

Advanced Poly-LED Displays

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ABSTRACT

Philips have been actively developing polymer OLED (poly-LED) displays as a future display technology. Their emissive nature leads to a very attractive visual appearance, with wide viewing angle, high brightness and fast response speed. Whilst the first generation of poly-LED displays are likely to be passive-matrix driven, power reduction and resolution increase will lead to the use of active-matrix poly-LED displays.

Philips Research have designed, fabricated and characterized five different designs of active-matrix polymer-LED display. Each of the five displays makes use of a distinct pixel programming- or pixel drive-technique, including current programming, threshold voltage measurement and photodiode feedback. It will be shown that the simplest voltage-programmed current-source pixel suffers from potentially unacceptable brightness non-uniformity, and that advanced pixel circuits can provide a solution to this.

Optical-feedback pixel circuits will be discussed, showing that they can be used to improve uniformity and compensate for image burn-in due to polymer-LED material degradation, improving display lifetime.

Philips research has also been active in developing technologies required to implement poly-LED displays on flexible substrates, including materials, processing and testing methods. The fabrication of flexible passive-matrix poly-LED displays will be presented, as well as the ongoing work to assess the suitability of processing flexible next-generation poly-LED displays.

Keywords: OLED, LTPS, Polymer LED, Displays, poly-silicon

1. INTRODUCTION

Organic-LED (OLED) displays offer the possibility of very high quality flat displays. They are emissive displays which allows the removal of the backlight when compared to LCD displays, allowing thinner form-factor, with almost perfect viewing angle and much faster response speed. OLEDs are typically small molecule materials, requiring complex deposition procedures, whilst the long-chain equivalents, Polymer-LEDs (poly-LED) can be deposited by much simpler methods. A monochrome display can be made using spin-coating, whilst a colour display can be made using ink-jet printing to deposit separate red green and blue sub-pixels, removing the need for a colour filter.

Initial poly-led displays were based around the passive matrix method of addressing, where the diode behaviour of the poly-LED is exploited. Passive matrix displays are addressed row-by-row. In this scheme each row only emits light whilst addressed. This has the effect that as resolution increases, so the instantaneous-brightness of each row during emission is much higher. This places effective limits on the size and resolution of a passive matrix display, as power consumption and drive voltage increase.

In order to overcome the difficulties with passive-matrix displays as resolution increases it is possible to include a memory element in each pixel. In this case the brightness value for each pixel is loaded during address and the pixel then emits after addressing ceases, throughout the frame time. In this way the instantaneous brightness of each pixel is independent of resolution. For this form of active-matrix display a voltage-controlled current-source needs to be included in each pixel (the controlling data voltage being stored on a capacitor during for the frame time). A simple voltage-controlled current-source can be created by using a thin-film transistor (TFT) in its saturation region. The simple voltage-controlled current-source pixel [1] is shown in figure 1. In this pixel the address TFT (Ta) allows the pixel to be addressed so that a data voltage can be stored at the gate of the drive TFT (T1). This data voltage, with

respect to the power row, causes a defined current to flow through the poly-LED. It can be assumed here that poly-LED brightness is proportional to poly-LED current-density in the first order.

This simple pixel can allow high aperture, high resolution displays to be created. Also its close similarity to a standard LCD pixel circuit can allow existing AMLCD technology to be re-used. However, the pixel now incorporates a p-type TFT used as a current source with a high duty cycle. Poly-silicon is therefore required. Poly-silicon has much greater stability and allows much higher mobilities, reducing the size of the drive TFT and enabling CMOS.

For this pixel the current (I_{ds}) is dependent on the drive TFT mobility (μ) and threshold voltage (V_t) as:

$$I_{ds} \propto \mu(V_{gs} - V_t)^2 \quad (1)$$

Where V_{gs} is the gate-source voltage of the drive-TFT.

For a poly-silicon display, both mobility and threshold-voltage vary randomly across the plate from pixel to pixel. This means that each component TFT will have an error in its mobility and threshold voltage (compared to their nominal values), independent of its neighbouring devices. In a simple current-source pixel the brightness is defined by the data voltage ($V_{gs} - V_t$). If threshold voltage and mobility vary then the pixel brightness will be subject to an error. Across a display this error manifests itself as random, fixed, spatial non-uniformity. This non-uniformity can be defined as the standard-deviation of pixel brightness, for a uniform field, divided by the mean display brightness, expressed as a percentage value.

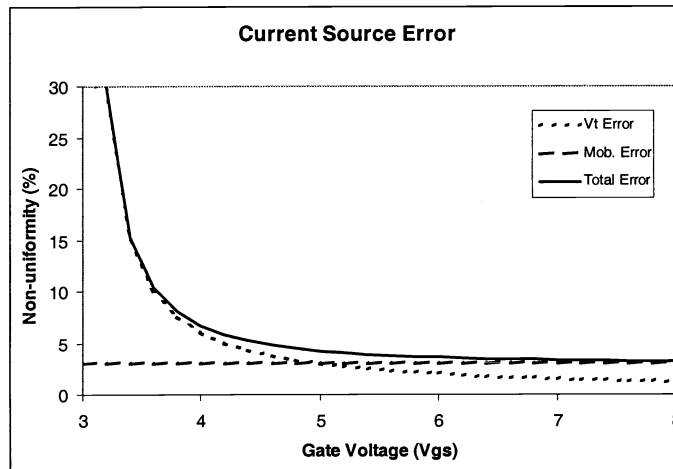


Figure 2. Current source non-uniformity

As errors that originate from threshold-voltage non-uniformity increase rapidly with decreasing data voltage the display will be highly non-uniform at low brightness. At high brightness, mobility non-uniformity becomes evident. This trend is shown in figure 2. This graph shows the theoretical display brightness non-uniformity for a display with a nominal threshold-voltage of 3V, with mobility and threshold-voltage non-uniformities of 3%, over a working data-voltage range of 5V. The high level of non-uniformity implied in this plot would be unacceptable. A non-uniformity much in excess of 3% is likely to be highly visible. Therefore in order to make a high quality display with good uniformity, especially at low brightness levels, the dependence of pixel brightness on drive-TFT characteristics must be reduced.

