Highly Flexible Low Power Consumption AMOLED Displays on Ultra-Thin Stainless Steel Substrates

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Abstract

We present results demonstrating that low power consumption phosphorescent AMOLED displays can be fabricated on ultra-thin (25µm) stainless steel substrates, combining an amorphous silicon backplane with a top emission phosphorescent OLED frontplane. We will present preliminary results of flexibility testing on these displays.

1. Introduction

Portable communication devices are becoming ubiquitous as their functionality and convenience continue to improve. A key component of such devices is the display on which information is communicated. Most are made of glass and are therefore breakable. The future of displays for portable applications is flexible (or conformable) and rugged. Over the last few years there has been much work on fabricating OLED displays on flexible substrates such as plastic [1] and metal foil [2]. In this work our goal is to demonstrate truly flexible AMOLEDs built on ultra-thin 25µm thick stainless steel substrates.

In this paper we show the AMOLED pixel design, incorporating a model for the OLED electro-optic performance into a SPICE circuit simulation program. We then outline key process steps in the flexible AMOLED fabrication. The use of phosphorescent OLEDs enables low power consumption AMOLED displays to be realized. We demonstrate a TFT backplane process that operates when bent to the tight diameter of 5 mm.

2. AMOLED fabrication

The display specifications for our prototype flexible AMOLED display are given in Table 1.

Table 1. Specification of our flexible AMOLED display.

Item	Specification
Size	3 inch (diagonal)
Resolution	160 (H) × 120 (V)
Pixel Size	381 µm × 381 µm
TFT design	a-Si TFT – 2 TFT structure
Peak brightness	150 cd/m^2 monochrome
OLED design	Top emission PHOLED
Substrate	Flexible metal foil

To model the 2-TFT amorphous silicon pixel we used a SPICE simulation which included the Luminance-Current-Voltage (LIV) characteristics of our green phosphorescent OLED (PHOLED™) top emission devices. The OLED model is based on Ref [3] where the OLED current density, j, is related to the applied voltage (or electric field E) by

$$j_{tu} = A_{tu} E^2 \exp(-E_{tu} / E) .$$

The modeled result is in good agreement with measured data, as shown in Figure 1.

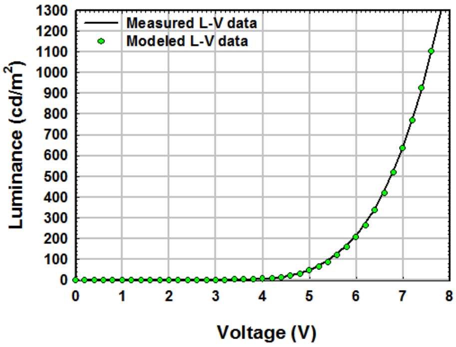

Figure 1. Comparison between measured and modeled data for a green PHOLED top emission structure.

Figure 2 shows one example of a pixel layout design. The W/L of the switching and driving TFTs are 30 μm / 5 μm and 704 μm / 5 μm, respectively.

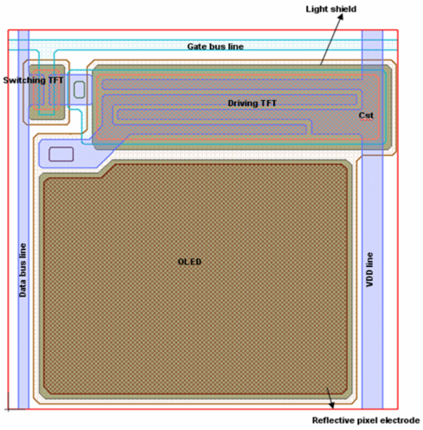

Figure 2. Pixel layout for 3-inch flexible AMOLED.

Standard mechanical grade stainless steel foil, which typically has an average surface roughness of 10 nm rms, is planarized for use in AMOLED displays. In this work we use a spin-coated polymer material chosen because of its superior planarization capability.

