19.1: Invited Paper: Next-generation active-matrix polymer OLED displays

N.C. van der Vaart and E.A. Meulenkamp
Philips Research Laboratories, Prof. Holstlaan 4, 5656 AA, Eindhoven, The Netherlands.
N.D. Young
Philips Research Laboratories, Cross Oak Lane, Redhill, RH1 5HA, England.
M. Fleuster
Philips New Displays Business Development, PolyLED, Jan Campertstraat 5, Heerlen, The Netherlands.

Abstract

Since 1992, Philips has been developing polymer OLEDs resulting in a first commercial monochrome display just 10 years later. Philips is now focusing on the technology development required to mass-produce full-color polymer OLED displays, based on passive and active-matrix addressing. High precision inkjet printing has been chosen as the deposition technology for the OLED material. In this paper, we give an overview of the activities of Philips in the area of mobile OLED applications and explore the route towards large screen OLED television.

1. Introduction

Organic Light-Emitting Diode (OLED) displays have attracted a lot of attention over the past decade and hold the promise to play a significant role in the display market. It is a relatively new technology, and the first products are just starting to enter the market for mobile phones and digital still cameras [1]. Displays with a larger diagonal are forecasted to enter the market somewhere in 2006-2009. Several companies have already demonstrated OLED displays in the range of 10" to 24" diagonal, with a clear focus of working towards television applications [2-5]. The main drive to work on OLED displays is the potential of an excellent image quality (high peak brightness and dark room contrast, fast response time, wide viewing angle) combined with an ultra-thin form factor (< 2 mm) and low power consumption.

Since 1992, Philips has been developing OLED displays based on light-emitting polymers (LEP). The first commercial monochrome Polymer OLED (PLED) displays entered the market in 2002 (in a shaver) and in 2004 (in a mobile phone) [6]. Philips is now focusing on the development of the technology required to mass-produce full-color polymer OLED displays, based on passive-matrix and active-matrix driving, and utilizing high-precision inkjet printing [6]. The three most important challenges towards industrialization are the development of the inkjet printing process for full-color displays, the performance (initial and during life) of the LEP materials under application conditions in ink jet printed devices, and the development of the necessary mass-production equipment [6]. In this paper, we discuss these challenges, give an overview of the activities of Philips in the area of mobile applications and explore the route towards large screen polymer OLED television. We discuss the complete display chain from active-matrix design and fabrication, through PLED panel fabrication, driver electronics, display-specific video processing, to display perception aspects.

2. Polymer OLED device layout

A polymer OLED display consists of an anode, usually ITO, with on top a hole-injection layer (PEDOT) and a light-emitting polymer (see Figure 1). The layers are printed by accurately placing small drops of ink on the substrate using a piezo-based multi-nozzle print head. To facilitate the separation of the colors, dams are placed between the red, green and blue sub-pixels. The whole stack is covered with a metallic cathode to allow electrical contact to be made to the device. In an active-matrix structure, current is supplied to each OLED pixel by a separate Thin Film Transistor (TFT), which drives a current through the device via the anode to the common cathode and generates light via electro-luminescence. The whole device is packaged with another glass plate or a thin film encapsulation layer [7,8].

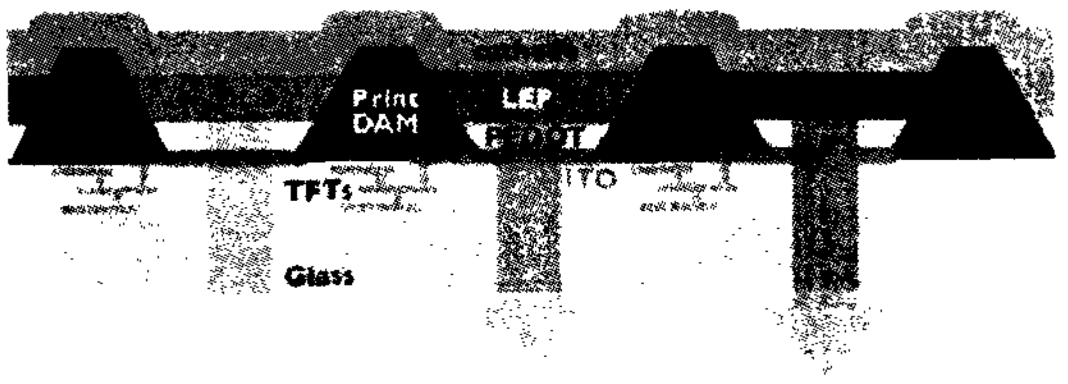

Figure 1 Schematic of an active-matrix PLED pixel triplet.

3. Inkjet printing of Polymer OLEDs

Several methods to realize RGB color generation in OLED displays have been demonstrated successfully. The most commonly used patterning methods are small molecule OLED (smOLED) deposition using vacuum evaporation with shadow masks [9], placing color filters on top of a white-light emitting OLED layer [10] and Polymer OLED deposition with inkjet printing [11]. Philips has chosen piezo-electric drop-on-demand inkjet printing, since this technology can easily be scaled to large substrates and provides a low-cost solution for making OLED displays. The use of expensive, high-accuracy shadow masks as required for smOLED deposition can be avoided in this way.

Inkjet printing has been used successfully by several companies to pattern the PEDOT (in an aqueous dispersion) and the light-emitting polymer (in an organic solvent) onto glass substrates. For example, in 2001, both Toshiba and Seiko-Epson showed a 2.8" display [12,13]. In 2002, Philips showed a 1.4" passive and a 1.6" active-matrix display [14]. In the same year, the first large screen was shown by Toshiba (17") [4]. Two years later, a 12.5" prototype was shown by Seiko-Epson on EDAX 2004 and they recently announced a tiled 40" display. Philips showed on the SID 2004 exhibition a variety of printed PLED displays ranging from 1" diagonal passive-matrix sub-displays, 2.6" active-matrix displays [6] to a 13" television screen [5]. These demonstrators illustrate that inkjet printing is becoming a mature technology.

