Active-Matrix OLED Display Backplanes Using Transfer-Printed Microscale Integrated Circuits

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Abstract

Active-matrix organic light-emitting diode (AMOLED) displays have been fabricated using backplanes with transfer-printed microscale silicon integrated circuits (ICs) in place of conventional thin-film transistors (TFTs). The ICs were fabricated using a commercial semiconductor foundry process, and the wafers were subsequently processed to prepare the ICs for transfer-printing. The microscale integrated circuits were transfer printed onto a glass substrate and interconnected using a single-level, thin-film metallization process. The resulting OLED display exhibited good pixel-to-pixel luminance uniformity, high luminance, excellent controllability, and high switching speed. The transfer-printing process achieved good positional accuracy and high yield.

Introduction

Conventional AMOLED devices are driven by an array of thin-film transistors deposited over a substrate prior to OLED deposition. Many alternative material technologies exist today for making TFT backplanes, including deposited amorphous Si, polycrystalline Si, microcrystalline Si, various metal-oxide semiconductors, and organic semiconductors. To achieve a high-quality display, these TFTs must precisely control the current in each light-emitting OLED pixel so that the overall display has uniform luminance (no mura), control without hysteresis, and with sufficient mobility and dynamic range to provide at least four decades of luminance for high contrast ratio. In addition, any viable display backplane technology must be stable with use over time, scalable to large-size glass for large displays, and have low manufacturing cost. The currently available TFT backplane technologies, many of which were developed for non-current-driven, active-matrix LCD displays, do not meet all of these requirements.

In sharp contrast to TFTs, transistors made in crystalline silicon by modern semiconductor foundries have very high mobility (greater than 1000 $cm^2/V*s$ compared to 100 $cm^2/V*s$ or less for typical thin-film transistors), good uniformity, and excellent stability compared to thin-film transistors. This paper describes a method for making high-performance AMOLED backplanes by transfer-printing small high-performance integrated circuits onto the backplane substrate. The manufacturing process and performance of the AMOLED display are described.

Transfer-printing is an emerging technology that enables massively parallel assembly of devices onto virtually any substrate, including glass, plastics, and metals [1, 2]. Transfer-printing is accomplished using a microstructured elastomeric stamp to selectively "pick-up" devices from a source wafer and then "place" the devices onto a target substrate. The process is massively parallel as the stamps are designed to transfer hundreds to thousands of discrete devices in a single pick-up and print operation.

The transfer-printing process has been described in detail in earlier reports [3, 4]. As typically performed, the transfer-printing process requires three elements: an elastomeric transfer-stamp, a source wafer which supplies the devices to be transferred, and a destination or target substrate. The transfer-printing process envisioned for fabricating display backplanes is schematically depicted in Figure 1. The elastomeric stamp is fabricated using well documented soft lithographic techniques [5]. The stamp is designed to have well-defined posts (see inset in Figure 1b) which correspond to the device size, distribution on the source wafer, and the desired separation on the target substrate. A transfer-printing tool [4] is used to precisely align the transfer-stamp to both the source and target substrates.

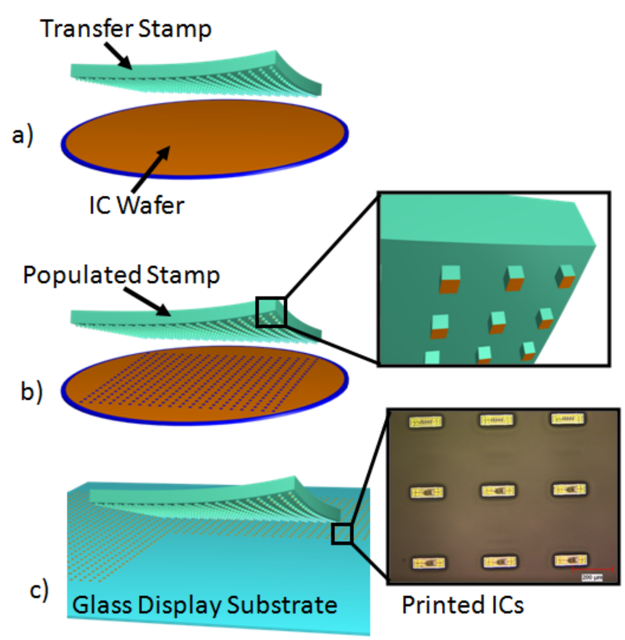

Figure 1. A schematic depiction of the transfer-printing process.

