Flexible Active Matrix Organic Light Emitting Diode (AM OLED) Displays

Kalluri R. Sarma, Jerry Roush, John Schmidt, Charles Chanley, Sonia Dodd
Honeywell International
21111 N. 19th Avenue, Phoenix, AZ 85027
kalluri.r.sarma@honeywell.com

Abstract: *Flexible displays are of high current interest for a variety of applications. In this paper we will first discuss recent developments in the enabling technologies for flexible displays - flexible substrates, TFT backplanes, display media, and thin film encapsulation. We will then discuss our current development efforts in low-temperature (150°C) a-Si TFT backplanes fabricated on PEN plastic substrates. Finally, we will describe our efforts on the design, fabrication and successful demonstration of flexible AM OLED displays fabricated using a-Si TFT backplanes on PEN plastic substrates using thin film encapsulation.*

Keywords: Flexible display; low-temperature a-Si TFT; flexible AM OLED; plastic substrate; thin film encapsulation

Introduction

The current high interest in the development of flexible displays for the commercial and military applications can be evidenced from the multiple conferences on flexible displays (such as the USDC Flexible Display and Microelectronics Conference [1], Intertech Flexible Display and Electronic conference [2]), various R&D Centers and Consortia focused on flexible display development (such the ASU/ARL Flexible Display center, FlexiDis), and numerous publications on flexible displays in technical Journals. Flexible display development is also benefiting from the developmental efforts in large area macroelectronics aimed at applications other than displays and vice versa.

Flexible displays fabricated using plastic or metal foil substrates have a potential for being very thin, light weight, highly rugged with greatly minimized propensity for breakage, and amenable to low-cost roll-to-roll manufacturing. OLED display media offers the advantage of being a rugged solid state structure for flexible displays. It also offers other potential advantages such as lower-power, superior image quality, and low cost compared to the current LCD displays. Flexible AM OLED displays can enable many unique applications, due to their inherent ruggedness, and unique form factors of conformability and rollability during use, transportation and storage.

Several enabling technologies must be developed to realize flexible displays. These technologies include: a) flexible substrates with the required characteristics and the associated substrate processes, b) TFT (thin film transistor) backplane, and display drive electronics designs and processes compatible with the selected flexible substrate, c) flexible display compatible display media, and d) thin film encapsulation / barrier layers for the protection of the OLED devices from oxygen and moisture in the ambient, for enhanced device life time.

Previously, we reported on the basic feasibility of fabricating an active matrix TFT backplane and AM OLED display on a flexible PEN plastic substrate using a 150°C a-Si TFT process [3-5]. In this paper, we will first discuss the recent status of the developments in the enabling technologies for flexible displays. We will then discuss our continuing efforts on development of low-temperature a-Si TFT backplanes on flexible PEN backplanes involving the design, fabrication and demonstration of flexible AM OLED displays with thin film encapsulation.

Flexible AMOLED Enabling Technologies

Flexible Substrates:
Thin metal foils such as stainless steel, and thin polymer substrate materials can be used as flexible substrates. Metal foil substrates offer the advantages of higher process temperature capability (for TFT fabrication), dimensional stability (no shrinkage of the substrate due to the temperature cycles associated with the TFT fabrication), and being impervious to oxygen and moisture. The limitations of the metal foil substrates include: requiring top emission OLED device architecture due to the opaqueness of the substrate, and poor surface smoothness characteristics. Use of metal foil substrates requires consideration of the capacitive coupling (parasitic capacitance) of the substrate to the backplane. The smoothness of the metal foil substrates must be increased by either polishing (for example by using chemical-mechanical polishing, CMP), or by applying additional surface smoothing layers, to achieve acceptable yield of the TFT and OLED devices to be fabricated. The backside of the metal substrate must be protected from the process chemicals during the backplane fabrication. Note that a metal foil substrate, by itself, is a good barrier (for oxygen and moisture) and it does not require an additional barrier layer. However, the display fabricated using the metal foil substrate would still require a good barrier layer to be applied on top of the OLED structure.