The first challenge is to realize accurate placement of the PEDOT and LEP ink droplet into each sub-pixel on the substrate. Present mobile phone displays use resolutions in the range of 100 to 150 ppi, but already in 2 years from now QVGA (320×240) displays at 200 ppi are expected to become mainstream. The resulting pixel is then only 127 µm, requiring absolute placement accuracies of only a few microns and droplet volumes of less than 5 pl. Furthermore, the layer thickness profile in each pixel needs to be controlled carefully. Each pixel has to be completely filled to avoid leakage currents or short circuits, and the layer thickness needs to be uniform to provide a low driving voltage, a good efficiency, and a long lifetime. This can be achieved by optimizing the ink formulation, the substrate pre-treatment, and the drying process. The pre-treatment consists of two plasma steps: one for making the ITO hydrophilic (to achieve a good pixel filling) and a second one for making the dam non-wetting (to avoid overflow to the neighboring pixels). A delicate balance has to be found between these plasma steps and the additional requirement of getting a flat layer in the pixel. When using the optimized ink formulation and the optimized process, a flat layer can be achieved (see Figure 2) and the performance of inkjet printed devices is then identical to that of spin-coated devices [6].

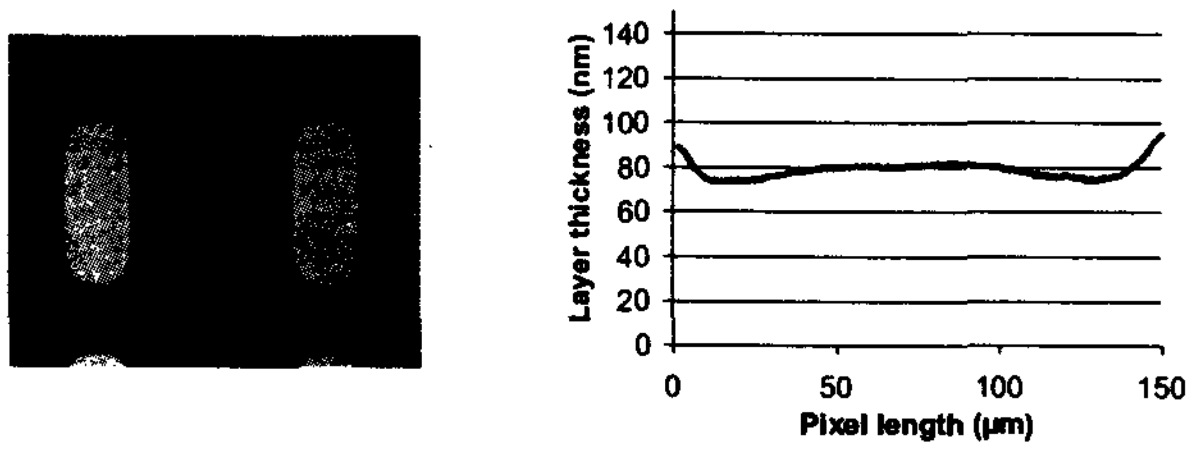

Figure 2 EL emission (left) and layer thickness profile (right) for an optimized ink measured across the pixel length [6].

Most printer systems for small mobile displays use only one nozzle for each row of pixels. By adapting the angle of the print head relative to the substrate, the nozzle pitch of the print head can be adjusted to fit the pixel pitch (see Figure 3a). In Ref. 5, we have presented a novel printing method for television applications. In comparison with mobile applications, pixels for television displays are relatively large (50 ppi). This makes it possible to use several nozzles on each multi-nozzle printer head to print a single sub-pixel (see Figure 3b). The print head moves from left to right and only the nozzles that are located above a predetermined position in the pixel are fired, while nozzles that are located above the dams are not used. The angle of the print head with respect to the substrate is adjusted in such a way that the droplet pitch (i.e. the spacing between two droplets measured perpendicular to the print head movement) is exactly an integer fraction of the pixel pitch in that direction. A major advantage of this graphical print method is that droplet size fluctuations from nozzle-to-nozzle are averaged out to a large extent. This gives more control over the layer thickness and the uniformity. We found that the resulting thickness variation from pixel-to-pixel is smaller than 2% [5].

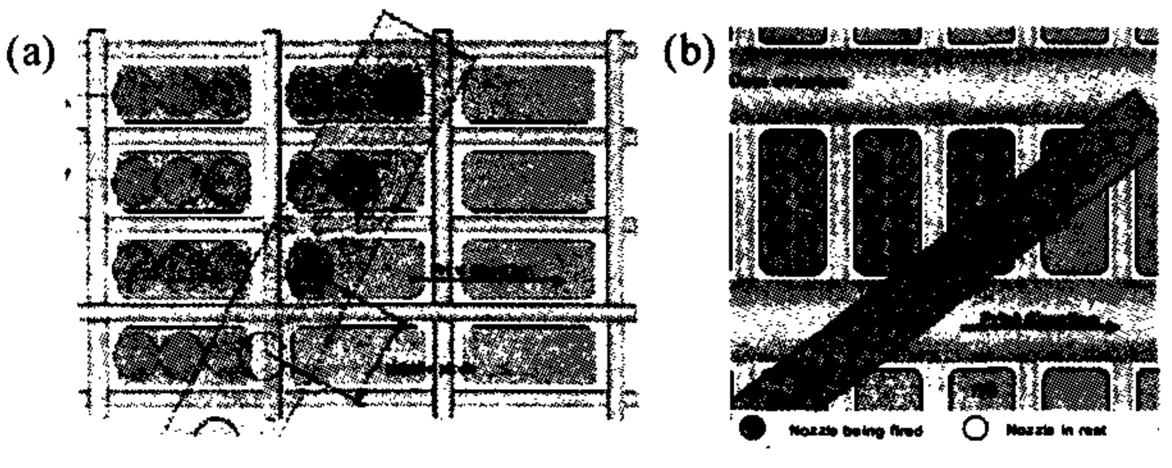

Figure 3 Schematic of line (a) and graphical printing (b) [5].