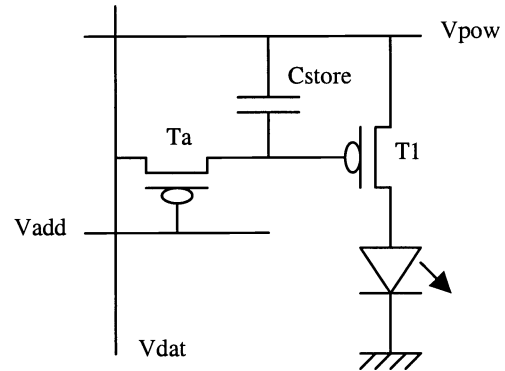


Figure 1. Simple current source pixel circuit

Using equation 1 we can show that the percentage current variation $\sigma(I)/I$ with respect to the threshold voltage variation $\sigma(V_T)$ is given by:

$$\frac{\sigma(I)}{I} = \frac{2\sigma(V_T)}{(V_{gs} - V_T)} \quad (2)$$

where V_T is the average threshold voltage. The same analysis for mobility gives:

$$\frac{\sigma(I)}{I} = \frac{\sigma(\mu)}{\mu} \quad (3)$$

where $\sigma(\mu)$ is the mobility variation and μ is the average mobility.

Three preferred methods of improving the displays uniformity have been identified [2]. These methods are:

- using the TFT as a switch so that the brightness is dependent only on the power voltage and the poly-LED characteristic (digital scheme),
- measuring the TFT threshold voltage in-pixel and adding the data voltage to it (Vt-compensation scheme),
- and addressing the pixel with the correct current and replicating that current through the poly-LED (current measurement scheme).

In order to understand the effects of TFT non-uniformity and to investigate the effectiveness of advanced pixel circuits, Philips Research have made a set of active matrix poly-LED displays. Five display types have been designed and made: a simple current-source pixel based display, a digital (area ratio greyscale) pixel based display, a threshold-voltage measurement pixel based display, a current measurement pixel based display and a fifth display incorporating optical feedback. The displays are all of 1.6 inch diagonal with a nominal resolution of 160x128 (130ppi). The active matrix substrates are of Low Temperature Poly-Silicon (LTPS) providing high mobility and stability [3]. These research displays have been made with a monochrome polymer material for ease of measurement, applied using spin coating. All four display types were measured for brightness non-uniformity. In order to fairly compare the compensation achieved with each pixel type, the four displays measured came from the same processed plate. This ensures the displays have TFT characteristics as closely matched, and distributed, as possible. Measurement was achieved using area integration over the pixel area. This method allows for variation in brightness across a poly-LED aperture and non-square pixel-apertures.

2. PIXEL OPERATION

The digital pixel is identical in schematic to the simple current-source pixel circuit (figure 1). However, in the digital pixel the TFT is operated in its linear region, with a large (digital) gate voltage. The circuit is then designed to give a very low drain/source voltage so that the current through the poly-LED is determined only by the poly-LED characteristic and the power line voltage. In this way the pixel can either be full-on or full-off with very high uniformity. Grey scales can then be shown using area-ratio grey-scale (ARG) or time-ratio grey-scale (TRG). The digital pixel brightness should be independent of TFT characteristic so should show brightness non-uniformity only due to polymer efficiency variations. However, as the poly-LED is voltage-driven, poly-LED differential ageing (burn-in) will be highly visible. Lack of analogue grayscale is also a disadvantage as ARG tends to reduce aperture, whilst TRG requires the display to be operated at very high refresh rates.

The current measurement pixel (figure 3) also offers a method of improving display uniformity by reducing the dependence of the pixel current on the characteristics of the drive TFT. The pixel is addressed as normal, but in this case the column data signal is in the form of a current. During the address phase the cathode is set open-circuit, this stops current flowing through the poly-LED during address. The operation of the pixel is best explained from an initial state with the pixel fully off. In this case the data current is drawn through the address-TFT (T_a) and the diode-TFT (T_d) from the bottom plate of the storage-capacitor (C_{store}). This pulls down the voltage at the gate of the drive TFT and current flows through the drive TFT onto the column. At the end of address equilibrium is reached with all the data signal current being provided by the drive TFT. In this way the drive TFT is set to give the correct current. After addressing the cathode is connected to earth and the poly-LED is illuminated. Current mirror displays should therefore compensate for non-uniformities in both threshold-voltage and mobility. As the poly-LED is now operated in a current-driven mode poly-LED differential ageing will be less visible than for the digital pixel.

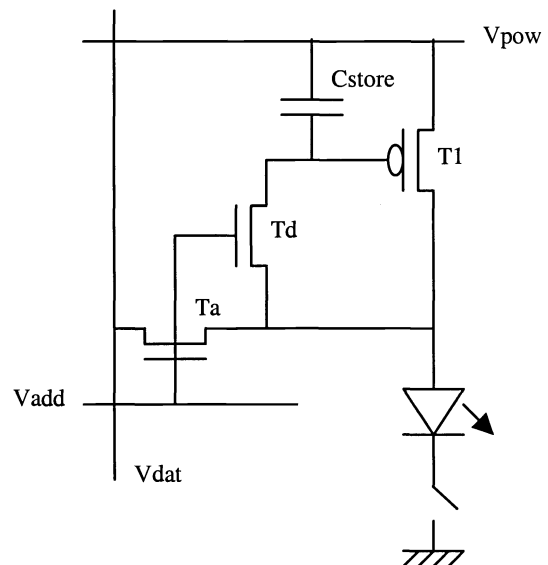


Figure 3. Current measurement pixel circuit

However current programming requires accurate column pre-charging, and will still limit the maximum refresh rate of the display.

Another distinct method of improving uniformity in AM-LED displays is to use a V_t -compensation circuit. The circuit is shown in figure 4. The operation of the pixel is as follows. The pixel is addressed with TFT T_a turned on. T_s and T_d are then both turned on, bringing the drain of T_1 low, and T_s then switches off. T_d connects the drain of T_1 to its own gate, so T_1 is turned full on. Current flowing through T_1 charges up its gate and switches it off, until equilibrium is reached when T_1 is just switched off. At this point V_t is stored on C_1 . T_d is then switched off and the gate of T_1 allowed to float. Voltage data is then applied to the column putting the data voltage across C_{store} . In this way the gate-source voltage of T_1 is now $V_{data} + V_t$, compensating for threshold voltage non-uniformity. T_s is then switched on to allow the pixel to illuminate. Voltage programming also allows much simpler drive electronics and faster refresh rates than current programming. However, the threshold-voltage measurement pixel will not compensate for mobility non-uniformity and so will not be as uniform as the current measurement pixel.