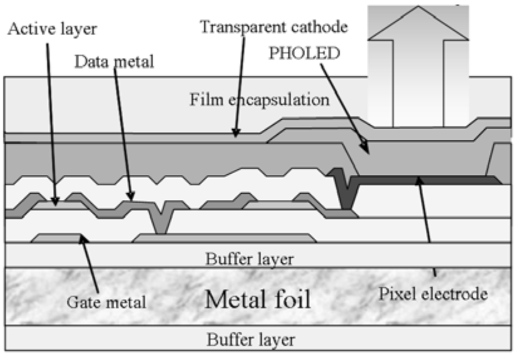

Figure 3. A cross-sectional view of a sub-pixel of AMOLED on flexible metal foil.

TFT fabrication

Figure 3 shows a cross-sectional view of a pixel in a 3-inch AMOLED display with top-emission. The substrates are 25 μm, 304 SUS foil. MoW was deposited on PI planarized metal foil by DC sputtering for gate bus line. A 400 nm silicon-nitride, a 150 nm a-Si:H and a 50 nm n^+ a-Si:H layers were deposited consecutively by plasma enhanced chemical vapor deposition (PECVD). After forming a-Si:H islands by dry etching. MoW was deposited on the n^+ a-Si:H and then patterned for data bus lines. The n^+ layer between the source and drain electrodes was subsequently etched away. Finally a 400 nm thick SiN_x was deposited for passivation and via-holes were formed.

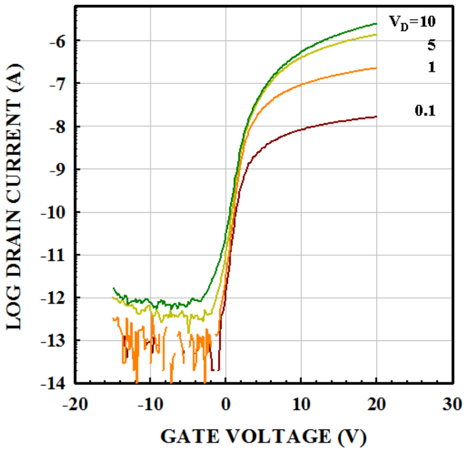

Figure 4. Transfer characteristics of a-Si:H TFT (W/L = 30 μm / 5 μm) fabricated on a planarized 25 μm metal foil substrate.

Figure 4 shows the transfer characteristics for an a-Si:H TFT fabricated on the planarized, 25 μm stainless steel foil. The TFT exhibited the field-effect mobility of 0.51 cm^2/Vs, a threshold voltage of 1.51V, and a sub-threshold slope of 0.89 V/decade.

Phosphorescence

Low power consumption AMOLED displays can be achieved with high efficiency phosphorescent OLEDs (PHOLEDs). In conventional fluorescent OLEDs, the internal quantum efficiency is limited to approximately 25 % since only the singlet excitons recombine to emit light. In a PHOLED system, however, heavy metal atom centers enable efficient spin-orbit coupling [4]. The spin-orbit coupling allows both singlet and triplet excitons to be harvested as phosphorescent radiation in the guest-host systems, leading to internal quantum efficiencies of up to 100 % [5]. The higher efficiencies lead to at least three times reduction in display temperature rise compared to a fluorescent OLED display [6]. This is an important consideration for mobile devices.

The very high IQE makes PHOLED technology ideal for both flat panel display and solid-state lighting applications, and close to 100% internal emission efficiency has now been reported for all primary colors. Additionally, phosphorescent device lifetimes have rapidly increased to be competitive with the best in the industry. Lifetimes for red PHOLEDs with external quantum efficiency (EQE) values of 20-21% are reported with LT50 lifetimes of > 200,000 hours at display level luminance of 1,000 cd/m^2. Green PHOLEDs with LT50 = 240,000 hours from 1,000 cd/m^2 with EQE = 19% (64 cd/A) have been realized, and advancements are continuously being made in blue PHOLED device performance.