For the PLED television prototype, Philips has designed and built a new type of inkjet printer, with four multi-nozzle print heads that are mounted on one common stage [5]. Usually four separate printers are used, each with their own stage and multi-nozzle print head, to print the PEDOT as well as the red, green and blue LEP layers. An advantage of this new printer is that the plates do not need to be aligned between print runs. The machine is capable of printing up to 24" displays, but larger sizes are also possible by simply increasing the size of the stage.

4. Active-Matrix Addressing.

It is theoretically possible to make OLED displays with large sizes and high resolutions, without the use of an active-matrix back plane. This is because (in contrast to LCDs) high multiplex ratios (well in excess of 200:1) can be achieved with these devices, where all light is emitted over the line time (in direct response to the data signals) rather than over the frame time. However, there are practical problems associated with performing such 'passive' addressing using high current pulses over short times. Firstly, the high currents cause large voltage drops (and therefore power dissipation) down row and column conductors, and switching them at the line rate leads also to large capacitive power losses. The associated voltage drops cause further problems with image uniformity. Secondly, for most OLED materials the lifetime is found to depend more than linearly on the current density, i.e. driving at lower currents for longer times leads to a longer device lifetime. For these reasons, active matrices are essential above diagonals of a few inches and for high resolutions displays [15].

In active-matrix addressing, a TFT pixel circuit is used (see Figure 4), which basically stores a data value in the pixel, and then drives the OLED at this constant level over the entire frame time. In this way, the lowest possible current is used for the longest possible time, and the pixel capacitance is switched at a low frequency (i.e. the frame rate) and thus the performance with respect to image uniformity, power consumption and lifetime is greatly improved. This basic active-matrix principle can be extended in many ways. For example, the OLED can be driven over some fraction of the frame time (duty cycling) and either the drive level or the duty cycle can be varied locally by using in-pixel techniques such as 'optical feedback' (OFB) to compensate for differential ageing of the pixels (see below).

Firstly, we consider the most basic pixel circuits (see Figure 4). Current is supplied to each OLED device by TFT TS. In most schemes, this transistor operates in its saturation region where the current depends on the gate voltage, but is almost entirely independent of the voltage at the drain (and thus the current is insensitive to any voltage drops down the power lines). This current drives the OLED, which emits light more or less linearly proportional to the current. This transistor is most often referred to as the 'current source' or 'drive transistor', and appears in all active-matrix pixel circuits. The drive TFT needs to be programmed to supply the correct current to the OLED. This is realized by a matrix of addressing lines (rows) and data lines (columns) just as is used in AMLCDs. However, with OLEDs it is possible to use either current or voltage programming of the TFT circuit. The simplest way to address the driving transistor, and thus the OLED, is to write a data voltage on the gate of the drive TFT by means of a selection switch and then store it on a capacitor (see Figure 4). This original pixel circuit of Brody *et al.* is known under several names such as current source or 2 TFT circuit [16]. However, one problem with this circuit is that the data is stored with respect to the power line voltage, and thus image dependent voltage drops on the power lines can give rise to cross-talk. A powerful way of overcoming this problem is to add a second TFT switch between the driving transistor and the OLED, so that the current flow can be switched off (and thus the power line voltage drop removed) during addressing. This so-called 3 TFT circuit was first introduced by Hunter *et al* [17], and this extra switch appears in many more complex circuits to provide this type of function. This effect can also be obtained with a 2 TFT circuit by switching the cathode potential, though this can only be performed frame-at-a-time rather than line-at-a-time.

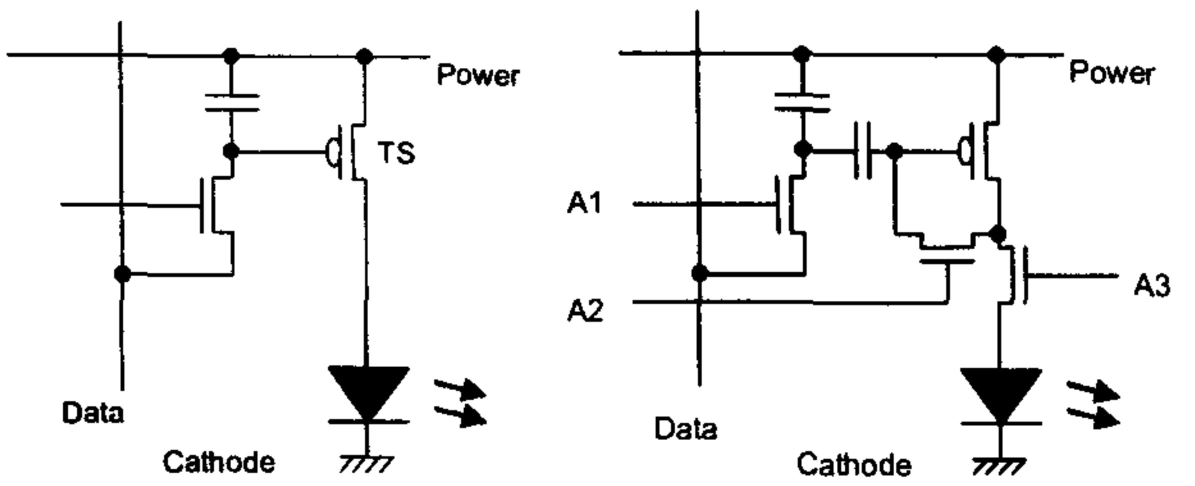

Figure 4 The basic 2 TFT Poly-Si pixel circuit (left) [16] and a more advanced 4 TFT V_t correction circuit (right) [19].

