Full Color Top Emission AMOLED Displays on Flexible Metal Foil

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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. For portable applications flexible (or conformable) and rugged displays will be the future. In this paper we outline our progress towards developing such a low power consumption active-matrix flexible OLED (FOLED™) display. We demonstrate full color 100 ppi QVGA active matrix OLED displays on flexible stainless steel substrates. Our work in this area is focused on integrating three critical enabling technologies.

The first technology component is based on UDC's high efficiency long-lived phosphorescent OLED (PHOLED™) device technology, which has now been commercially demonstrated as 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 PARC's Excimer Laser Annealed (ELA) 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, and in this device we employ a multilayer thin film Barix encapsulation technology in collaboration with Vitex systems. Drive electronics and mechanical packaging are provided by L3 Displays.

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 report our progress on the development of full color active matrix OLED (AMOLED) displays on steel foil substrates for low power consumption, high information content, rugged and flexible/conformable applications.

While most FOLED work to date has been on thin plastic films, the maximum process temperature of the backplane is limited by the thermal properties of the substrate. Conventional Si-based TFT backplane processes for AMOLED displays require temperatures in excess of 300C which cannot be supported by current practical plastic substrate candidates. For early demonstration of flexible or conformable AMOLED displays, we have therefore chosen a steel foil substrate.

Our displays integrate the three key enabling technologies toward power efficient flexible AMOLED displays: high efficiency top emission phosphorescent OLEDs (PHOLEDs™), low temperature poly-Si TFT backplanes, and flexible thin film encapsulation. To our knowledge this is the highest resolution full color AMOLED display on flexible steel foil to date.

Feature	Description
Resolution	320x3x240, 100 ppi
Pixel Design	2-TFT, RGB Stripes
Gray Scale	64 levels
Substrate	6 inch square metal foil, 100µm thick
TFT backplane	Low temp 350^{o}C poly-Si
Encapsulation	Multilayer thin film
Electrical Connection	One-sided

Table 1. AMOLED Display on Steel Foil Specifications

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], the next generation of high efficiency phosphorescent OLED (PHOLED) devices are rapidly being developed and commercialized [4]. 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, and adjusting for optical effects such as outcoupling [5,6], the internal quantum efficiency of such devices has been estimated to be close to 100%.

For our first demonstrations of poly-Si TFT driven full color AMOLEDs on steel foil, we have employed both phosphorescent red and green dopants, with a fluorescent blue pixel. Table 2 shows the performance of our chosen OLED system. We calculate the total power that will be required to drive a QVGA display using this system is 400mW. The fluorescent blue will be replaced with phosphorescent blue when we achieve long lifetime for saturated blue emission, which will lower the power requirement further. Today, significant progress in blue PHOLED lifetime has been reported with >17,000 h for a light blue device with CIE (0.16,0.29) at an initial luminance of 200 cd/m^2 .

Table 2. Performance of OLED Materials

Material	CIE(x,y)	cd/A	$t_{1/2}$ (h)	cd/m^2
Red PHOLED	(0.65,0.35)	21	300,000	500
Green PHOLED	(0.32,0.63)	65	40,000	1,000
Fl Blue	(0.14,0.15)	8.5	10,000	200

To demonstrate the reduction in power consumption from incorporating our high efficiency PHOLED technology into an AMOLED display, Figure 1 shows simulations of the power consumption for 2.2" diagonal active-matrix full-color display for an all fluorescent display, together with incorporating one (red), two (red and green) and all three color (red, green and blue) of UDC's phosphorescent OLED devices (PHOLEDs).