A transparent plastic substrate has the advantage of being compatible with both the bottom emitting and the top emitting OLED device architectures. A transparent plastic substrates is also compatible with transmissive and transflective AM LCD displays, thereby making them suitable for a broader range of applications. Also,

some plastic substrate materials, such as polyethylene naphthalate (PEN) films (Teonex® brand – Q65) [6-7], are fully compatible with the TFT fabrication chemistry. The major limitations of the available plastic substrates include: limited process temperature capability, lack of dimensional stability (during TFT processing involving high temperatures), and differences in the linear thermal coefficient of expansion (TCE) between the plastic substrate and the TFT thin films. TCE mismatch is an issue for stainless steel substrates as well, particularly if higher process temperatures are utilized.

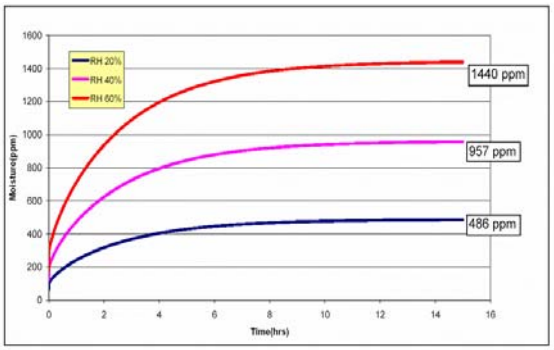


Figure 1. Moisture absorption of PEN

Based on a combination of considerations including: high optical transmission in the visible range (>87%), low moisture pickup, reasonable dimensional stability, reasonable surface smoothness, compatibility with TFT process chemistry, and the reasonable TCE match with the TFT thin films, we have selected polyethylene naphthalate (PEN) substrates (Q65) [7] for our development program. This substrate allows a TFT fabrication temperature of 150°C. It should be noted that while PEN (Q65) is superior to other available plastic substrates with respect to moisture pickup, dimensional stability, and smoothness etc., substantial improvements are still needed in these characteristics for AM OLED display applications.

We developed a pre-stabilization process involving annealing of the plastic substrates in vacuum at 160°C for 4 hours to increase the dimensional stability. The need for dimensional stability of the plastic substrate can be illustrated when we consider the typical design rules used in the TFT backplane fabrication. For a typical 3 μm design rule used (for a contact via, as an example), a shrinkage (mis-alignment) of more than 1.5μm is problematic. The as received "heat stabilized PEN substrate" shrinks by about 0.05 % during TFT backplane processing. This translates to a mis-alignment of 250 μm over a span of 50 mm (for a 2-inch display). Clearly, this level of shrinkage (dimensional in-stability) is not acceptable. With the developed pre-stabilization process, the shrinkage during TFT backplane processing is reduced to 1.5 μm over a 60 mm span (~ 25 ppm or 0.0025 %). Also, as all other plastic materials Q65 PEN substrate absorbs moisture resulting in a dimensional change [8]. Figure 1 shows the moisture absorption in PEN with time as a function of relative humidity, RH, at 20°C ambient temperature. Note that every 100ppm of moisture absorption results in a dimensional change of about 45ppm. To eliminate the dimensional changes associated with moisture absorption / de-sorption during TFT processing, we developed a moisture barrier deposition process. After the substrate pre-stabilization, and prior to the TFT array fabrication, a plasma deposited SiNx film was deposited on both sides of the PEN substrate. The SiNx film maintains the substrate's dimensional stability by eliminating moisture absorption during the TFT array fabrication processes, and the associated dimensional changes that occur with moisture absorption.