Another major issue with the 2 TFT pixel circuit is that any non-uniformities in the drive TFT directly show up as non-uniformity in the pixel brightness. The eye is much more sensitive to random point-to-point variation than to gradual long-range variation. Poly-Si TFTs by their very nature tend to show point-to-point variations in both threshold voltage and mobility. This is because the Poly-Si material is granular, and a statistical variation in grain size and grain properties leads to a statistical variation in the electrical properties. In some studies it is assumed that the variation in the electrical properties of the TFT is proportional to the variation in the number of grains under the gate [18]. This may be a little simplistic because the grains themselves may have variations in quality, and furthermore the current flow will be weighted to flow preferentially through the better grains. However, we do find that the uniformity is better for TFTs with large gate areas, and the TFT sizes are carefully selected with uniformity in mind. The uniformity in both the threshold voltage and the mobility of poly-Si TFTs is characterized by a standard deviation of ~1-5% for all forms of material we have studied. Variations in mobility translate directly into variations in brightness, and we find that these are hardly perceivable for the best poly-Si materials. However, variations in the threshold voltage (V_T) are much more problematic. The pixel brightness is proportional to $(V_G\text{-}V_T)^2$ where V_G is the gate voltage applied to the drive TFT. Thus, at low gray levels (i.e. when $V_G \sim V_T$) the errors can be large, and speckle is visible on the display.

V_T variation is also a problem for displays made with amorphous silicon (aSi:H) TFT back planes rather than poly-Si back planes. Although aSi:H shows excellent uniformity initially, these devices have poor stability, and the threshold voltage is found to drift in time. Consequently, the threshold voltage can vary from point-to-point by as much as 5V after displaying a static image at room temperature for thousands of hours.

In theory, both mobility and threshold voltage variations can be dealt with by addressing the pixel circuit with a current, i.e. 'current programming'. These pixel circuits sense the addressing current and then mirror the same current to the drive TFT [19]. This approach ensures the best uniformity since it automatically compensates for variation of both μ and V_T. However, in practice the programming of these circuits is slow due to the large parasitic column capacitance and the low program currents, particularly at low gray levels and for large displays.

Asymmetric current mirrors have been proposed in order to deal with this problem. In this case, the programming is via large currents into a large TFT in the pixel, and this is then converted into a small current through the drive TFT by the pixel circuit. However, the characteristics of the large and small TFTs have to be well matched, and in the case of poly-Si TFTs, relative variations in the TFT mobility can still translate into brightness variations. For aSi:H TFTs this approach is actually impractical because the larger TFT of the matched pair is too large to fit into the pixel. Thus, we believe that the best approach is to use a voltage programmed pixel circuit which corrects only for the variations in V_T. Examples of V_T correction pixel circuits are the well-known Dawson circuit [20] (in PMOS) and a variation of this circuit by Fish *et al.* [19] (in CMOS technology). In these pixel circuits, the signal is written on top of the threshold voltage of each driving transistor (see Figure 4). Variations of V_T are therefore compensated, while mobility variations remain uncorrected. In order to realize this, the addressing scheme performs an initial calibration of the V_T of the driving transistor. A similar correction scheme has been proposed using one less TFT and one less capacitor, whereby the OLED itself is used as a switch [21]. However, in order for this scheme to work the reverse bias leakage of the OLED must be exceptionally small to prevent charge leakage from the capacitor during the programming time.

Other pixel circuit schemes worthy of consideration are the optical feedback (OFB) circuits described by Fish *et al.* [22]. In these circuits, a photo detector is integrated in the pixel to monitor the light emission from the OLED. The signal from the photo detector can then either be read out by external electronics, or can be used within the pixel to adjust the light output of the OLED. Relatively simple pixel circuits can be used to simultaneously (i) correct for the non-uniformity in the OLED and drive transistor (ii) correct for the differential ageing of the OLED and the drive transistor (in the case of aSi:H) and (iii) to reduce the power consumption in the pixel. In one particular embodiment (the so-called 'snap-off' circuit) the data voltage is stored on a capacitor, and through some pixel circuitry, this maintains a constant current through the drive TFT held in either the linear or saturated condition. The voltage on this capacitor is then discharged by the photo detector at a rate proportional to the light being emitted by the OLED. Once a given amount of charge has been discharged (as determined only by the capacitance, the data voltage, the V_T of the 'snap-off' TFT, and the amount of light emitted) the circuit turns off the drive TFT, and stops the current supply to the OLED.

In the Philips' PLED television, a poly-Si back plane is used with the threshold voltage correction circuit of Figure 4 [5]. This enables us to demonstrate a uniform image over a lifetime equal to that of the OLED's themselves. In the future, we see a shift in the world to aSi:H back planes for large displays [21], since the cost of these is substantially lower than for poly-Si. Such back planes should also be able to compensate for OLED and TFT ageing effects by applying OFB techniques, using the basic aSi:H TFT as the photo detector (i.e. at no extra process cost). For small, high resolution displays we envisage the use of poly-Si rather than aSi:H, not just on the usual grounds of footprint, cost, and system integration, but also on the ground that it is difficult to fit all the circuitry in the pixel in the case of aSi:H.

5. Display addressing

In active-matrix LCD displays, a lot of effort is put in the reduction of motion artifacts. Basically, two different effects cause motion blurring. The first effect is the slow response time of the liquid crystal material. This problem is not present in OLED given its very fast response time. The second effect is the sample-and-hold artifact. When light is generated continuously in a frame, moving objects in the image will be perceived as blurred due to the eye tracking of these objects. Driving the display with a short duty cycle will reduce this artifact and very sharp moving images can be obtained. While in LCDs a short duty cycle is obtained by scanning or blinking the backlight, in OLED this can be accomplished in the addressing scheme (see Figure 5).

