Flexible Low Power Consumption Active-Matrix OLED Displays

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ABSTRACT

Advanced mobile communication devices require a bright, high information content display in a small, light-weight, low power consumption package. In this paper we will outline our progress towards developing such a low power consumption active-matrix flexible OLED (FOLED™) display. Our work in this area is focused on three critical enabling technologies.

The first is the development of a high efficiency long-lived phosphorescent OLED (PHOLED™) device technology, which has now proven itself to be capable of meeting the low power consumption performance requirements for mobile display applications.

Secondly, is the development of flexible active-matrix backplanes, and for this our team are employing poly-Si TFTs formed on metal foil substrates as this approach represents an attractive alternative to fabricating poly-Si TFTs on plastic for the realization of first generation flexible active matrix OLED displays. Unlike most plastics, metal foil substrates can withstand a large thermal load and do not require a moisture and oxygen permeation barrier.

Thirdly, the key to reliable operation is to ensure that the organic materials are fully encapsulated in a package designed for repetitive flexing. We also present progress in operational lifetime of encapsulated T-PHOLED pixels on planarized metal foil and discuss PHOLED encapsulation strategy.

Keywords: OLED, phosphorescence, top emission, PHOLED, metal foil substrate.

INTRODUCTION

Much of the interest in OLED displays comes from the unique features offered by this technology, many of which surpass those of AMLCD's, particularly for mobile applications. The first and perhaps most important characteristic is that by employing phosphorescent OLED (PHOLED) technology, OLED displays can consume significantly less power than their backlit LCD counterparts. In addition, OLEDs are an emissive display technology, using extremely thin films of organic materials to produce light. OLED displays have a very thin form factor, determined predominantly by just the substrate thickness, as opposed to conventional LCD's which require a backlight. Considerable focus is now being given to developing flexible OLED displays on non-rigid substrates, such as metal foil and plastic, to produce more rugged, thinner, conformable and even rollable displays for novel mobile applications.

In this paper we will discuss the three critical technology areas to fabricate flexible AMOLEDs: phosphorescent OLED (PHOLED) device technology, flexible active-matrix backplanes, and thin film encapsulation.

RESULTS

Phosphorescent OLED Technology

Low power consumption is a key display requirement for mobile applications. The first efficient small molecule OLED devices were invented by Tang et al from Kodak in the 1980's, and in these conventional fluorescent small-molecule OLEDs [1] light emission occurs as a result of the recombination of singlet excitons, and the internal quantum efficiency is limited to approximately 25%. Based on the pioneering work by Professor Stephen Forrest at Princeton University and Professor Mark Thompson at the University of Southern California [2,3], UDC is developing the next generation of high efficiency phosphorescent OLED (PHOLED) devices. In the phosphorescent system, all excitons may be converted into triplet states through inter-system crossing around a heavy metal atom. These triplet states emit radiatively, enabling the extremely high performances shown in Table 1.

EL Color	Red	Green	Blue
CIE – (x, y)	(0.65,0.35)	(0.32,0.63)	(0.14,0.13)
Efficiency @ 1,000 cd/m^2	18 cd/A	37 cd/A	9 cd/A
Lifetime (hours)	40,000@ 500 cd/m^2	25,000 @ 1000 cd/m^2	Under development

Table 1. Performance of a selection of UDC PHOLEDs

Work on further stability and efficiency improvements as well as long-lived deep blue phosphorescent emission is ongoing [4, 5, 6] .

To demonstrate the performance of our high efficiency material system, Figure 1 shows updated simulations of the power consumption for 2.2" diagonal active-matrix full-color display for UDC's phosphorescent OLED devices (PHOLEDs), state of the art fluorescent small molecule materials (FLOLED), and a backlit AMLCD. For the OLED displays we assume a 45% efficient circular polarizer, and that 30% of the pixels are illuminated. OLED drive voltage is 6V with a 4V drop across the driver TFT. Color balance is 5:3:2 for G:R:B. The use of PHOLED technology enables displays to have lower power consumption than a backlit AMLCD, significantly extending battery life for mobile devices, and providing significant power savings compared to the use of fluorescent OLED technology.