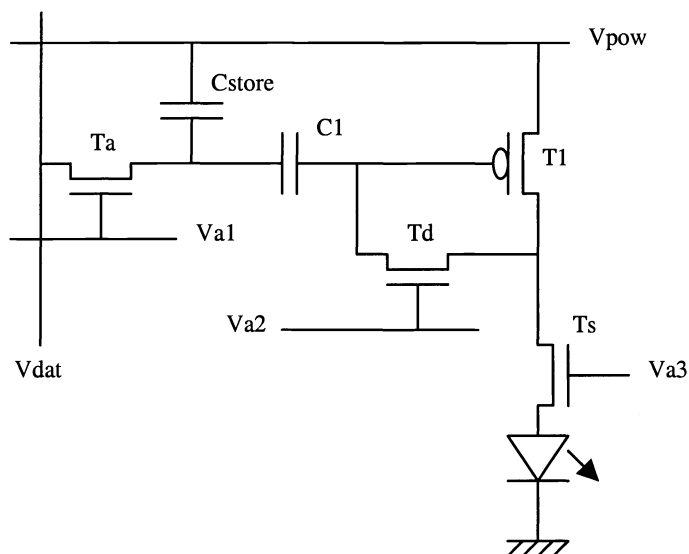


Figure 4. Threshold-voltage measurement pixel circuit

3. UNIFORMITY

Pixel-to-pixel variations in drive-TFT characteristics cause brightness non-uniformity in poly-LED displays. This brightness non-uniformity can be described as the percentage brightness error relative to the intended pixel brightness. Variation in the drive-TFT mobility causes a fixed relative-error at all brightness levels, although this can dominate at higher brightness levels, mobility error is generally less severe than threshold-voltage error. The non-uniformity associated with V_t variation becomes increasingly severe at low brightness. A simple-current source pixel will therefore be unacceptably non-uniform at low mean brightness.

Figure 5. shows the brightness non-uniformity of a digital pixel based display. The digital pixel greatly reduces the pixel currents dependence on the TFT characteristics. The digital display should therefore only show non-uniformity resulting from the polymer characteristic variations from pixel to pixel. This is demonstrated in the results measured from the digital display. Here a fixed 2.3% brightness non-uniformity can be seen across all grey levels.

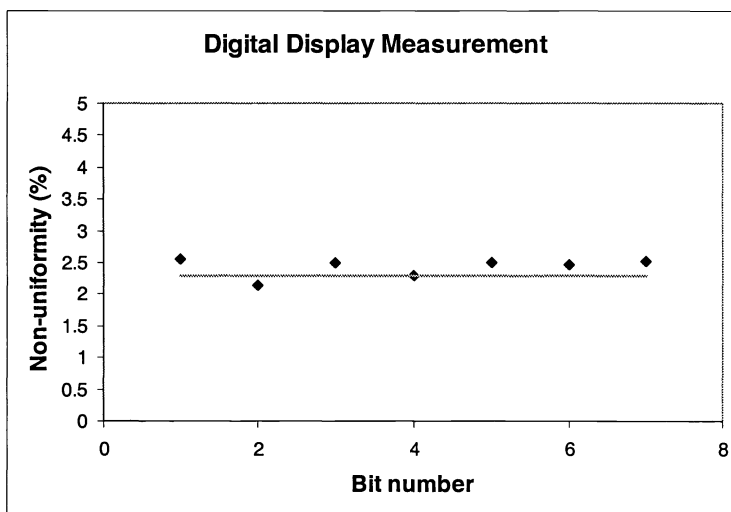


Figure 5. Digital pixel based display non-uniformity

The current-source pixel based display shows non-uniformity originating from the polymer, TFT mobility and TFT threshold voltage. Analogue circuit simulations of the current source display show non-uniformity of the form shown in figure 6. Here the simulated non-uniformity is broken down into its constituent parts for a display with 3% V_t variation and 5% mobility variation. The 2.3% polymer non-uniformity baseline as measured in the digital display is assumed. As in the theoretical calculations the mobility non-uniformity is effectively fixed with brightness at 6%, only rising at very low brightness levels. The non-uniformity due to pixel-to-pixel threshold voltage variation can then be seen to dominate the display non-uniformity and increase rapidly at low brightness levels.

Figure 7 shows the measured non-uniformity for the advanced pixel-circuit displays. The nominal 2.3% polymer non-uniformity baseline is also shown.

The current measurement pixel accurately matches the pixel current to the data-current. In this way the pixel should overcome both V_t variations and mobility variations in the first order. Therefore the display should only exhibit brightness non-uniformity resulting from polymer non-uniformity. However, the drive TFT drain-source voltage is not the same during programming as during driving which can introduce errors. Also, parasitic capacitance associated with the TFTs in the pixel cause capacitive feed-through (kickback) in the pixel. This feed-through can cause mobility non-uniformity to become evident. As such the display shows some non-uniformity arising from these secondary effects. The current measurement non-uniformity can be seen to converge with the polymer non-uniformity baseline at high brightness, but departs from this ideal value at lower brightness levels.

The threshold voltage compensation pixel accurately measures the drive TFT threshold voltage before the addition of the data voltage, effectively removing threshold voltage based brightness variation. This should lead to lower overall non-uniformity, and a flatter non-uniformity graph over most brightness levels. This effect is evident in the measured results, with reduced display non-uniformity.