In an address & flash addressing scheme all pixels are addressed line-at-a-time. After this addressing phase, all pixels are activated simultaneously. The duty cycle can be altered by controlling the time that the pixels emit light. To keep the total light of the display constant, it is necessary to increase the light output during the active periods by a factor of (1/duty cycle). This introduces larger peak currents in the display, and consequently larger voltage drops in the power lines.

Peak currents are reduced in the scrolling-bar addressing scheme. The duty cycle can now be altered by changing the time between the on- and off-addressing of each line, i.e. the height of the scrolling bar. At each time instant, a fixed number of lines emits light which divides the peak currents over the frame period. We note that using vertical power lines is particularly beneficial for the scrolling-bar addressing scheme, since the current of the horizontal bar is smeared out over all vertically running power lines. Accordingly, the voltage drop is significantly lower in the scrolling bar scheme compared to the address & flash scheme.

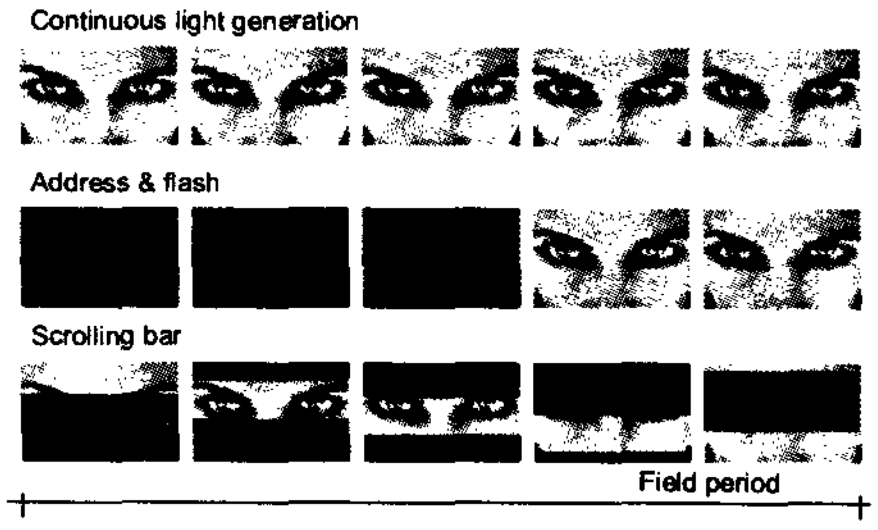

Figure 5 Three addressing schemes for OLED displays [5].

The emissive character of OLED displays allows an extremely high local peak brightness. This effect improves the perception of the display: in dark scenes we want to combine a high local peak brightness with the perfect black state of OLEDs in other areas of the image, while in white scenes the average brightness is dimmed. This mechanism results in sparkling images as known for CRT displays. There are several ways to implement this in OLED displays. A first approach is to alter the duty cycle in the addressing scheme depending on the spatially averaged image content. Figure 6 illustrates this principle. For a low image load, the duty cycle is increased by increasing the height of the scrolling bar, while for a brighter image the duty cycle is decreased. For a voltage programmed pixel circuit it is also possible to alter the peak brightness of the display by means of the maximum data voltage swing. For images with a low image load, this maximum data voltage can be increased resulting in a large peak brightness, while for images with a high image load the data voltage swing can be reduced.

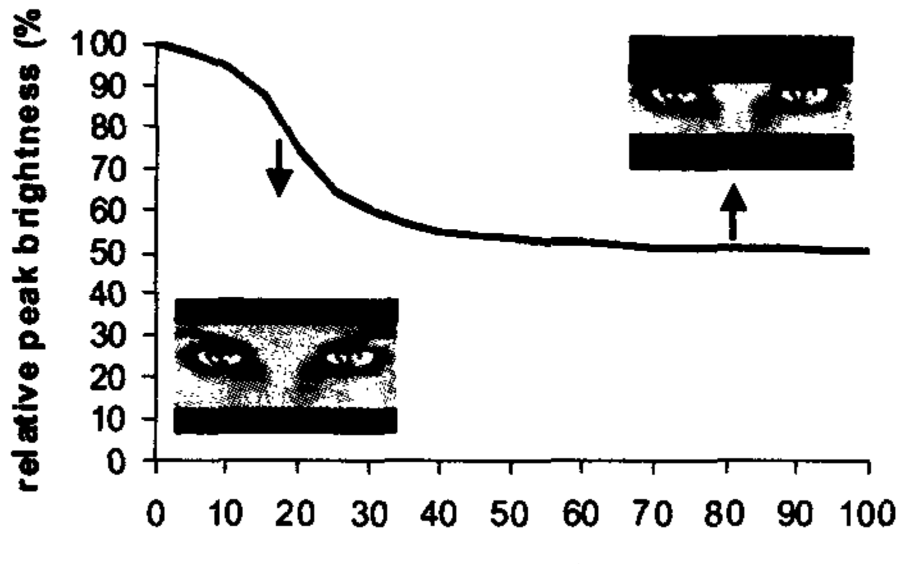

Figure 6 Adaptive image brightness control [5]

6. Video signal processing in OLED displays

Besides standard video processing like image scaling and frame rate conversion, video signal processing can also be used to enhance video quality of OLED displays. Especially color and grey level rendering can be improved. The color points of OLED displays differ from the standard EBU color points. Consequently, colors will not be displayed as originally intended, which can be corrected for by a color conversion algorithm. Basically, this algorithm maps the EBU color points to the color gamut of the polymer OLED display by means of a matrix multiplication. Colors that cannot be displayed by the OLED display are clipped to the boundaries of the OLED color gamut [5] or, alternatively, processed by a more sophisticated algorithm [23]. As a result, images are represented more naturally (e.g. skin tones).