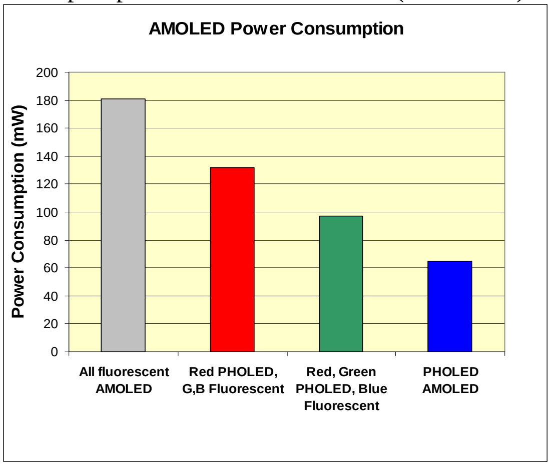

Figure 1. Power consumption of 2.2" video-rate display with replacement of fluorescent OLED pixels by higher efficiency phosphorescent OLED technology pixels

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.

LTPS Backplane

Previous demonstrations of AMOLED backplanes on steel foil, both a-Si [5] and poly-Si [6], have been achieved. For the array fabrication we used an excimer laser annealed (ELA) poly-Si TFT process [7] to enable future use of shift registers and/or multiplexing circuits to reduce the number of external connections. The metal foil process was developed based on PARC's original ELA poly-Si TFT process on glass substrate [8].

Starting with standard mechanical grade stainless steel foil, we first apply a polymer surface planarization and insulating layer. Next a 500 Å of a-Si is then deposited by PECVD as poly-Si precursor. The a-Si is transformed to poly-Si by successive ELA. After non-self aligned source/drain contacts lithographically defined, gate oxide is also deposited by PECVD, and metal gate is formed by another photolithography step. The cross over dielectric, data line metal, OLED anode, and OLED active aperture are formed after a standard hydrogenation process. The pixel design is a standard 2-TFT PMOS sample-and-hold circuit with RGB stripes.

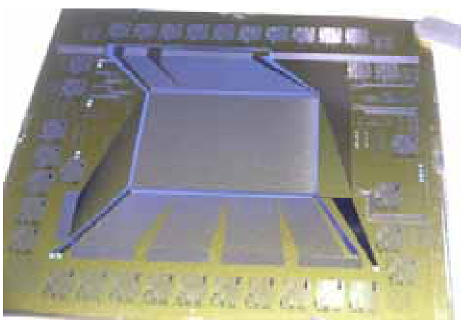

Figure 2. Poly-Si TFT backplane for AMOLED on 6"x6" steel foil.

Figure 2 shows a picture of a completed backplane on steel foil with various test structures along the periphery. A representative transfer characteristic from a switch transistor is shown in Fig. 3 with a pixel circuit diagram in the inset. The PMOS TFTs typically achieve a mobility of 60 cm^2/Vs and threshold voltage -4±2 V.

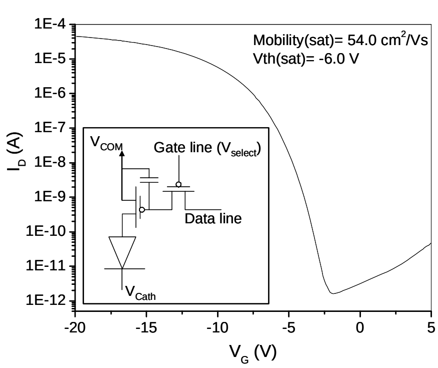

Figure 3. I_D-V_G characteristic of a poly-Si PMOS transistor on steel foil. *Inset*: 2-TFT pixel circuit showing the switch and drive transistors, capacitor, and OLED.

A picture of a completed top emission AMOLED display on steel foil showing color bar test pattern is presented in Fig. 4. In the inset, the individual red, green, and blue pixels can clearly be seen. The emissive layers were deposited through a 100 ppi shadow mask using conventional thermal evaporation; all common layers were deposited through a separate mask. The non-white vertical lines, bright/dark rows, and individual pixel outs represent defects in the display which we are currently working to decrease.