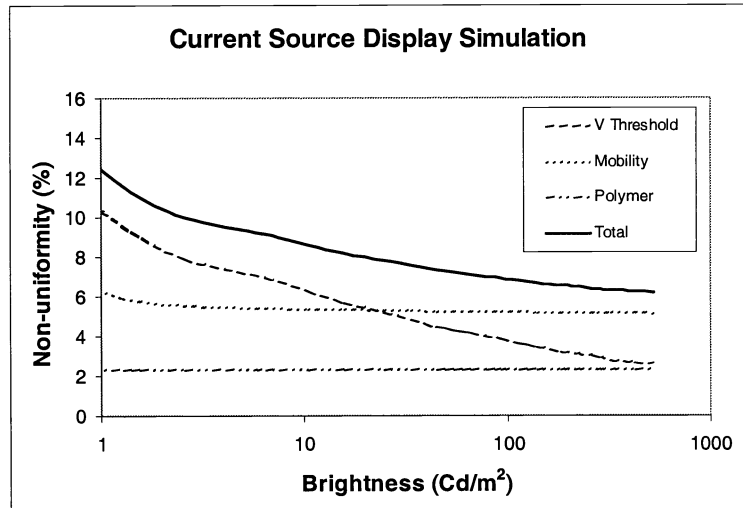


Figure 6. Current-source pixel based display simulated non-uniformity

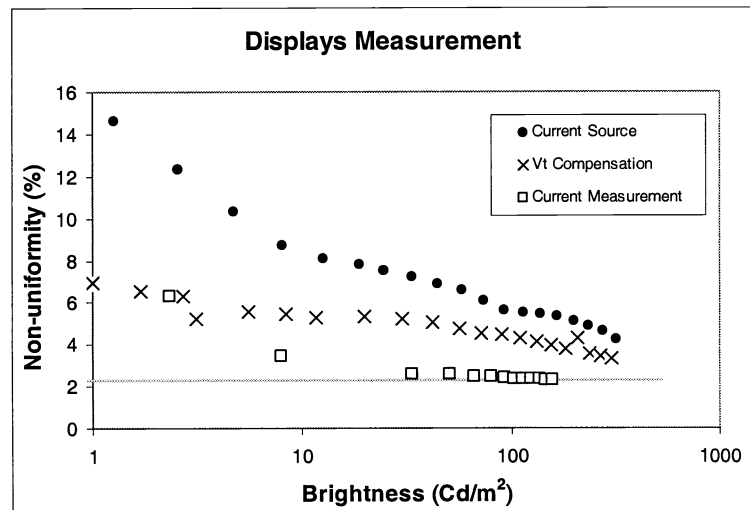


Figure 7. Advanced pixel circuit based displays measured non-uniformity

4. POLYMER BURN-IN

Poly-LED materials have a limited lifetime, defined as the time the poly-LED can be illuminated for, before its efficiency degrades to half its initial value. It is usual to assume the polymer has a linear relationship between current density and brightness, so that the brightness of a pixel is directly proportional to the current through it. However, if a pixel ages with use, then this relationship changes, and a pixel that has been used may, for a given current, be significantly dimmer than an unused neighbour. This leads to a burn-in effect, such that if an image is shown for a significant time it will age the pixels used to show it. Then when a plain field is shown at a later time, a negative shadow of the image will still be visible. In figure 8, the image on the left would eventually lead to the burned-in image on the right for a uniform grey image.

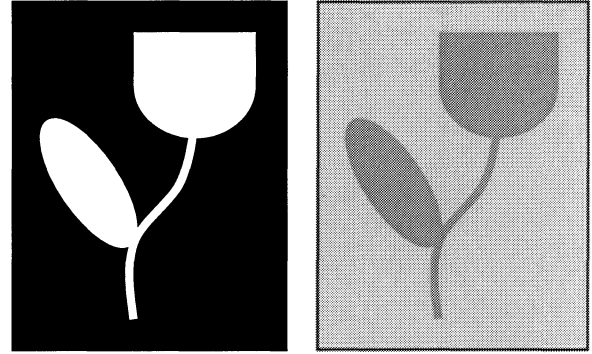


Figure 8. Polymer burn-in example

In order to overcome this effect it is necessary to directly measure the light output from a poly-LED in order to know the poly-LED efficiency. This action can be achieved “in-pixel” with the circuit in figure 9. This circuit acts to measure the brightness of the poly-LED and compensate for burn-in [4].

The pixel is addressed in the same way as the simple current source pixel, with an analogue voltage stored at the gate of the drive-TFT. This low-voltage causes a current to flow through the drive-TFT, as $I_{ds} = k(V_{gs} - V_t)^2$. This current causes light to be emitted from the poly-LED with an unknown efficiency. Some of this light is incident on the photodiode causing a photocurrent to flow onto the gate of the drive TFT. This increases the voltage on the gate of T1, discharging the storage capacitor and reducing V_{gs} . This in turn acts to turn off Td and dim the pixel. By the end of the frame time the pixel is effectively fully dark. A bright pixel will switch off fast, and a dim (aged) pixel will be lit for longer. If the current through the poly-LED is given as in equation 1, the differential equation for the voltage on the storage capacitor is given by:

$$C \frac{dV}{dt} = -\frac{\beta}{2} \eta_{PD} \eta_{led} (V_{gs} - V_T)^2 \quad (4)$$

where C is the storage capacitance, T is the frame time and η_{PD} is the photodiode efficiency. Then it can be stated that:

$$Q = \int_0^T I(t) \cdot dt = \frac{L_{av} T}{\eta_{led}} \quad (5)$$

Where Q is the total charge through the poly-LED over a frame time, $I(t)$ is the current through the poly-LED and L_{av} is the average integrated light over a frame time. Equation 4 can be solved to give:

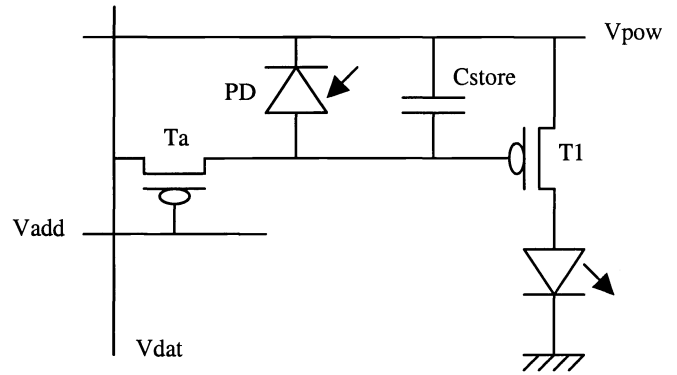


Figure 9. Optical-feedback pixel circuit

$$Q = \left(\frac{C(V(0) - V_t)}{\eta_{PD}\eta_{led}} \right) \left(\frac{T/\tau}{1 + T/\tau} \right) \quad (6)$$

Which in turn gives the integrated light output over a frame time as:

$$L_{AV}(T) = \frac{C}{\eta_{PD}} (V_{gs}(0) - V_T) \left(\frac{T/\tau}{1 + T/\tau} \right) \quad (7)$$

where τ is the time constant of the circuit given by:

$$\tau = \left(\frac{2C}{\eta_{PD}\eta_{led}\beta(V_{gs}(0) - V_t)} \right) \quad (8)$$

with beta relating to the drive TFT characteristics:

$$\beta = \frac{W}{L} \cdot \frac{\epsilon_0 \epsilon_r \mu}{t_i} \quad (9)$$

Now for large values of τ this simplifies to:

$$L_{AV}(T) = \frac{C}{\eta_{PD}} (V_{gs}(0) - V_T) \quad (10)$$

The average light output is now independent of both the TFT mobility and the LED efficiency: This optical-feedback mechanism has therefore implemented burn-in compensation.