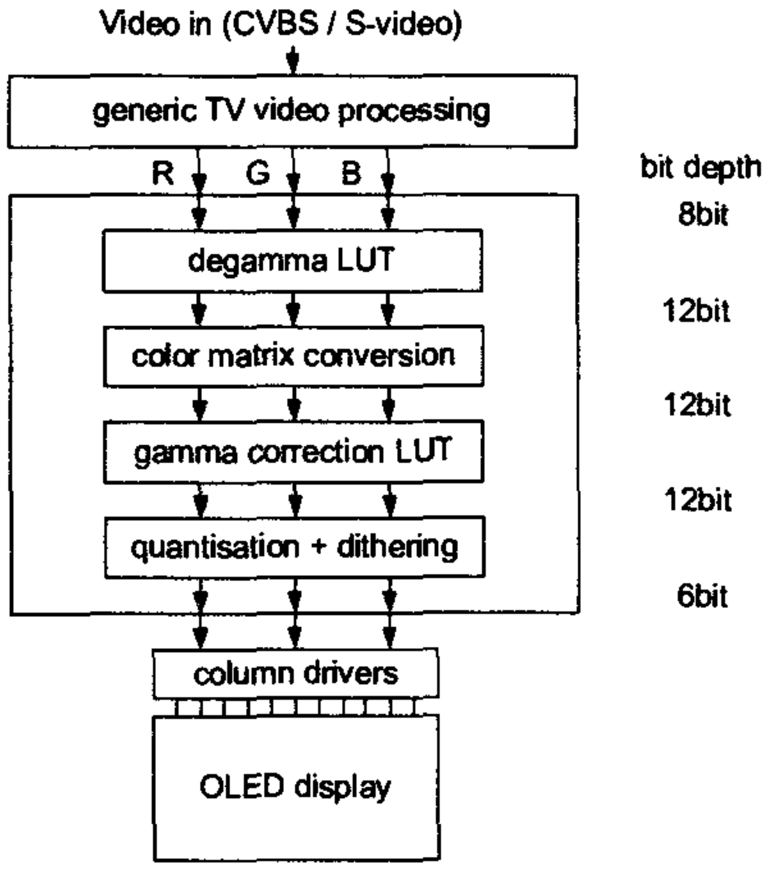

Figure 7 OLED specific video processing path [31].

The human visual system perceives luminance differences instead of absolute luminance. Therefore, luminance recorded by a camera is coded in a non-linear way, which is known as the gamma relation. Conventional CRT televisions exhibit the inverse relation, which ensures correct display of the video. Thus, in order to display the video correctly, an OLED display should have a gamma relation equal to that of the cathode ray tube:

$$L \propto \left(\frac{video_{in}}{video_{max}}\right)^{\gamma}, \text{ with } \gamma \approx 2.2. \qquad (2)$$

The gamma of an OLED display is determined by the pixel driving circuit in the active-matrix. When current addressing is used, the gamma relation is linear. When voltage programming is used, the gamma relation is determined by the quadratic voltage-current relation of the driving transistor (see Section 4).

The difference between the desired, CRT-like relation and the OLED gamma relation must be compensated for. One option is to implement this in the digital signal-processing domain. By means of a Look-Up-Table, the video is processed to obtain the over-all desired gamma relation. Because of the non-linear nature of this operation, the bit depth of the signal is increased. At the end of the signal processing chain, the video data is quantized and dithering is used to suppress quantization errors. An alternative is to adapt the grey level distribution in the column drivers, as is also done in an LCD display to correct for its gamma relation.

Both color processing and gamma correction are implemented in Philips' PLED television demonstrator [5]. The threshold voltage correction circuit realizes the favorable quadratic gamma relation of the system. Figure 7 shows the video signal-processing path of the display. A Look-Up-Table is used to remove the gamma that is applied at the camera from the 8bit input video. The bit depth is increased to 12 bit because this is a non-linear operation. Then, a 3x3 color conversion is performed. This conversion is followed by a Look-Up-Table that sets the gamma relation of the entire display chain. In this display, 6 bit column drivers are used, so the video data is quantized. Error diffusion is used to obtain a perceptually larger gray scale accuracy [24].

7. Polymer OLED materials

The lifetime, efficiency and color points of the polymer materials have improved significantly over the past ten years. Initially changes in cleaning and packaging and the introduction of a new anode (PEDOT:PSS) led to large lifetime extensions [25]. Tuning of the LEP composition further improved lifetime and efficiency. This resulted in the desired color ("Super Yellow" from Covion [26]) and paved the way for the first commercial products comprising a PolyLED display. More recent improvements are related to polymer design. The first LEPs were based on poly-phenylene-vinylene (PPV). Recent LEPs are based on a different concept, where a blue 'host' material can be combined with red or green 'dyes' (color tuning), and with units that affect charge transport properties. This versatile approach has been adopted by the major materials suppliers [27], and has resulted in a range of ink-jet-printable materials that span a wide color gamut (see Figure 8). The lifetime of red and green materials is already sufficient for several applications. Blue lifetime is expected to reach that level this year [6]. For a recent overview of the Philips effort we refer to Vulto *et al* [28].

Table I. Overview of lifetime (hr) of LEP within Philips, assuming 1/1/1 color ratio for R/G/B (100% duty, no polar).

250 cd/m^2 FOS peak white	Red	Green	Blue
Full on (250 cd/m^2 peak white)	10,000	15,000	2,000
On with average video content	192,000	396,000	49,600

In the literature, material performance is often specified at a luminance of 100 cd/m^2. However, the luminance needed in applications is usually significantly higher. For televisions, a peak white luminance is needed in the range of 200 to 600 cd/m^2. Table I gives lifetime values (to half brightness) that are relevant for a TV application that combines top emission with a high aperture (90%) and alternative ways (no polarizer) to achieve sufficient contrast. The values apply to a standard two layer device (PEDOT:PSS/LEP) using a Ba/Al cathode. Higher values have been reported by introduction of a third layer between PEDOT: PSS and polymer [29,30]. Table I also includes lifetime values for video applications, which were calculated [31] from video content statistics of DVDs and taking into account the relation between luminance and lifetime [28,29]. This gives much larger lifetimes to half brightness. However, for static images differential aging remains a problem that needs other solutions (see section 3).