TFT Backplane Technology

TFT backplane technology is a crucial enabler for the fabrication of flexible AM OLED displays. The conventional glass substrate based TFT process cannot be used with the flexible plastic substrates, primarily because of the low-process temperature constraint. Because of the limitations of lower process temperature, lack of dimensional stability, and the thermal stresses due to the TCE mismatch between the TFT thin films and the substrate, new low temperature plastic compatible TFT processes must be developed. There are two main approaches for producing plastic backplanes:

1. Conventional (high temperature) TFT fabrication on a rigid glass substrate, followed by transfer of the TFT circuit (backplane) on to a flexible plastic substrate by adhesive bonding at a temperature less than 150°C. This process is referred to as Device Layer Transfer (DLT) process.
2. Fabrication of TFT array directly on the flexible plastic substrate. This involves fabricating poly-silicon (ULTPS – Ultra Low Temperature Poly Silicon), or a-Si:H, or Organic TFT (OTFT) at a temperature less than 150°C directly on the flexible plastic substrate.

Two different methods are used to produce TFT backplanes directly on flexible substrates. In one method, the flexible substrate is first bonded to a rigid carrier-substrate such as glass using a temporary adhesive, for ease of handling during TFT array fabrication. After the TFT array is fabricated, the flexible substrate with the backplane circuit is separated from the temporary adhesive (and the carrier substrate). The temporary adhesive needs to be compatible with TFT process conditions. In the second method, the TFT array is fabricated on the flexible substrate directly, without the use of a carrier. We adopted this second method in our approach.

Table I shows a comparison of the various TFT technology options. The DLT process [9, 10] provides a viable approach for flexible displays, when low cost is not a consideration. This approach can provide the most optimum TFT device performance with respect to mobility, leakage current, stability and uniformity as the

TFTs are fabricated using conventional LTPS (low temperature polysilicon at ~ 400°C) process, and then transferred on to the flexible plastic substrate at a low temperature. Even single crystal silicon TFTs from a silicon wafer can be transferred on to a plastic substrate. While several companies have demonstrated this approach, it is not believed to be the best solution for low cost flexible displays.

The ULTPS TFT approach has the potential for providing high mobility CMOS TFT devices suitable for driving the OLED pixels, as well as for fabricating the row and column drivers directly on the plastic substrate [11]. However, low temperature (< 150° C) processes must be developed for depositing a high quality gate dielectric. Also, hydrogen plasma passivation is required for achieving the desired TFT performance with low leakage current and threshold voltage stability and uniformity. Important progress continues to be made on this approach. Organic TFTs (OTFT) provide the ultimate potential for very low cost manufacturing. Impressive progress continues to be made on this approach [12,13], and TFT performance (mobility, threshold voltage, and leakage current) adequate for driving an OLED pixel has been demonstrated. However, this technology is still developing and is not believed to be sufficiently mature for the present development effort.

Table I. Comparison of the available TFT options

	Device Layer Transfer	Poly-Silicon (ULTPS)	a-Si:H	Organic TFT
Circuit Type	CMOS	CMOS	NMOS	PMOS
Device Performance				
- Mobility	Excellent	Good	OK for Pixel	OK for Pixel
- Off-Current	Excellent	OK	Excellent	OK
- Uniformity	Good	Issue	Good	OK
- Stability	Excellent	Issue	Issue	Issue !!
Cost	High	Medium	Low	Very Low ?
Maturity	Low	Low	Medium	Very Low

The a-Si TFTs used in the current commercial AM LCDs, are fabricated at a typical process temperature of 300°C. However, PEN plastic substrate requires a-Si TFTs to be processed at 150°C. Low temperature a-Si TFT processes have been developed recently [e.g. 3, 14]. These processes produce TFTs with mobility, threshold voltage and leakage current comparable to devices processed at 300°C. Low temperature a-Si TFT provides adequate TFT device performance for OLED pixels requiring drive currents in the μA range that are typical of the state of the art OLED materials and device structures. The combination of low cost potential, adequate device performance, and mature existing manufacturing infrastructure, makes a-Si the preferred technology option. However, one issue with low temperature a-Si TFT is the long-term stability of these devices under expected AM OLED operating conditions. In particular, threshold voltage, V_t, stability of the drive TFT is one area of concern. Several potential solutions are being investigated / developed for managing the TFT device stability to eliminate this concern with a-Si TFTs.