The pixel action is shown in figure 10. This plot shows data taken from the measurements of two pixels [5]. The first pixel is one with poly-LED efficiency of 10Cd/A corresponding to an unused pixel, and the second pixel is one with poly-LED efficiency of 5.5Cd/A corresponding to an aged pixel. It can be seen that the un-aged pixel is initially lit at a much higher brightness. However the feedback action dims the aged pixel more slowly than the un-aged pixel. This effect is also shown on the plot. Initially there is a 45% difference in brightness. But the difference in integrated light-output between the pixels soon falls to less than 15%.

Simulations of this behaviour show that very good poly-LED efficiency compensation can be achieved using this technique. The plot in figure 11. Shows the brightness error associated with a optical-feedback pixel. In this plot the nominal efficiency of a poly-LED is assumed to be 10Cd/A. The plot then looks at three scenarios, of a poly-LEDs aged to 9Cd/A, 7Cd/A and 5Cd/A respectively. The percentage brightness error these pixels would introduce is then shown as a function of frame time. The feedback mechanism takes time to implement, and so better compensation is possible with longer frame times. The plot shows that for frame times of 3ms most of the effect has occurred and initial

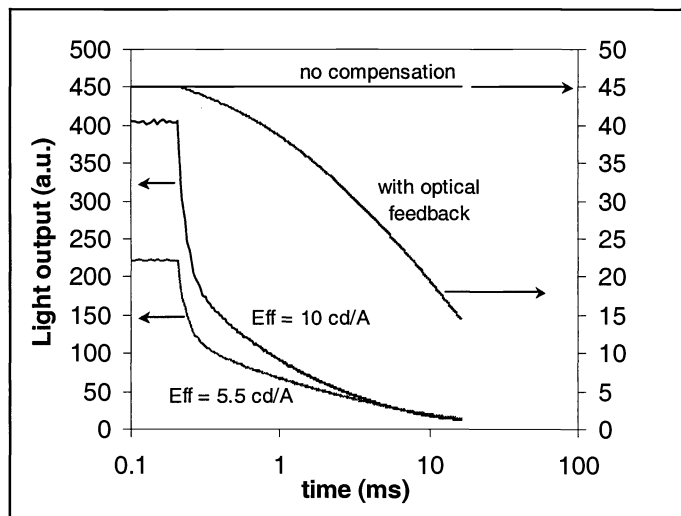


Figure 9. Measured optical-feedback operation

non-uniformities of 50% can be reduced to well under 10%.

This effect is demonstrated in figure 10. In this image a section of an optical feedback display is shown. In figure 10a the section is shown displaying the checker-board pattern to be burned-in. Figure 10b shows the differential ageing of the poly-LED material. This image was taken by holding all the addressing TFTs (Ta) on. This directly connects the columns to the gate of the drive TFT (T1), overcoming the feedback effect, and driving the display as a simple current-source. In 10c the display is driven with optical-feedback. In this image no burn-in is visible.

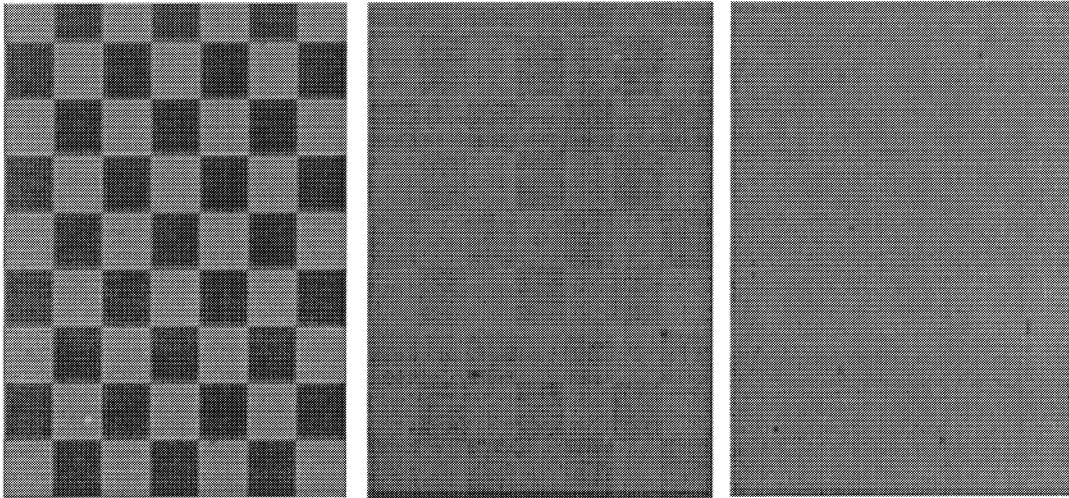


Figure 10. (left-to-right a,b,c) Burn-in reduction using optical-feedback effect

5. OPTICAL FEEDBACK LIFETIME AND UNIFORMITY

In a first approximation the efficiency of our poly-LED material degrades as a function of the total charge through the LED. If $\eta_{led}(0)$ is the initial efficiency of the poly-LED, Q_T is the total charge that has passed through the poly-LED during its lifetime and C and α are scaling factors, the efficiency of the poly-LED can be expressed as [5]:

$$\eta_{led} = \eta_{led}(0) - CQ_T^\alpha \quad (11)$$

This relation shows very close agreement with measured poly-LED behaviour with $\alpha=2.8^{-1}$. This relation suggests that over time, a poly-LED driven with a constant current will grow dim as its efficiency falls. This has important implications for any display driven with a constant current-source, as their brightness would fall with use, limiting their life time. The optical-feedback display should increase the lifetime of a display by removing the brightness dependence on polymer efficiency.

