	20
I	130	Uniform	30	1.24 ± 0.02	20
II	100	Uniform	36	1.46 ± 0.02	40

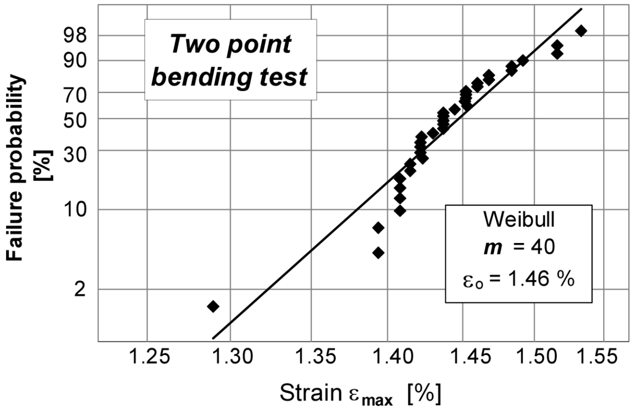

Figure 9. Weibull graph for the critical failure strain of sample II.

6. DISCUSSION

6.1 Failure of Brittle Layers

In the sections 4 and 5 a variety of failure modes for flexible displays is presented. Knowledge of at least the dominant failure modes is required for the development of reliability models and scaling rules. These types of models, applied to brittle materials, like glass and ceramics, use weakest link statistics, in many cases Weibull statistics.

In the previous section Weibull statistics is used to describe the critical failure strain of a brittle conductive layer (ITO) on a polymer substrate. During the test the polymer substrate behaves completely elastic[11]. The results, obtained by tensile loading of the brittle layer on the substrate differs significantly from the behavior of (bulk) brittle materials:

(3) The presence of large edge cracks does not affect the critical strain of the thin layer. Nearly identical failure strains are obtained for the smooth etched ITO lines with straight crack-free edges and uniform ITO layers with heavy damaged ITO edges.

(3) The critical failure strain of the uniformly coated sample (1.24 %) is even slightly higher than that of the ITO lines (1.17%). This is not expected when a distribution of weakest spots in the surface area is responsible for the failure behavior. The tested ITO area is larger for the stronger sample.

(3) The length of the ITO edges, tested in the two point bending test, is similar for the uniform ITO layer and the etched ITO line. The difference in crack density at the ITO edges is not responsible for the larger critical failure strain of the uniform ITO layer.

(3) Identical strength distributions ($m = 20$) are obtained for the same substrate type (I, table I). For the other substrate type a significantly higher failure strain (1.46 %) and a Weibull modulus $m = 40$ are reported. These differences reflect the different deposition conditions.

(3) High Weibull moduli (m 20) are only obtained in bulk materials characterization with well-defined process conditions. They are observed, for instance, when well defined surface damage is applied, for instance with powder blasting.[12] A Weibull modulus m 40 is only obtained for quite deterministic stress levels, for instance with the intrinsic strength of glass fibers.[13]

Crack initiation and crack propagation are two clearly different phenomena in the mechanics of thin layers on substrates[7]. The experiments on the ITO layer indicate that not the crack initiation but the crack propagation dominates the critical failure strain of the ITO layers. The fact that the poor quality of the ITO edge of the uniformly coated sample does not affect the failure strain clearly supports the propagation-controlled mechanism. A well-defined crack propagation threshold leads to a high Weibull modulus (m 20). The level of this threshold is determined by layer properties, like internal stress, layer thickness and adhesion to the substrate.

Leterrier[14] et al. studies the crack evolution of brittle silicon oxide coatings on polymer substrates with the fragmentation test. The number of cracks is counted as a function of the applied strain. The evolution of the crack density in a sample just above the crack onset strain is described with Weibull statistics. Weibull moduli

2.5 m 12 are reported. This is significantly lower than the m 20 obtained from our tests with, using resistance measurement on ITO. It is noted in this respect that the phenomena might be slightly different. Leterrier reports on the appearance of cracks within a limited area, observed with a microscope. The cracks may have a limited length. A significant increase of the resistance of an ITO layer is expected either with a large amount of small cracks in the layer, or a crack over nearly the full layer width. The differences in Weibull moduli might be related to differences in crack *initiation* or crack *propagation* limits.

For narrow lines a sudden increase of the resistance is observed; for wider lines a more gradual increase is measured. In a model description[9] of the resistance increase in the tensile test, the presence of conducting material in the crack is assumed to be responsible for the gradual resistance increase. This model does not account for the presently observed line width dependence of the resistance increase.

In the present set of experiments, with 0.75 mm wide ITO lines, the sudden increase in resistance and the well-defined, propagation controlled critical failure strain is obtained. In many applications in electronics industry significantly smaller details are present. For active matrix addressed displays, for instance, transistors and connection lines significantly smaller than 100 μm are applied. When the size of the cracks, initiated for instance around a defect, have a stable size, comparable to the size of the component, crack initiation-controlled mechanisms and not the propagation control may govern the resistance of the lines.

Cracks in a (oxygen and/or water) barrier coating degrade the performance of the hermetic coating. For this reason, crack initiation is expected to be a dominant failure mechanism for the performance of OLED displays, requiring hermetic coatings.

6.2 Reliability Models

Glass is the dominant substrate material in the display industry. The brittle failure behavior of glass is exploited in production processes, and taken into account in applications. Knowledge of the failure behavior, and the mechanisms leading to failure, is quite important in the production of reliable products. An appropriate combination of stress distributions, failure statistics and crack extension models is used in reliability models for brittle materials.

This type of modeling is also required for new products, entering the market. Flexible displays are nowadays quite appealing, both due to their flexibility and the robustness of the cell. From fracture mechanical point of view, the base polymer substrate has certainly a higher failure strain than a glass substrate. The limiting strain for the substrate can be related to the onset to non-elastic deformations or to brittle failure behavior, thus the presence of large cracks.