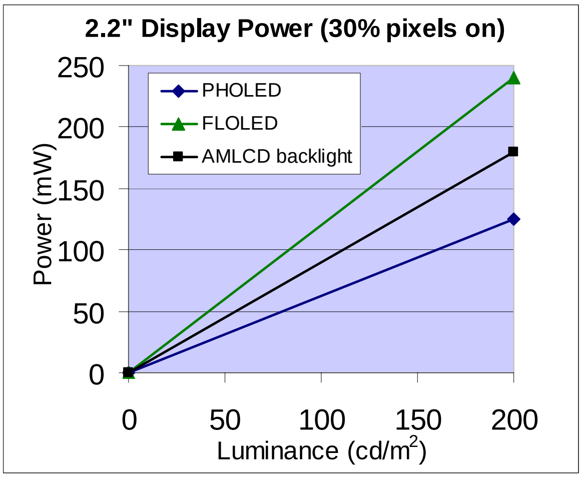

Figure 1. Simulated power consumption for a 2.2" cell phone display using phosphorescent OLEDs (PHOLED) fluorescent OLEDs (FOLEDs), compared to an AMLCD backlight

The high conversion efficiency of PHOLEDs has additional benefits to AMOLED technology, and particularly for flexible AMOLED displays. The lower drive current requirements of PHOLEDs will make it easier to use amorphous silicon (a-Si) (and eventually organic TFTs) as the backplane TFT technology. These technologies will be very important as they enable backplanes to be fabricated at lower temperatures than conventional LTPS, facilitating the launch of AMOLEDs on plastic substrates.

In addition the lower drive current requirements of PHOLEDs reduces the display power consumption, and therefore the display operating temperature, which will extend the display operational lifetime. Lower pixel currents will also provide more tolerance for the bus line resistance, enabling thinner metallization, which will also simplify the manufacture of displays on flexible substrates.

Flexible Backplanes for AMOLEDs

To date the backplane technology of choice for small size rigid AMOLEDs is LTPS. For flexible backplanes there are essentially two technology paths, in addition to a transfer approach we are not considering in this work, as it is not scalable to large area manufacturing. The two choices are either to use a plastic substrate with a low temperature TFT technology (OTFT or a-Si), or else a metal substrate which allows for a higher temperature (poly-Si) TFT process.

Table 2 provides a summary of the characteristics of the main TFT technologies applicable to flexible substrates.

	Poly-Si	a- Si	OTFT
Type	CMOS	NMOS	PMOS
Performance			
Mobility	Very good	OK for PHOLEDs	OK
Leakage	OK	Very good	OK
Stability	Good	Issue	Issue
Uniformity	Issue	OK	Issue
Production	Maturing	Excellent	N/A
Cost	> Medium	Medium	Low ??
Plastic compatibility	Under Development - difficult	Good	Excellent

Table 2. Summary of the characteristics of the main TFT technologies applicable to flexible

There is currently a great interest in driving AMOLEDs using a-Si TFTs because of its low cost potential, particularly for larger size displays. The development of a-Si based AMOLEDs also provides a path for flexible AMOLEDs on plastic. For high resolution flexible AMOLEDs it will be important to integrate sufficient electronics to allow the display to only be connected from one side, so for these displays poly-Si is the backplane technology of choice. While several groups are investigating fabricating poly-Si TFTs on plastic, stable and spatially uniform OLED pixel driving circuits have not yet been demonstrated. So UDC is pursuing poly-Si TFT backplanes on metal foil for its first flexible phosphorescent AMOLED display prototypes.

Table 3 shows a comparison of key performance metrics comparing plastic versus metal foil substrates for AMOLED applications. Metal foil has advantages of being more rugged and able to withstand higher processing temperatures than plastic. As a disadvantage, conventional metal foils are rough and require planarization before deposition of TFTs and OLEDs. In addition, metal foil substrates require the application of OLEDs with transparent cathodes.

	Metal substrate	Plastic substrate
Ruggedness	Good	Poor
Temperature	Good	Poor
Dimensional stability	Predictable	Plastic flow
Permeation	Good barrier	Needs barrier
Thermal conductivity	Very good	Poor
CTE	Medium	High
Roughness	Rough	Smooth
Transparency	None	Good
Cost	Low	Low to High

Table 3. Comparison of key characteristics of metal and plastic substrates for AMOLEDs

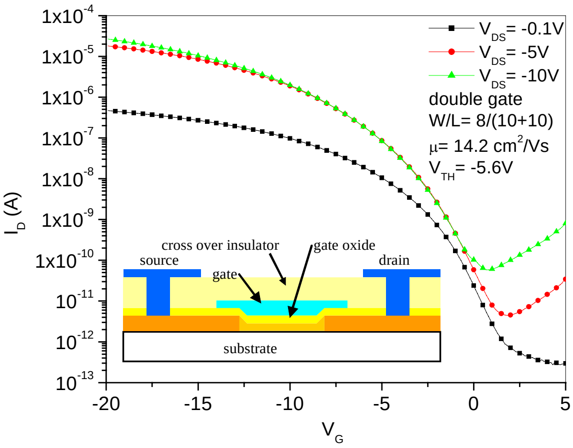

Figure. 2. I_D-V_G characteristics at three different source-drain voltages for a poly-Si TFT fabricated on metal foil substrate.