Display Media Technology:

A variety of display media are being considered for flexible display applications [1]. For a reflective display based on modulating the reflected ambient light, bistable display media such as electrophoretic, cholesteric LC mode, and MEMS type displays are being investigated. Bistable reflective displays have the ultimate low-power potential. However, for night time viewability, front lighting is required which increases the display power consumption. Other general shortcomings of this type of display media are slower display response time, and poor color capability compared to transmissive LCD displays and OLED displays.

AM OLED (Active matrix organic light emitting diode display) technology offers a significant potential for realizing rugged, full color, lightweight, low power and low cost flexible displays. AM OLED technology based on rigid glass substrates is advancing rapidly. Small size (~2–inch diagonal) displays are currently used in products such as mobile phones. AM OLED technology continues to make progress towards realizing superior, low-power and low-cost large size (e.g. 40-inch) for applications such as TV [15].

Thin Film Encapsulation:

Since the plastic substrates are not impermeable enough to protect the OLEDs, a barrier layer must be added to the substrate. Further whether using a plastic substrate or a stainless steel substrate, the top side of the OLED must be protected with an impermeable encapsulation layer. For protection of an OLED display the barrier layer must have a permeability less than 1e-6 gm/m^2/day for moisture and 1e-5 mL/m^2/day for oxygen. Vitex [16] has developed an elegant approach for the barrier layer as shown in Figure 2. In this approach the barrier layer consists of a multi-layer stack of inorganic barrier films and organic compliant films as shown in Figure 2. In this scheme, the inorganic films serve as a barrier film for oxygen and moisture, organic layers serve the planarization/smoothing function, and multi-layers provide redundancy against pin hole defects in the barrier films. The Vitex films are transparent in the visible region and are compatible with top emission OLED displays. We have selected and used Vitex barrier layers in our flexible AM OLED demonstration displays discussed in the next section.

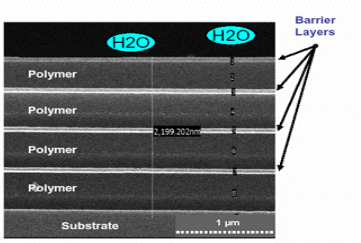
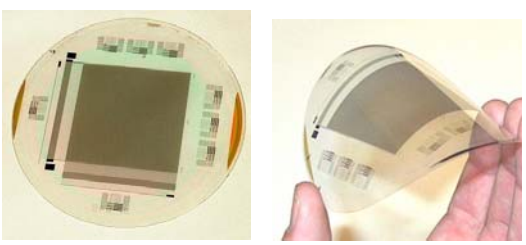


Figure 2. Vitex Barrier comprising a multi-layer stack of organic and inorganic films [16]

Flexible AM OLED with Thin Film Encapsulation

Based on the 150°C a-Si TFT process developed earlier [3], we developed and optimized a 7–mask TFT backplane process using the PEN plastic substrate. The process is similar to that of conventional high temperature CHP (Channel Passivated) type a-Si TFT process. However, the process recipes for the TFT thin film depositions, particularly for the a-Si and SiNx dielectric layers are optimized for a 150°C process, to achieve mobility, and leakage current characteristics comparable to the high temperature processed TFTs [3,13]. Further, the mask and process design details are optimized by taking into consideration the expected level of plastic substrate shrinkage during the TFT process, and thin film stresses due to CTE mismatch. As an example, the ITO pixel electrode process has been implemented as a lift-off process as opposed to an etch-type process to reduce the thin film stress and to increase the yield. Four-inch diameter, 125 µm thick Q65 PEN plastic substrates [7] are utilized for fabricating the backplanes for the test displays. Two backplane (test display) designs have been developed. The first design involved a 64x64 pixel monochrome display with an 80 dpi (dots per inch) resolution to demonstrate the basic feasibility with proof of concept test displays. The second design involved a 160x160(x3) pixel display to demonstrate a display with a larger size and higher resolution, and to determine display size and resolution limits. Figure 3 shows photographs of fully processed 160x160(x3) pixel backplanes on 4-inch diameter PEN plastic substrates. The design included various test structures and process control monitors placed at the periphery of the pixel arrays.