It is convenient to calculate lifetime using a discrete algorithm to sum the total poly-LED charge over many frames. This can be done using the relation in equation 6 rewritten for a numerical solution. In this case the total charge through the poly-LED will be given by the expression in equation 12, where C is the value of the

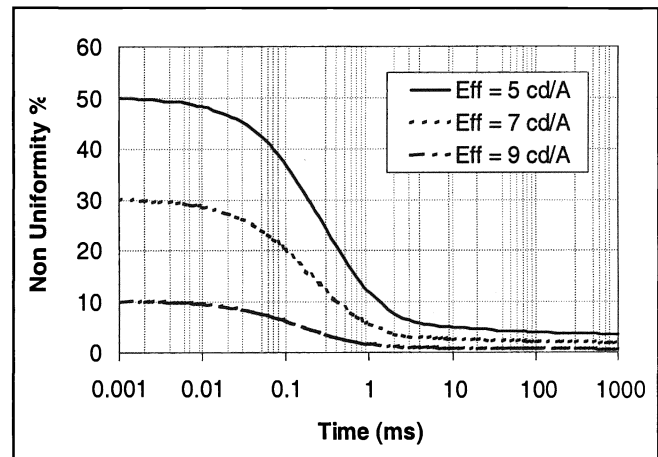


Figure 11. Theoretical optical-feedback results

storage capacitor. Here n represents the frame number, so the charge through the LED is calculated using the poly-LED efficiency from the previous frame.

$$Q(n) = \left(\frac{C(V_{gs}(0) - V_t)}{\eta_{PD}\eta_{led}(n-1)} \right) \left(\frac{T/\tau(n-1)}{1 + T/\tau(n-1)} \right) \quad (12)$$

The expression consists of two parts, the first relates to the current flow, and the second relates to the effect of the finite frame time. In the first part, η_{led} will fall over time, acting to increase the current through the poly-LED. In the second part the time constant, τ , is now defined as:

$$\tau(n) = \left(\frac{2C}{\eta_{PD}\eta_{led}(n)\beta(V_{gs}(0) - V_t)} \right) \quad (13)$$

As the polymer ages, τ increases relative to the frame time and so the compensation becomes less effective. The light output over the frame time therefore becomes:

$$L_{av}(n) = \left(\frac{C(V_{gs}(0) - V_t)}{\eta_{PD}T} \right) \left(\frac{T/\tau(n-1)}{1 + T/\tau(n-1)} \right) \quad (14)$$

This has profound effects on the useful lifetime of a display made with polymers that suffer appreciable ageing. The compensation reduces the effect of burn-in and so increases a displays lifetime. The plot in figure 12. shows the effect of ageing on a display. The graph considers two scenarios. The first is for a simple current source type display, drive TFT W/L of 20/15 μ m, V_{sig} of 5V and mobility of 2.8x10⁻³. In this display the current through the poly-LED is held constant over time. The drop in efficiency of the polymer is therefore directly observed as a rapid initial drop in brightness. The second curve is for an optical feedback display, with poly-LED efficiency of 10Cd/A, photodiode efficiency of 4x10⁻⁵A/Cd at the same initial brightness as the current-source display. In this display the light output should be held constant. However, due to the finite frame time, some drop in light output is observed. In this type of display the initial drop is not observed. Instead the light output falls gradually until the frame time is insufficient to allow compensation and the light output rapidly drops.

As seen in equation 5, in the ideal case the pixel brightness is independent of TFT mobility and poly-LED efficiency.

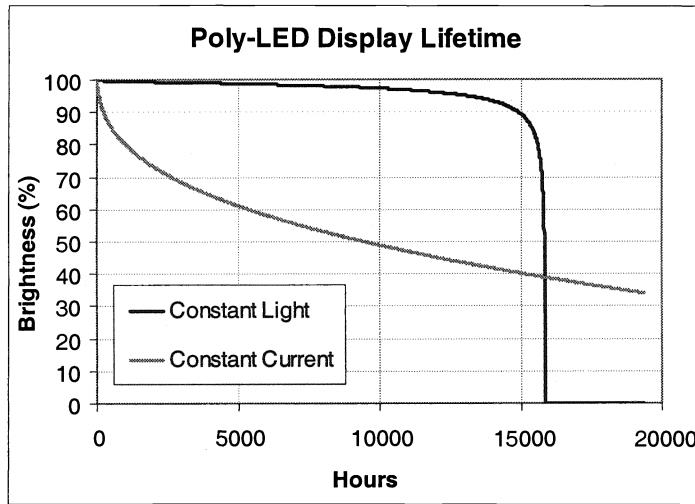


Figure 12. Simulated life-time improvement

The inclusion of the sub-threshold behaviour of the drive TFT will also eventually mean that the brightness is independent of threshold-voltage. However this only occurs at infinite frame times. There will therefore be some dependence on device threshold-voltage. Figure 13. shows the effect of varying threshold-voltage, and the compensation effect of the optical feedback for increasing frame time. In this graph a threshold-voltage offset is assumed. This causes an initial brightness error. As previously explained, this initial error is more pronounced for lower gate voltages. Then, as the drive-TFT turns off and begins to operate in the sub-threshold region threshold-voltage compensation occurs. It can be seen that with very long frame times good compensation is possible. However the effect is slow, and there is almost no compensation for short frame times.

Figure 14. shows the measured non-uniformity of the optical-feedback display. The photodiode display will compensate well for both polymer non-uniformity and mobility non-uniformity, leaving only threshold-voltage non-uniformity to effect brightness. The figure shows this trend. It can be seen that the optical feedback mechanism provides good uniformity at higher brightness levels where mobility and polymer based non-uniformity tends to be more dominant but at lower brightness levels, where threshold-voltage non-uniformity tends to dominate, the effect is negligible.