After the transfer-stamp has been aligned to the source wafer it is brought into contact with an array of devices. The transfer-stamp is then lifted away from the source wafer such that the transfer-stamp is now populated with devices, as shown in Figure 1b. This transfer process is facilitated by

[1] This work was carried out at Eastman Kodak Company prior to December 2009

taking advantage of the peel-rate dependent adhesion between the stamp elastomer and the surface of the device [6]. Next, the printer moves and aligns the populated stamp to the target substrate. Once aligned, the chips are brought into physical contact with the target substrate and the transfer-stamp is raised so that the devices are transferred to the target substrate, as shown in Figure 1c.

Recently the authors have demonstrated transfer-printing yields (using silicon chips) in excess of 99.9% for over 30,000 chips printed. Placement accuracy measurements on these printed silicon chips indicate that all of the chips are being printed within ±3 μm (6σ).

Fabrication of OLED pixel-driver ICs

The processes developed for fabricating integrated circuit source wafers for transfer-printing applications have been discussed in detail previously [4]. A condensed process flow schematic is illustrated in Figure 2.

The OLED pixel-driver ICs were designed and manufactured using a commercially available 0.6 μm SOI-CMOS process. The starting SOI substrate had a 5 μm thick device silicon layer and a 1 μm thick buried oxide (BOx) layer. The OLED pixel-driver circuits were designed using two polysilicon layers and two metal wiring layers. The total interlayer dielectric (ILD) thickness is approximately 3 μm. Metal keep-out zones were implemented to allow for the subsequent IC release process following the CMOS process, as shown in Figure 2a.

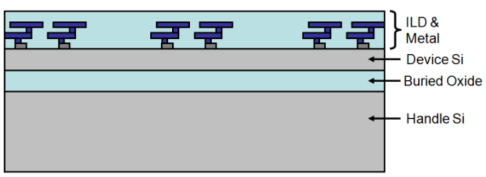

Figure 2a. Schematic of the SOI wafer following the foundry fabrication of the pixel-driver integrated circuits.

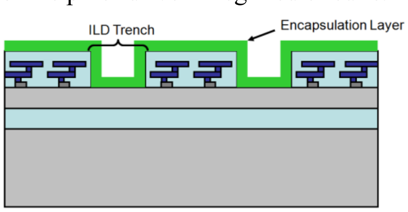

Figure 2b. Formation of the ILD trench and circuit encapsulating layer.

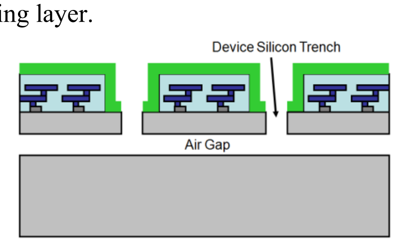

Figure 2c. Formation of a trench through the device silicon layer and removal of the buried oxide leaving an air-gap under the ICs.

Next, the post-CMOS process began by forming a trench in the ILD layers down to the device silicon layer, shown in Figure 2b. Following the formation of this trench, an encapsulation layer was deposited. The purpose of the encapsulation layer was to protect the circuit during the subsequent sacrificial BOx etch process.

Following the encapsulation process, a trench was formed in the device silicon layer, as shown in Figure 2c. This process generated an access channel for the BOx etchant, and also formed the silicon tethers that secure the IC to the handle silicon substrate. The tethers are not shown in the process flow schematics (Figure 2), but are shown in Figure 3, an electron micrograph of an OLED pixel-driver IC that was ready for transfer-printing. After forming the device silicon trench, the BOx was sacrificially removed using hydrofluoric acid. The encapsulation layer was removed from the pixel-ICs following the sacrificial BOx etch.