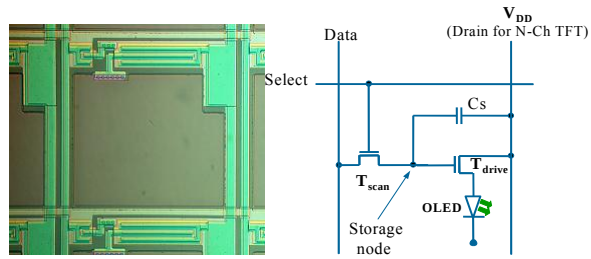


(a) **(b)**

Figure 3. Active matrix backplanes fabricated on flexible PEN plastic substrate: a) 160x160x(x3) pixel array, b) Illustrating flexural capabilities

Figure 4a shows photographs of the pixel region in the fabricated backplane illustrating the layout of the scan and drive TFTs, and the storage capacitor in a 64x64 pixel backplane. Figure 2b shows the electrical schematic of the pixel with 2 TFTs/pixel.

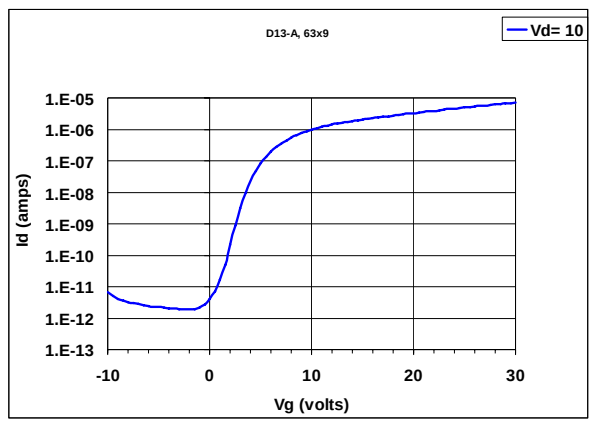
One of the critical requirements for successful backplane fabrication is maintaining registration of various TFT mask levels during processing as the substrate dimension changes due to shrinkage and moisture absorption. Using the substrate pre-stabilization process, and SiN_x barrier layers, we achieved acceptable dimensional stability and layer-to-layer alignment accuracy sufficient for fabricating functional backplanes and displays.



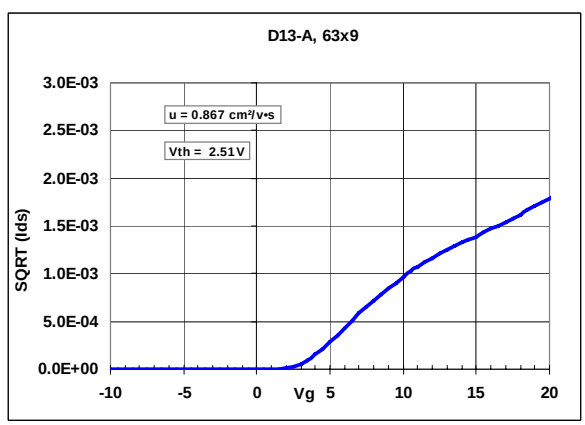
(a) (b)

Figure 4. (a) Photograph of a fabricated pixel in a 64x64 pixel backplane, and the (b) electrical schematic