Figure 2 shows a representative transfer characteristic from a poly-Si PMOS transistor on metal foil, along with the device structure as inset. Reasonable TFT performance is achieved with p-channel mobility of around 14 cm^2/Vs, threshold voltage of -5.6 V, and leakage current of 5 pA for -5 V source-drain voltage.

Top Emission AMOLEDs

The fabrication of OLED displays on metal substrates requires the emission of light from the top OLED

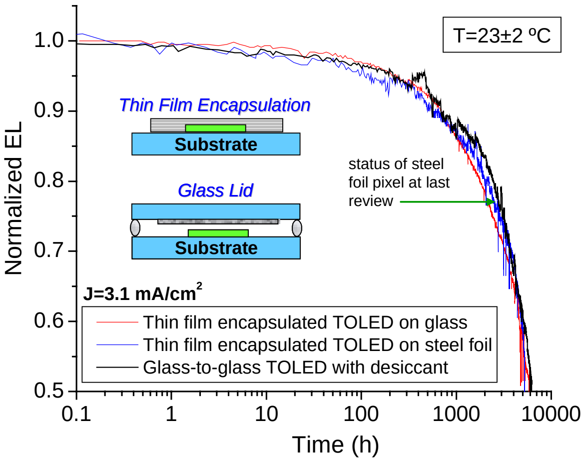

Figure. 3. Preliminary data comparing the lifetime of thin film encapsulated TOLEDs fabricated on both glass and metal substrates

surface. As to date, the best OLED performances (lifetime-efficiency product) have been obtained by depositing OLEDs in sequence from anode to cathode, the use of metal substrates necessitates that the OLEDs use transparent cathodes. Additionally, in most AMOLED displays the TFT pixel circuit occupies a significant fraction of each sub-pixel, reducing the pixel aperture ratio, particularly if more complex 4 or 5 TFT compensation pixel circuits are employed, so top emission OLEDs can be fabricated over the TFTs to significantly increase the aperture ratio.

Using our transparent compound cathode consisting of a thin metal layer e.g. MgAg, and a transparent conductive oxide, such as ITO, we have present data [7] showing a higher luminous output from a top emission OLED as compared to an equivalent bottom emission OLED.

Encapsulation for Flexible AMOLEDs

Another critical component for flexible AMOLEDs, is the development of a flexible permeation barrier. OLED's degrade as a result of exposure to atmospheric oxygen and water, causing oxidation and delamination of the metal cathode [8], as well as detrimental electrochemical reactions within the organic layers. Since most OLED work to date has been focused on the development and manufacture of glass-based displays, the degradation problem has been ameliorated by sealing the display in an inert atmosphere using a glass or metal lid attached by a bead of UV cured epoxy resin [9]. Metal is also an ideal oxygen/water permeation barrier, so OLEDs fabricated on metal foil only require encapsulation after deposition.

One potential solution to providing the necessary barrier properties to prevent water and oxygen from causing OLED degradation is to use a multi-layer barrier coating between the OLED device and the environment .

Specifically, UDC and Vitex have demonstrated long lived thin film encapsulated OLEDs fabricated on metal foil substrates prepared by PARC. Figure 3 shows preliminary data comparing the lifetime of thin film encapsulated TOLEDs fabricated on both glass and metal substrates, compared to a standard TOLED in a glass to glass package [10].

Extrapolated lifetime for the thin film encapsulated pixel on steel foil is 5,000-6,000 hours, or the same as that on glass, while the transparent glass-to-glass TOLED pixel lifetime will be approximately 8,000-10,000 hours.

Flexible Phosphorescent OLED Displays

Figure 4 shows examples of thin film encapsulated phosphorescent TOLED icons demonstrated at the 2004 SID conference in Seattle, WA. These photographs clearly show our ability to produce long lived OLED displays on metal substrates. We are currently integrating poly-Si backplanes with thin film encapsulated top emission PHOLED devices to demonstrate a flexible AMOLED full color display.

Figure 4. Examples of thin film encapsulated phosphorescent TOLED icons demonstrated at the 2004 SID conference by UDC, Vitex Systems and PARC.

CONCLUSIONS

We have outlined key technical components for the development of low power consumption flexible AMOLED displays. The use of phosphorescent OLED technology is critical to reduce power consumption for mobile applications, and we have show how these emissive display elements can be combined with appropriate substrates and TFT backplanes, and then packaged with a multi-layer thin film encapsulation to enable long-lived flexible AMOLED displays.

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