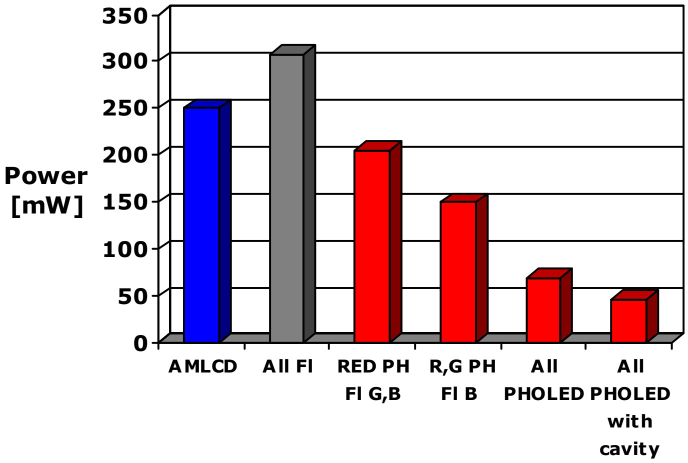

Figure 5 – Simulated power consumption roadmap for 2.8” AMOLED display using different combinations of fluorescent and phosphorescent OLED technologies. Assumptions are 180 cd/m^2, 30% video rate, 4V OLED and 4V TFT. Also shown is equivalent power consumption for backlit AMLCD.

Figure 5 shows simulations of the power consumption of a 2.8” display operating at 180 cd/m^2 showing video content for various technology options. Also shown for comparison is power consumption of an equivalent AMLCD backlight operating at 225 cd/m^2, having similar visual performance to an AMOLED operating at 180 cd/m^2. While the AMLCD backlight consumes 250 mW, an AMOLED using only fluorescent technology would consume 308 mW. The plot shows power savings that can be achieved by incorporating PHOLED technology. Firstly using just a red PHOLED sub-pixel power consumption can be reduced to 205 mW, the addition of green PHOLED sub-pixels leads to a further power reduction to 150 mW, and the use of an all PHOLED system will reduce power consumption to 69 mW. Finally we can see that using microcavity effects to further increase emission in the forward direction, an all PHOLED display consuming only 46 mW could be realized.

Top emission OLED

OLED displays on metal substrates require the emission of light from the top OLED surfaces.

Two different approaches in making transparent cathodes include: 1) the use of a thin metal and 2) the use of a compound cathode which includes a thin metal layer and a transparent conductive oxide (TCO) layer. With the first approach, although the structure maybe simpler, the transparency of the cathode is typically low. When a compound cathode is used, a wide range of conductivity-transparency performance can be obtained by tuning the two layers.

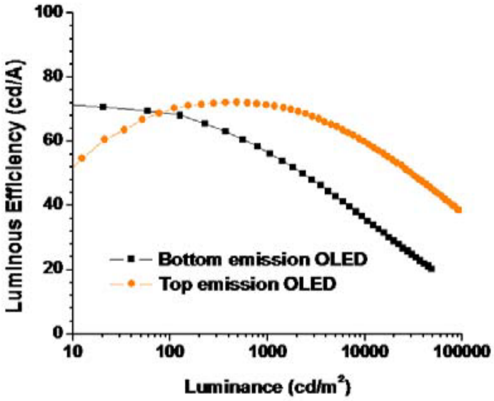

Figure 6. Luminous efficiency curve of a top emission OLED (orange circles), compared with that of a bottom OLED (black squares).

TCO cathodes can also improve the lifetime of the OLED displays because they have good barrier properties, and can also provide protection for organic layers when further processes, such as thin film encapsulation, are employed.

Using a transparent compound cathode consisting of a thin metal layer and a transparent conductive oxide, in Figure 6 we present data showing the luminous efficiency from a top emission OLED as compared to an equivalent conventional bottom emission OLED. Even though the top emission device is not fully optimized, it shows greater luminous efficiency than the conventional bottom emission device.

Flexibility testing

Bending or stretching a flexible display induces strain in the electrical performance of TFT during and after mechanical strain is applied.