Figure 5 shows the typical performance of a 150°C TFT in a fabricated backplane. Figure 5a shows the transfer characteristics for a TFT with a W/L ratio of 63µm / 9µm. This device shows an on-current, I_{on} , of 7 µA, and an off-current, I_{off} , in the picoamp range. Figure 5b shows a plot of $\sqrt{I_{ds}}$ versus V_{gs} (=V_{ds}) for the TFT in saturation. This TFT shows a mobility of 0.87 cm^2/v.s and a threshold voltage, V_t, of 2.5V. These performance characteristics are sufficient to drive an AM OLED pixel.



a



b

Figure 5. Typical TFT Characteristics in a fabricated backplane: a) transfer characteristics, b) Square $\sqrt{I_{ds}}$ versus V_{gs} (=V_{ds}) for a TFT in saturation

OLED Display Fabrication

During the initial development phase, the fabricated backplanes were integrated with the OLED display media and laminated to a cover glass using an adhesive. The cover glass protects the AM OLED from oxygen and moisture in the ambient air. We fabricated test displays using both the backplane designs. While the 160x160(x3) pixel backplane is designed for a R, G, B color display with a 80 cgpi resolution, we chose to fabricate a 480x160 pixel monochrome using this backplane as a first step to validate the active matrix design and fabrication for large size and high resolution capabilities. Monochrome OLED devices were fabricated on the a-Si backplanes on the Q65 substrates, using standard OLED materials, device structures, and processes.

Flex cables associated with the row and column drivers are then bonded to the row and column bus pads on the display with a heat seal connection, to complete the display assembly. The display assembly is then connected to the display drive electronics system for test and evaluation.

Separate versatile drive electronics systems are designed to exercise and evaluate each test display. Both the test displays utilized a conventional AM LCD COTS row driver. Since no suitable commercial gray-scale driver was available for a display of only 64 columns, a simple 64-channel sample and hold (S/H) circuit was devised for the column driver. Analog VGA data is amplified and level-shifted such that it corresponds with the optimal operating range of the display under test. A 1:64 multiplexer switches the pixel data to the appropriate hold amplifier; one for each column of the display. For the 160x160(x3) pixel test display an AM LCD type column driver is used with a chip on flex (COF) implementation.

Results and Discussion

Table II shows the salient design features of the 64x64 pixel test display designed and fabricated. The basic design features of the 160x160(x3) pixel test display are similar to the ones in Table II except for a subpixel pitch of 100µm x 300µm and an active display area of 48 mm x 48 mm with an 80 cgpi resolution.

Table II. Salient features of the 64x64 pixel test display

Display Resolution	64 x 64 Pixels
Color	Monochrome Yellow
Pixel Pitch	80 dpi - 300 x300 microns
Active Area	19.2 mm x 19.2 mm
Active Matrix Element	150 C a-Si TFT , Inverted staggered structure, CHP type
AM OLED Pixel Design	2 TFT / Pixel, Voltage Programmed Current Drive
Backplane processing	7 Mask process
Display Driving	External Row / Column drivers

The display test and evaluation process initially consisted of interconnecting the display assembly to the drive electronics system and exercising the display with various test images and evaluating the display performance as the display drive voltages are optimized. For control purposes, a-Si TFT backplanes and AM OLED displays were fabricated on rigid glass substrates using the same 150°C process along with the backplanes and displays on plastic substrates.

Figure 6 shows the photographs of test images in a 64x64 pixel test displays fabricated on flexible PEN plastic substrates. Figure 7 shows the photograph of test images on a 160x160(x3) pixel test displays we fabricated. While these displays show a few pixel and line defects, they were found to function as designed. The fabricated displays are found to be capable of displaying grayscale images and full motion video. In general the control displays fabricated using glass substrates were found to perform similarly except for having fewer pixel and line defects. The surface quality of the PEN plastic substrate was found to have a significant impact on the quality of the displays fabricated with respect to pixel and line defects observed. Displays fabricated on PEN substrates with improved surface quality exhibited significantly fewer display defects.