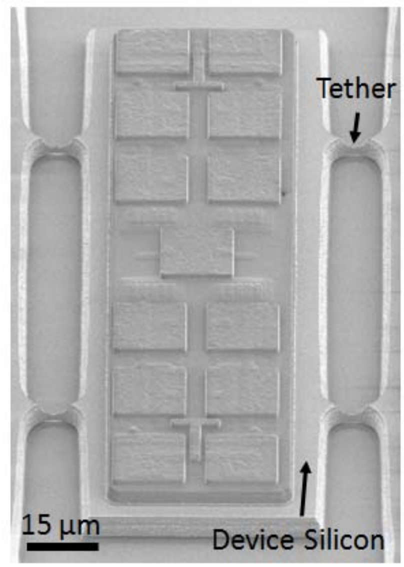

Figure 3. An electron micrograph of an pixel-driver IC that is ready for transfer-printing.

Fabrication of AMOLEDs using Transfer-Printed ICs

Figure 4 shows the process flow developed for fabricating experimental AMOLED displays. First, as shown in Figure 4a, an alignment mark level was fabricated on the glass substrate. This was done using standard metal deposition, photolithography and etching techniques. In addition to serving as an alignment mark for the transfer-printing, this patterned metal level can be used for electrical routing or light blocking purposes. Next, a thin (~1-2 μm) spin-on polymer adhesive was applied to the substrate. This layer serves to enhance the transfer-printing yield by making the process more tolerant to particles and surface defects. Then, the pixel-driver ICs were transfer-printed onto the backplane substrate. Figure 5 is a scanning electron micrograph of a single pixel-driver IC that has been transfer-printed onto a backplane substrate. The physical dimensions of the pixel-driver ICs were 167 μm x 50 μm x 8 μm. Following transfer-printing, the backplanes underwent an oven bake to fully cure the adhesive layer. Following this thermal cure, transfer-printed ICs pass the “scotch tape test” and can be processed using standard methods (spin-coating, wet processing, spin-rinse dry, etc…).

To accommodate the ~8 μm of surface topography created by the printed ICs, a spin-on photosensitive dielectric polymer was applied to the backplane substrate, as shown in Figure 4b. This polymer layer was removed from the display edge-seal area (not shown in Figure 4) using photolithographic techniques. Vias to the metal connection pads in the pixel-driver ICs were fabricated by generating a photoresist mask and then dry-etching through the spin-on dielectric and the oxide passivation down to the aluminum pads in the IC. Following formation of the vias, a single metal layer was formed by sputter deposition, and patterned using standard photolithography and etching.

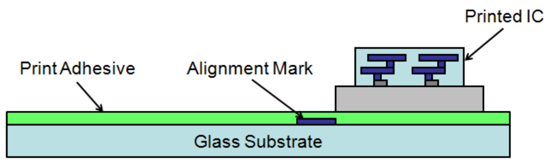

Figure 4a. The pixel-driver IC is aligned and transfer-printed to an adhesive-coated glass substrate.

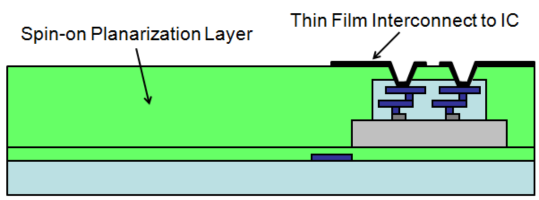

Figure 4b. An encapsulating polymer layer is spun onto the populated substrate. Vias are fabricated through the insulating layers down to the top-most metal in the IC. Metal is deposited and patterned to form the backplane wiring.

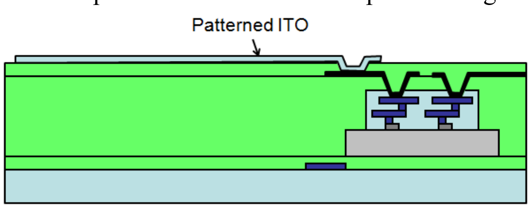

Figure 4c. An additional insulating layer is coated onto the substrate. A via is fabricated down to the interconnect metal. ITO is deposited and patterned to form the pixel anode.

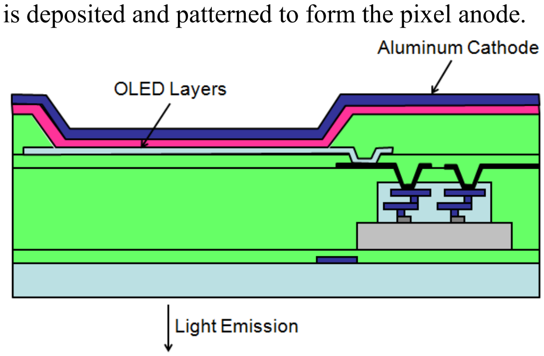

Figure 4d. Cross-section of the completed AMOLED with a transfer-printed IC.