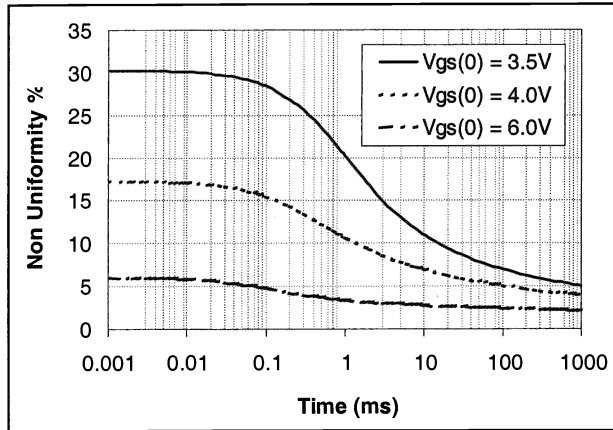


Figure 13. Theoretical optical-feedback threshold-voltage compensation

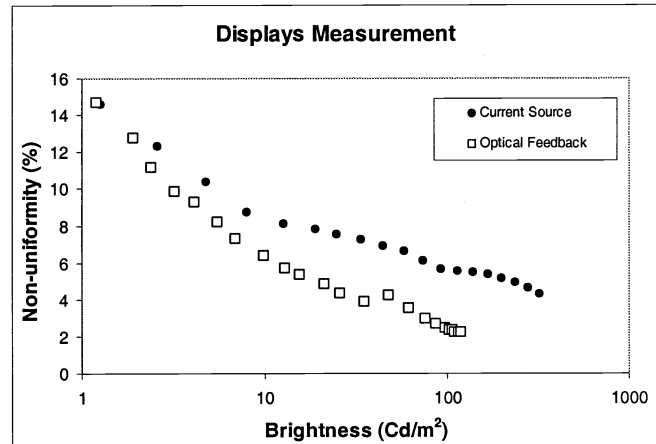


Figure 14. Measured optical-feedback based display non-uniformity

6. COLOUR PRINTING

The displays described so far were made using spin-coating to apply the polymer layers. Whilst this method offers a fast, reliable and low-cost method of fabrication, it can only be used to deposit a continuous layer of polymer, and so cannot be used to fabricate a colour display. Instead, a colour display requires a method of accurately positioning and depositing colour polymers [6]. To fabricate a full-colour display Philips Research have used ink-jet printing to deposit light-emitting polymers. Using software-driven piezo-electric drop-on-demand ink-jet printing it is possible to deposit very small drops of low viscous liquids. To limit the spreading of the polymers they are printed between barriers of photo-resist. These photo-resist “dams” precisely define the poly-LED borders and so red, green and blue columns can be formed. Using this method full-colour displays have been fabricated, using the simple current-source pixel, at 128x160 pixel resolution, with 200 micron pitch. This is shown in figure 15.

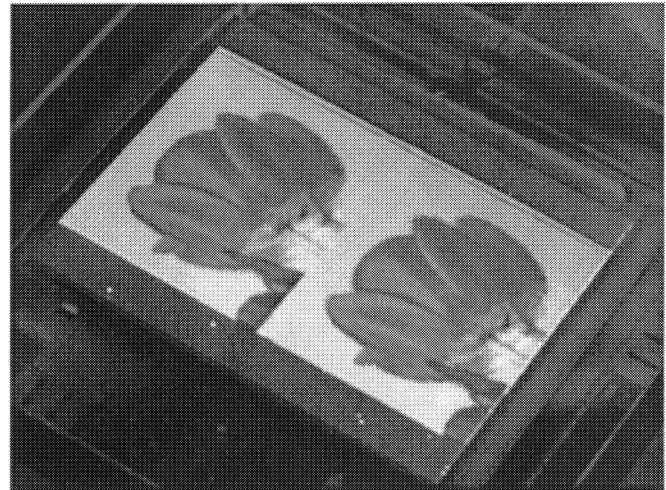


Figure 15. High-resolution full-colour active-matrix poly-LED display

7. FLEX-LED

Humans are not made with straight lines and right angles. A more intuitive and natural interaction would naturally occur with devices that are not flat and rectangular. Current design tends to move away from the square form factors dictated by the displays. On the other hand, today's cell phones, PDA's and hand held computers are relatively fragile mostly due their displays. A considerable amount of devices such as mobile phones reach their end of life due to broken (glass) displays. Figure 16 shows an artist's impression of a flexible display which could be rolled up in a device while not in use. Flexible PLED displays has to potential to enable thin, lightweight, conformable devices providing more design freedom. In the long term low cost mass production options (reel-to-reel processing) could also be achieved. Behind this driving vision, several fundamental issues are to be considered. While the previous sections makes it clear that that for large area and high resolution devices active matrix driving schemes are required, it is interesting to focus first on passive matrix driven devices as a first step to solve several materials and processing issues. Contrary to most LCDs, PLEDs still offer the possibility of video compatible refresh rates even with the relatively simple diode driving schemes.

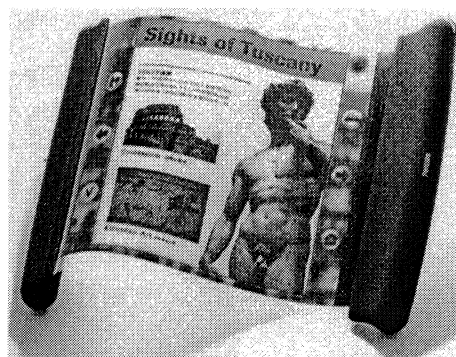


Figure 16 : Artist's impression of a flexible display.
(from Philips "Vision of the Future" design project)

Several intrinsic PLED advantages (emissive, low voltage, high brightness) were summarised in the previous sections. From the mechanical stand point, the thickness of the solid-state electro-luminescent stack ($< 5\mu\text{m}$) is highly beneficial. The excellent viewing angle provided by the Lambertian emitting behaviour is also very advantageous for flexible devices assuming they will be used while in the curved state, as the display doesn't need to be provided with complicate optical compensation layers required by LCDs for instance.

Transparent flexible substrates are either based on micro glass sheets (typically $100\mu\text{m}$ thick, or less) or on polymer multilayer composites. Polymers are flexible but permeable to water and oxygen that degrade the device cathode. Inorganic diffusion barriers are therefore necessary. Micro glass substrates are hermetic and inert, but also brittle. In both cases, handling is a matter of concern since standard equipment is designed and optimised to handle relatively thick glass substrates. The hermeticity and mechanical properties of the base substrates are essential to insure sufficient lifetime and device performance. The current specifications for permeation rates of substrates for PolyLED are on the order of $10^{-3}\text{ cc/m}^2/\text{day}$ at standard temperature and pressure for O_2 and $10^{-6}\text{ gr/m}^2/\text{day}$ for H_2O respectively. The best permeation test for a given substrate is making a (working) PLED device. This can be quite time consuming. A permeation test, the "calcium test", was developed in order to evaluate flexible plastic substrates for OLED applications [7]. Based on the corrosion of reactive metal films, this all-optical method is used to quantify the water transmission rate of substrates provided with high-performance diffusion barriers. Calcium readily reacts with water and oxygen entering the test cell and becomes progressively transparent. This

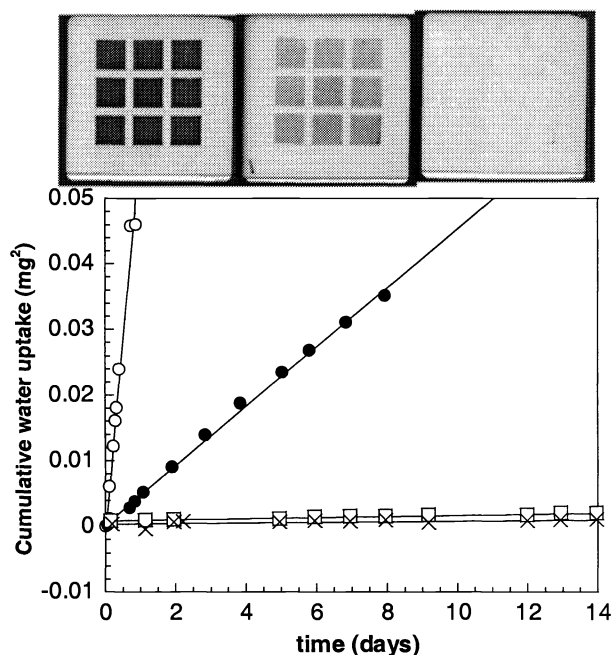


Figure 17. Photographs of calcium test cells at different times. Permeation rate plots for LCD substrates: Teijin (○); Sumitomo (●) and Vitex Flexible Glass (□) and glass substrates (x).