Figure 6. Test images in a 64x64 pixel test display fabricated.

Figure 7. 160x160(x3) pixel test displays fabricated

Following the design verification by demonstration of displays fabricated Q65 flexible PEN substrates, we fabricated, flexible AM OLED test displays using the same backplane designs, but used Barix thin film encapsulation [16]. Figure 8 shows a schematic cross-section of the AM OLED display fabricated. The Barix (barrier film) is of the order of only a few microns. Thus the thickness of the flexible display fabricated is about ~130 microns. Figure 9 shows the photographs of a flexible AM OLED test display fabricated along with its flexural capabilities. The fabricated displays were found to function essentially similar to the test displays in Figure 6 using the glass substrate lamination. While we

had not made systematic life time measurements of the OLED displays we fabricated, the observed lifetimes clearly indicated the effectiveness of this approach.

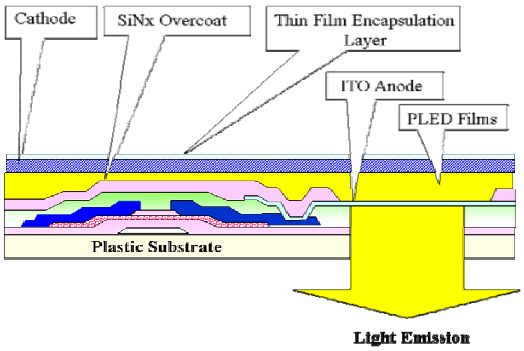


Figure 8. Schematic cross-section through the AM OLED test display with thin film encapsulation

The evaluation and characterization of the flexible displays we fabricated highlighted handling issues for these displays. The flexible displays can tolerate flexing up to a critical bend radius. However, when the display gets bent with a radius smaller than the critical radius, it leads to cracking of the overcoat layer on the plastic substrate, and this crack propagates through the address bus lines. The cracked bus structures cause the displays to exhibit intermittent line failures, gross line failures, or large regions of non-functioning areas including complete display failure. We have verified that by using appropriate tooling and fixtures during display assembly operations, these failures can be prevented. Special bezels were designed and constructed to hold the test displays. The bezel protects the display during assembly and subsequent handling and testing.

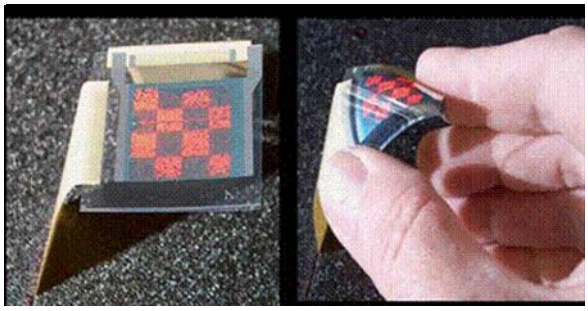


Figure 9. AM OLED with thin film encapsulation

While we have demonstrated the feasibility fabricating small (48mm x 48 mm) size displays with 80-cgpi resolution, we believe that even larger size displays and higher display resolutions will be possible by further improvement of the dimensional stability of the plastic substrates.

Summary

We have developed a 150°C a-Si TFT process and backplane designs for fabricating AM OLED displays on flexible Teonex® Q65 (PEN) plastic substrates. Monochrome AM OLED test displays were fabricated using these plastic backplanes and a thin film Barix encapsulation layer to demonstrate flexible displays. Test display sizes up to 2x2-inch with an equivalent resolution of 80 cgpi are demonstrated. Appropriate handling of the plastic substrate (backplane) was found to be essential to minimize handling related damage (yield loss), particularly when fabricating large area displays. With further improvements in dimensional stability and design enhancements such as top emission OLED device architecture, this approach shows promise for fabricating large area, high resolution flexible AM OLED displays.

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