Next, as shown in Figure 4c, an additional photosensitive spin-on dielectric layer was applied to insulate the backplane wiring layer. Photolithography was used to fabricate the via down to the OLED anode connection pad, shown in Figure 7. Then, the transparent conductor indium tin oxide (ITO) was deposited and patterned to form the bottom electrode of the light-emitting elements. Figures 6 and 7 are optical micrographs of the backplane just prior to the deposition and patterning of the ITO layer. Figure 7 shows each of the 13 connections that were made to each transfer printed pixel-IC. Only a single backplane wiring level is required because metal levels in the IC allow the row-select signal to be routed from one side of the chip to the other side (see Figure 7); this is a major cost reduction in regard to large area backplane processing.

Following patterning of the ITO, an additional spin-on dielectric layer was applied and patterned to define the emission area of each light-emitting element, as shown in Figure 4d. Next, the OLED layers were deposited using a conventional vapor deposition process. Finally, a common aluminum electrode was formed over the pixel array. Figure 8 is an optical micrograph of the top side of the fully-fabricated AMOLED. Figure 9 is an optical micrograph of the completed monochrome AMOLED looking through the glass substrate. The backsides of the transfer-printed ICs are visible. The AMOLED was a bottom-emitter design and the layout, including all of the non-emitting area (ICs, backplane wiring) provided a 53% aperture ratio for light emission.

An experimental AMOLED display was designed and fabricated to study the performance of transfer-printed pixel-driver ICs. For this display, each pixel-driver IC was designed to drive four unique light-emitting elements. In a full-color display, these four light-emitting elements would correspond to red, green, blue and white subpixels. The display was designed so that the printed chip is placed in the center of the four subpixels, as shown in Figures 8 and 9. Each of the four pixel-driver circuits on the IC implemented a conventional two-transistor, one-capacitor design. Each printed ICs has 13 connection pads, as shown in Figures 5 and 7, one for power, four for data, four for row select and four anode connections to the light-emitting element.

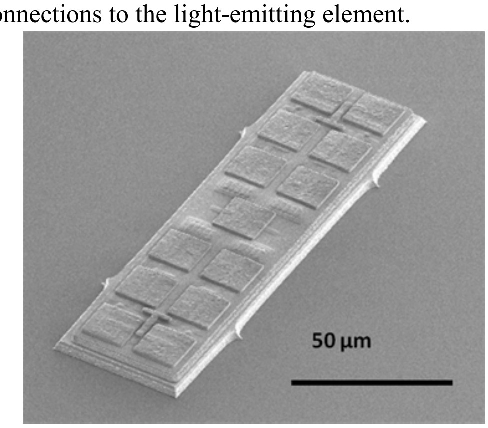

Figure 5. Electron micrograph of a pixel-driver IC transfer-printed onto the display backplane substrate.

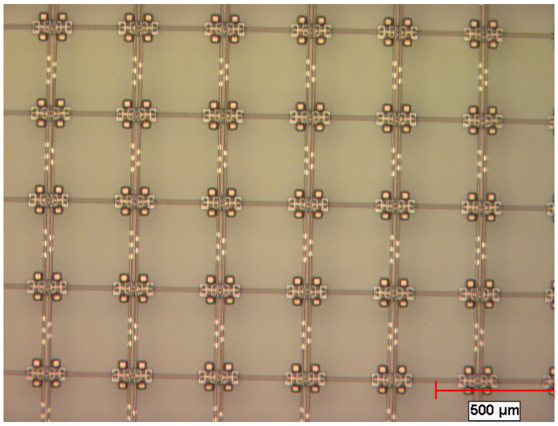

Figure 6. Micrograph of a portion of the fully interconnected AMOLED backplane (ready for ITO deposition).