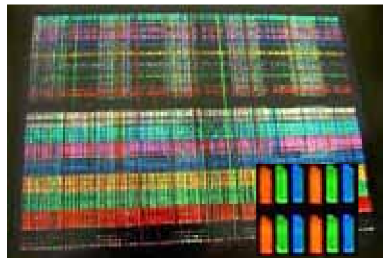

Figure 4. Top emission AMOLED display on steel foil with RGB stripes showing color bar test pattern (inset: subpixels in white region). Display shown is 320(x3)x240 with 100 ppi resolution.

Conformal Encapsulation

Flexible AMOLED displays require encapsulation that both protects the OLED from OLED contaminants (e.g., H_2O and O_2) and also allows the display to be flexed. In this work we used a multilayer stack with alternating polymer and high density inorganic layers to protect the OLEDs from contaminants such as moisture and oxygen. The inorganic layers act as diffusion barriers to water/oxygen while the polymer layers decouple defects in the oxide and provide stress relief during flexing [9].

The encapsulation process includes deposition of Al_2O_3 layers, which are reactively sputtered onto the display via an energetic plasma, and polyacrylate layers, which are deposited via flash evaporation of the monomer followed by UV curing [10]. Recent results for top emission samples encapsulated in this manner are included in Fig. 5. The figure includes lifetime data for green PHOLED top emission test pixels on glass and steel foil substrates with either glass lid or multilayer thin film encapsulation. All samples achieved lifetimes to half luminance around 5,000 h. We note that the TOLED device structure was not optimized for lifetime.

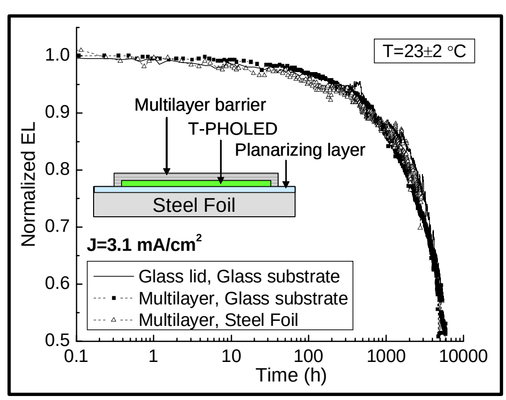

Figure 5. Operational lifetime results for three top emission PHOLED test pixels on glass substrate or steel foil with glass lid or multilayer thin film encapsulation.

Drive Electronics

The drive electronics convert standard analog video input signals into the drive signals required for the AMOLED display. The drive electronics consist of two circuit card assemblies: the tape automated bonding (TAB) circuit interface card and the display manager card. All of the electronics and TAB drivers are commercially available components. Since the TAB drivers were designed for use on AMLCD displays, the TAB driver signals were logically inverted to accommodate the AMOLED LTPS backplane.

Figure 6 shows a digital image demonstrated on a full color AMOLED display on steel foil with thin film encapsulation. Scrolling text and full motion video were also achieved on this display. The 4” diagonal QVGA display resolution is 100 ppi.

Figure 6 Full color image demonstrated on a thin film encapsulated, 100 ppi, 4” diagonal AMOLED display on steel foil.

CONCLUSIONS

We have demonstrated a poly-Si TFT driven, full color top emission AMOLED display on steel foil with 100 ppi resolution. To the best of our knowledge, this is the highest resolution full color AMOLED display on metal foil that has been demonstrated to date. The maximum processing temperature of the backplane was 350C and was limited by our choice of planarization layer on the substrate. The red and green OLEDs were based on UDC phosphorescent OLED technology while the blue was fluorescent. All OLEDs employed a top emission structure. The QVGA display was encapsulated using a multilayer thin film barrier stack, and the final encapsulated display was driven using commercially available AMLCD drivers and electronics. While we are continuing to improve our display yield on steel foil substrates, we believe our results demonstrate a viable path towards the achievement of high resolution flexible and conformable AMOLED displays for low power consumption, high information content portable communication applications.

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