The substrate is a multi-layer stack. Cohesive and/or adhesive failure of one of the layers might lead to cell failure. Section 5 describes the loss of conduction of a tensile loaded ITO layer. It is strongly related to the crack evolution in the brittle layer. Brittle functional layers seriously limit the applicable deformations of the flexible display cell. The allowable deformation of the presently tested ITO layer is slightly above 1%.

The critical strain of the presently tested brittle ITO layer is determined with relatively small samples in a short lasting test in ambient conditions. For the prediction of the reliability of a real product, tests under more severe conditions and at longer timescales are required. This requires knowledge of the behavior of different materials as a function of time and temperature. For polymeric materials, incorporation of time-dependent deformation behavior, like creep and relaxation or plastic deformation, might be necessary. For thin brittle layers phenomena like slow crack might contribute to a lowering of the critical strain.

Apart from these phenomena, stress concentrations due to display constructions might seriously lower the applicable safe deformation. Near a seal line, for instance, preferential failure might occur (figure 4). All these factors result in a different, and probably significant lower, safe critical strain.

A large variety of mechanisms is responsible for the failure of a flexible displays. Production and market introduction of complete new products like flexible displays requires knowledge of the critical failure mechanisms. This knowledge is necessary to development reliability models.

7 CONCLUSIONS

Different failure modes for flexible display substrates are presented. Brittle layers, such as inorganic permeation barriers and transparent conductors (ITO) fail at strain levels of about 1%. They predominantly limit the allowable substrate deformation.

The critical failure strain of the conducting ITO layer does not depend on the presence of cracks in this layer. This is not in agreement with models used to predict the reliability of (bulk) ceramics.

During production, application and use of flexible displays, mechanical load is exerted on the substrates and the display cell. A good understanding of the different possible failure mechanisms is required in the development of flexible displays towards a reliable product. Appropriate reliability models are presently not available for flexible displays.

8. ACKNOWLEDGEMENT

The author acknowledges Judith de Goede and Jeroen Alberts for their contributions to the experimental work. Part of the work is done within the IST program (IST-2001-34215 FlexLED) of the European Community.

REFERENCES

1. P.J. Slikkerveer, Bending the Display Rules, Options and Challenges for Flexible, Proc. EuroDisplay 2002, Nice, 1–4 oct. 2002, pp 273–276.
2. A. Weber, S. Deutschbein, A. Plichta and A. Habeck, Thin Glass-polymer Systems as Flexible Substrates for Displays, SID 02 digest, Boston, 21–23 may 2002, pp. 53–55
3. P. Kazlas, A. Ritenour, J. Au, Y. Chen, J. Goodman, R. Paolini and H. Gates, Card-size Active-matrix Electronic Ink Display, Proc. EuroDisplay 2002, Nice, 1–4 oct 2002, pp 260–262.
4. P. Slikkerveer, G. Nisato, N. Kooyman, P. Cirkel and P. Bouten, A Fully Flexible, Cholesteric LC Matrix Display, SID '02 digest, Boston 21–23 may 2002, pp 27–29.
5. G. Nisato, P.C.P. Bouten, P.J. Slikkerveer, W.D. Bennett, G.L. Graff, N. Rutherford and L. Wiese, Evaluating High Performance Diffusion Barriers: the Calcium Test, Proc. IDW '01, Nagoya, 16–19 oct 2001, pp 1435–1438.

6. N. Young, M.J. Trainor, D.T. Murley, D.J. McCulloch and R.J. Wilks, LPTS for AMLCD on Glass and Polymer Substrates, Proc. IDW '99, 1999
7. J.W. Hutchinson and Z. Suo, Mixed Mode Cracking in Layered Materials, Adv. Appl. Mech., 29 (1992) pp. 63–191.
8. Y. Leterrier, C. Fischer, L. Médico, F. Demarco, J.-A. E. Månson, P.C.P. Bouten, J. de Goede, G. Nisato and J.A. Nairn, Mechanical Properties of Transparent Functional Thin Films for Flexible Displays, Proc. Soc. Vacuum Coaters, 46th annual conference, San Francisco, may 2003, to be published.
9. D. R. Cairns, R. P. Witte II, D. K. Sparacin, S. M. Sachsmann, D. C. Paine, and G. P. Crawford, Strain-dependent Electrical Resistance of Tin-doped Indium Oxide on Polymer Substrates, Appl. Phys. Lett. 76 (2000) 1425–1427
10. Y. Leterrier, L. Médico, F. Demarco, J.-A. E. Månson, M. Escola-Figuera, M. Kharazzi-Olson and U. Betz, Mechanical Integrity of Transparent Conductive Oxide Film for Flexible Polymer-based Displays, submitted to Thin Solid Films.
11. P.C.P. Bouten, Failure test for brittle conductive layers on flexible display substrates, Proc. EuroDisplay 2002, Nice, 1–4 oct 2002, pp 313–316.
12. P.J. Slikkerveer, P.C.P. Bouten, F.H. in 't Veld and H. Scholten, Erosion and damage by sharp particles, Wear 217 (1998) 237–250.
13. C.R. Kurkjian and U.C. Paek, Single-valued Strength of "Perfect" Silica Fibers, Appl. Phys. Lett. 42 (1983) 251–253.
14. Y. Leterrier, J. Andersons, Y. Pitton and J.-A. E. Månson, Adhesion of Silicon Oxide Layers on Poly(ethylene terephthalate). II: Effect of Coating Thickness on Adhesive and Cohesive Strengths, J. Polym. Phys. 35 (1997) 1463–1472.