Figure 7 shows the transfer characteristics at drain voltage V_d= 0.1 V of an a-Si:H TFT on a planarized 25μm metal substrate measured during bending inward or outward. The TFT was on the surface of a cylinder of 5 mm diameter. Gate leakage current was low even during the substrate was being bent. However, the threshold voltage increased and thus the on-current decreased when the TFT was bent inward.

Figure 8 shows the relative field-effect mobility μ/μ_0, threshold voltage V_{th}/V_{th0}, and sub-threshold slope S/S_0 as a function of strain (ε), where μ is the mobility under an imposed strain and μ_0 is the mobility at flat state. The field-effect mobility increases when the substrate bends outward and decreases as substrate bends inward. The mobility near the flat substrate, using the data within the global strain (ε)±1%, can be expressed by

$$\mu/\mu_0 = 1+0.24\varepsilon$$

TFT performance was found to be unchanged even after the TFT was bent 10,000 times, which indicates good flexibility of the TFT on an ultra-thin metal foil.

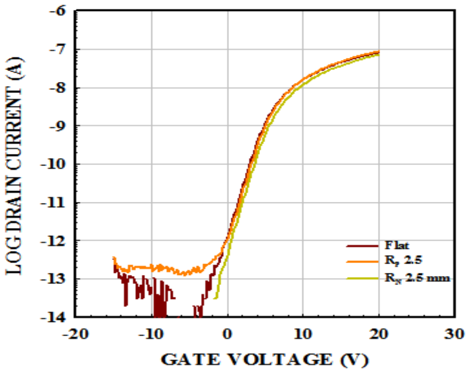

Figure 7. Transfer characteristics of a-Si TFT (W/L = 120 µm /5 µm) fabricated on 25µm metal substrate measured during bending inward and outward in 5 mm diameter. The drain currents flow along the cylinder.

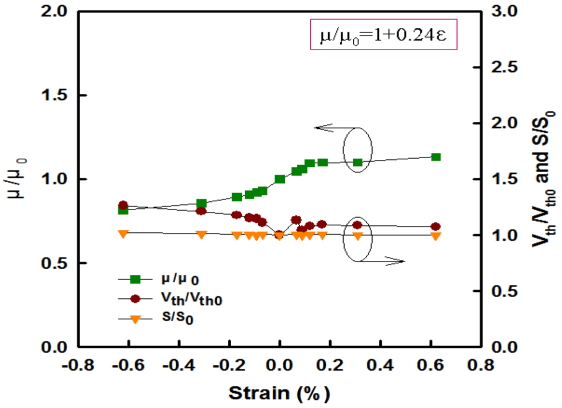

Figure 8. Relative field-effect mobility μ/μ_0, threshold voltage V_{th}/V_{th0}, and sub-threshold slope S/S_0 of an a-Si:H TFT on 25 um metal foil as a function of strain (ε).

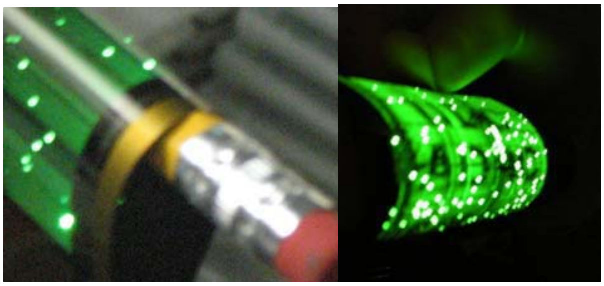

Figure 9 - Photographs of our flexible displays fabricated on 25µm foil.

Figure 9 shows photographs of our flexible displays fabricated on 25µm foil.

3. Summary

We have designed a low power consumption phosphorescent AMOLED display fabricated on ultra-thin (25µm) stainless steel substrates. Experimental results show the performance of amorphous silicon backplanes adequate to drive AMOLED displays, and flexibility results on these backplanes show that they can operate when conformed to a tight diameter of 5 mm. We have successfully fabricated AMOLED prototypes on ultra-thin foil substrates.

4. References

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