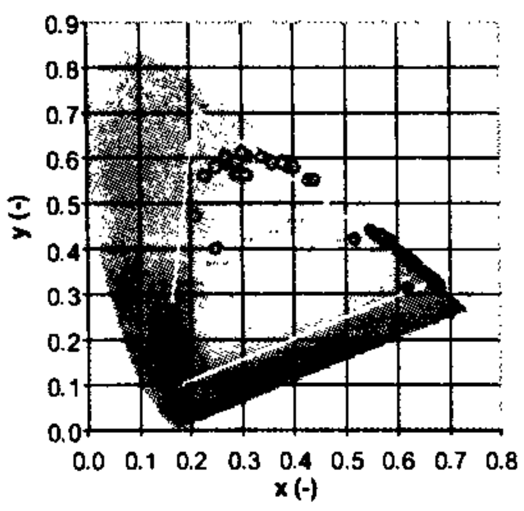

Figure 8 Overview of some LEP color points. The white triangle represents the EBU color gamut.

The efficiency of these long-living LEPs corresponds to an external quantum efficiency (EQE; photon/electron) of about 4%. Higher efficiency is needed for future generation (larger) displays, and is desirable for battery-powered hand-held applications. Recent major improvements in efficiency of laboratory devices show that a ten-fold enhancement can be reached. This enhancement comes from improvements in materials and device architecture, including optical out-coupling. On the materials side, a novel anode found at Philips resulted in a three-fold increase in the quantum efficiency to around 12% using *fluorescent* LEPs [32]. A similar value has been reported by other groups [33]. These results provide new insights into the much-debated singlet to triplet ratio [34].

Use of so-called triplet emitters that utilize both fluorescence and phosphorescence is another attractive method to increase the display efficiency. Many groups are developing new LEPs or solution-processable small molecules that provide three- to four-fold improvement over existing fluorescent LEPs in standard devices. The main point is that this can be achieved without any compromise of the technology's inherent simplicity and easy manufacturability. Recent examples include data on red phosphorescent polymers [35], and work by Brunner *et al.* and van Dijken *et al.* on new host materials for green phosphorescent emitters [36]. The status of fluorescent and phosphorescent materials is summarized in Table II. Rapid progress on red and green efficiency of phosphorescent materials is anticipated in the near future. High values have also been reported already by use of solution-processable small molecule emitters [see, *e.g.* dendrimer work in Ref. 29].

Table II. Overview of efficiency of LEP at Philips.

Efficiency (cd/A)	Red	Green	Blue
Fluorescent	2	10	5
Phosphorescent	10	40	--

8. Active Matrix Full Color PLED displays

While the first full-color PolyLED products will be passive matrix, Philips has also shown prototypes of active-matrix displays. Figure 9 shows a QCIF+ demonstrator with a resolution of 176 x 220 pixels made by full-color inkjet printing using an LTPS back plane [6]. In the same figure, a photo of Philips' first OLED television prototype is shown [5]. It is a 13"segment of a 30" diagonal High-Definition TV resolution (WXGA resolution (1365×768)) and was exhibited on the SID 2004 in Seattle.

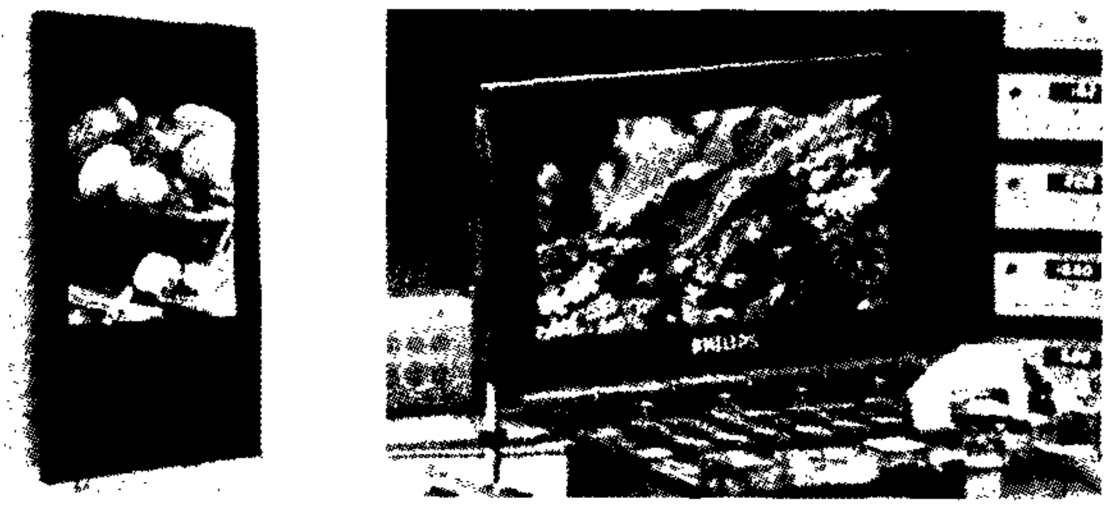

Figure 9 Active-matrix PLED displays: a 2.6" mobile main display [6] and a 13" television prototype [5] (see Table 1).

Table 1: Overview of the demonstrator specifications [5,6].