leads to a change in the optical transmission of the test cell, which can be monitored in time. The calcium layer can be deposited following patterns that simplify image analysis. The total area covered by metallic calcium as well as the optical transmission of this area changes in time. The change in transmission of the cells is then used to quantify effective permeation rates. The effective water vapor transmission rates (WVTR) of the substrate or sealant is obtained by fitting a straight line to the (effective) water uptake versus time curves. Effective permeation constants in the range of 10^{-1} to 10^{-6} g H₂O/m²/day have been determined experimentally. The lower detection limit of presently available commercial equipment is 10^{-3} gr H₂O/m²/day. The calcium test can also be used to identify micro-mechanical damage of the diffusion barrier layers on polymer-based substrates.

Barrier layers and transparent conducting oxide are thin and (relatively) brittle inorganic layers. While the overall mechanical properties (e.g. elastic modulus) of a polymer composite stack is essentially dominated by the base material (be it polymeric or glass), the mechanical behavior of these thin layers plays an essential role in the substrates. The transparent conducting oxide layer (typically ITO) is a crucial components of the substrate stack. Loss of functional performance of the device is directly correlated to the mechanical failure of the thin conductive coating. The resistance increase as a function of deformation can be measured in a bending test [8] which is used to quantify the maximum strain at crack onset. Critical strain ranges typically between 0.9% and 1.5%, the values vary as a function of thickness and ITO type. With a 100 μ m thick (polymer) substrate, the corresponding minimal radii of curvature allowed are 0.55 cm and 0.36cm respectively. These should be considered fundamental limits for the radii of curvature, other effects (e.g. stack integrity and cell design) will further increase the minimal curvature radii allowed. Substrates such as metal foils could also be used (with a top-emitting PLED architecture) however, the onset of plastic deformation of the base substrate can become then a limiting factor. A realistic radius for “roll-up-displays” is therefore in the centimeter rather than in the millimeter range, independently on the flexibility of the base material. Large area and high resolution devices are hardly possible with passive matrix driving, hence the perception of mechanical “flexibility” of the first devices could be rather limited.

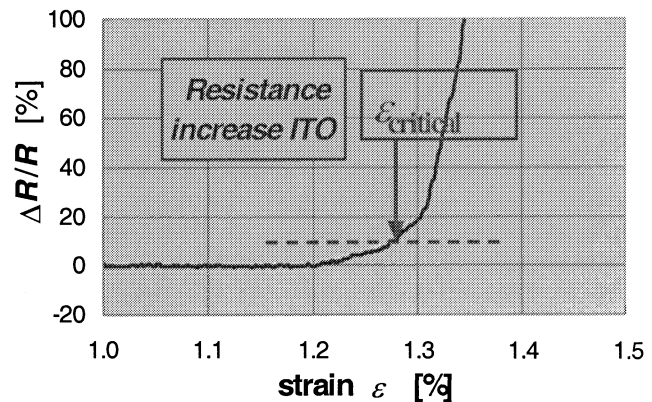


Figure 18: relative resistance of ITO versus strain as measured in a bending test.

While the TCO failure will have immediate repercussions on the display, it is clear that mechanical failure of the diffusion barriers (also thin inorganic layers) will result in a shortened lifetime of the device. The failure of oxide coatings on flexible polymer substrates is characterized during tensile loading in-situ in a microscope [9]. This technique is very valuable to quantify mechanical properties of the diffusion barriers, for instance adhesion and critical (failure) strains.

The processing of flexible substrates can be challenging: dimensional stability of the substrates is required for accurate alignment of consecutive lithographic steps. As far as polymer based composites are concerned, several reversible and irreversible effects take place during processing. The reversible phenomena are essentially due to thermal expansion and solvent uptake, for instance during and after wet etching processes, photolithographic steps and baking. The coefficients of thermal expansion (CTE) for most (transparent) polymers ranges from 50 to 90 ppm/°C; for a 6" square substrate this means that a size variation on the order of 10 μ m per degree centigrade is to be expected across the sample, while an alignment accuracy better than

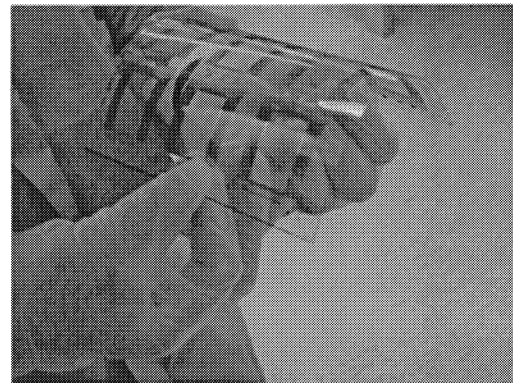


Figure 19: flexible PLED back-plane.

3µm is desired.. Solvent uptake and desorption occur during and after wet chemical processing or simply due to variation of the ambient relative humidity. Temperature and humidity control are therefore essential during lithographic processing. Quantifying the kinetics and magnitude of these effects for the polymer base substrate of choice is therefore advisable. Irreversible processes, such as polymer free volume relaxation at high temperatures, also take place. In this case, the shrinkage rate can be reduced by applying appropriate annealing steps before processing. [10]. Polymer base material with high glass transition temperature can be thermally stabilized prior to processing, enhancing the dimensional stability of the substrates during processing. Transparent polyarylates with glass transition temperatures above 300 C are a very interesting option for developing substrates for PLED. Up to now, passive matrix OLEDs were demonstrated [11] on substrates withstanding only low temperatures (< 200C).

While it is desirable to reduce the processing temperatures as much as possible, the previous sections presented several active matrix designs which require poly-silicon to be implemented; at the moment these processes still require rather elevated temperatures. Whilst the passive matrix flexible PLED technology is a necessary step forward, it is clear that the following generation of flexible devices should be active matrix driven.

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