	Mobile	Television
Size	2.6"	13"
Resolution	176 (x 3) x 220	576 (x 3) x 324
Sub-pixel size	79 µm x 237 µm	165 µm x 501 µm
Peak Brightness	250 Cd/m^2	300 Cd/m^2
Color points	R (0.66, 034), G (0.39, 0.58), B (0.16, 0.22)	
Panel thickness	1.8 mm	
Gray scales	RGB 6 bits	
Display type	Polymer OLED with bottom emission	
Active matrix	Low Temperature Poly Silicon	

9. Mass Production of Polymer OLEDs

Together with several partners, Philips has invested significant effort in the development of mass production equipment for a full-color PLED process [6]. Major focus has been on the inkjet printing equipment, since only this part of the process is specific for polymer OLED. For cost-competitive mass production, the process should be capable of handling glass sizes of at least up to Gen 3.5 at a throughput of more than 15 plates/hour. Mid 2003 Philips installed the world's first mass production line in its PolyLED production facility in the Netherlands using substrates of 350 mm x 350 mm size (see Figure 10). The line consists of four printers (one for PEDOT and three for the Red, Green, and Blue LEP material). Start of mass production is planned for the end of 2004 with a 1" passive full-color display as first product. In 2005, the first active-matrix displays are planned for mass production. In addition, the development of the next generation equipment has been started targeting at Gen 3.5 glass sizes.

Figure 10 Full-color inkjet PLED production line of Philips (Heerlen, The Netherlands) using Litrex PJ 140 printers [6].

10. Conclusions

Philips has brought the full-color inkjet printing process of polymer OLED displays to an industrial level by installing the world's first PLED full-color production line. A high-yield full-color process has been developed and the mass production will start at the end of 2004. The first products will be passive-matrix, but the production start of active-matrix driven full-color mobile PLED products is planned for as soon as 2005. The expected increase in solution-processed material efficiency and lifetime will allow fabrication of larger panels up to 30" or 40" diagonal within five years. In the future, a shift is expected towards low-cost aSi:H back planes. These back planes should also be able to compensate for OLED and TFT differential ageing effects by applying, for example, optical feedback techniques. The combination of inexpensive inkjet printing and a low-cost back plane process is then a very interesting route towards inexpensive large-area high-quality television. For small, high resolution displays we envisage the use of poly-Si rather than aSi:H, not just on the usual grounds of footprint, cost, and system integration, but also on the ground that it is difficult to fit all the TFT circuitry in the pixel. For both large and small displays, video processing will be used to improve the image quality further and to fully exploit the inherent strengths of OLED displays.

11. Acknowledgements

We would like to thank the PolyLED team in Heerlen and our Philips Research colleagues for their contributions. We also thank all our collaborators mentioned in the Philips references below.

12. References

[1] K. M. Vaeth, Information Display 19, 12-17 (2003).

[2] T. Sasaoka *et al.*, SID 2001 Digest, p. 384, 2001.

[3] S. Terada *et al.*, SID 2003 Digest, p. 1463, 2003.

[4] M. Kobayashi *et al.*, IDW 2002, p. 231, 2002.

[5] N.C. van der Vaart *et al.*, SID 2004 Digest, p 1284, 2004.

[6] M. Fleuster *et al.*, SID 2004 Digest, p 1276, 2004.

[7] H. Lifka *et al.*, SID 2004 Digest, p1384, 2004.

[8] L.Moro *et al.*, 5214-15, SPIE 2003, 2003.

[9] Fukuda *et al.*, SID 1999 Digest, p. 430, 1999.

[10] Kido *et al.*, Science, vol. 267, p. 1332, 1995.

[11] T. Shimoda *et al.*, SID 1999 Digest, p 376, 1999.

[12] H. Kamiura *et al.*, Asia display /IDW'01, p 1403, 2001.

[13] S. Miyashita *et al.* Asia display /IDW'01, p 1399, 2001.

[14] E.I. Haskal *et al.*, SID 2002 Digest, p. 776, 2002. A. Giraldo et al., ASID 2002, p. 43, 2002.

[15] T. van de Biggelaar et al, Proc SPIE, 4295, 134, (2001).

[16] T. P. Brody, IEEE Trans.Electr.Dev. 22, 739-748 (1975).

[17] I. Hunter et al, SID 1999 Digest, 1095, (1999).

[18] A. Wang et al IEDM'98, 277, (1998).

[19] D. Fish *et al.*, SID2002 Digest, p 968-971, 2002.

[20] R. Dawson qt al., SID 1998 Digest, p. 11-14, 1998.

[21] J L Sanford et al, SID 2003 Digest, 10, 2003.

[22] D A Fish et al, SID 2004 Digest, 1120, 2004.

[23] E. Langendijk *et al.*, SID 2004 Digest, pp 1258, 2004.

[24] R.W. Floyd and L. Steinberg, SID 1976 Digest, p75, 1976.

[25] P. van de Weijer *et al.*, "Light Emitting Polymers", edited by J. Shinar and J.R. Sheats, Wiley & Sons, New York, 2004.

[26] H. Becker *et al.*, Adv. Mater. 12, 42 (2000).

[27] The Dow Chemical Company (www.lumation.com), Covion Organic Semiconductors GmbH (www.covion.com), Sumitomo Chemical (www.sumitomo-chem.co.jp/english/index.html).

[28] S.I.E. Vulto *et al.*, SPIE 2003, 5214-15, 2003.

[29] J. Burroughes, IDRC 2003, workshop on OLEDs, 2003.

[30] M. Leadbeater *et al.*, SID 2004 Digest, p. 162, 2004.

[31] J. Hoppenbrouwers *et al.*, to appear in the IDW '04, 2004.

[32] E.A. Meulenkamp *et al.*, SPIE Photonics Europe 2004

[33] TDK press release on Appl. Phys. Spring Meeting, March 2003; Q. Xu *et al.*, Appl. Phys. Lett. 83 (2003) 4695

[34] See e.g. M. Segal, *et al.*, Phys. Rev. B 68, 075211 (2003); Y. Cao, *et al.* Nature 397, 414 (1999); J.-S. Kim et al J. Appl. Phys. 88, 1073 (2000); M. Wohlgenannt *et al.*, Nature 409, 494 (2001);

[35] K. McAloon *et al.*, OLED Asia 2004

[36] Brunner *et al.*, J.Am.Chem.Soc.(2004); A. van Dijken *et al.*,ibid. (2004); K. Brunner *et al.*, Fpi6, Ithaca, New York, 2004.