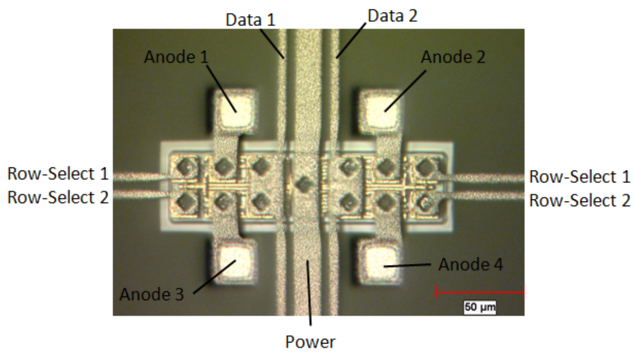

Figure 7. Optical micrograph showing the 13 interconnects that are made to each pixel-driver IC.

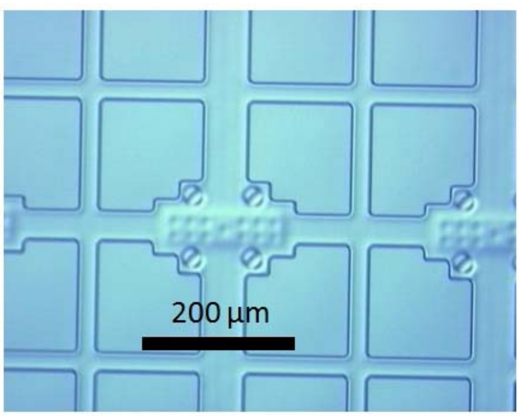

Figure 8. Photograph of the display substrate following deposition of the OLED layers and the top aluminum cathode layer.

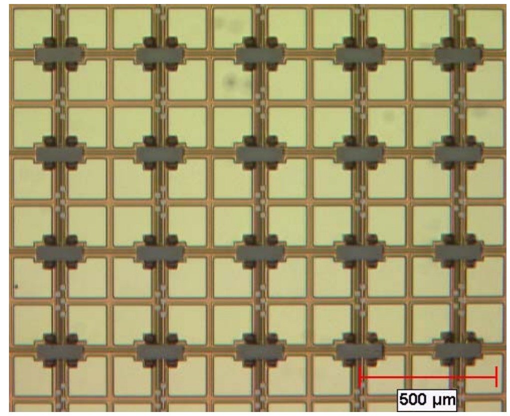

Figure 9. Photograph of the bottom-side of the fully fabricated display (looking through the glass substrate). The backsides of the printed pixel-ICs are visible.

Characterization of AMOLEDs

The display was designed as a section of a 32-inch 1080-line full-HD display (370 µm pixel pitch). The pixel layout was a four-subpixel red, green, blue, white (RGBW) pixel architecture. The displays had 64 × 64 subpixels (12 mm × 12 mm), and were placed 4-up on a 6-inch glass substrates. Transfer-printing of the pixel-ICs was performed using a transfer stamp holding 16 × 16 pixel-ICs with four stamping operations forming an array of 32 × 32 ICs to complete the display substrate. Figure 10a is a transfer-printing yield map for one of the fabricated displays. In this case, green pixels represent ICs that were successfully printed within the ±5 µm alignment tolerance. The black pixel represents a missing IC. Figure 10b is a photograph of the same display that is being driven at a uniform current level. Figure 11 shows the same maps for a second display. In both of these examples, each display had a single missing pixel-IC. The illuminated display exhibits a dark row to the right of the missing pixel-IC because the row-select line is being driven from the left side of the display. The complete dark row defect, in Figure 10b, was due to a poor edge connection to the display. Figure 12 is a photograph of a video image displayed on one of the AMOLED displays.

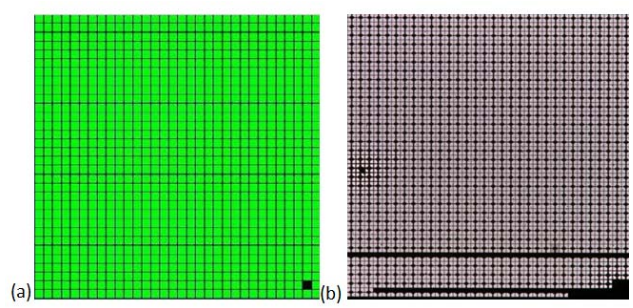

Figure 10 a. Transfer-printing yield map b. Photograph of uniformly illuminated monochrome AMOLED display.

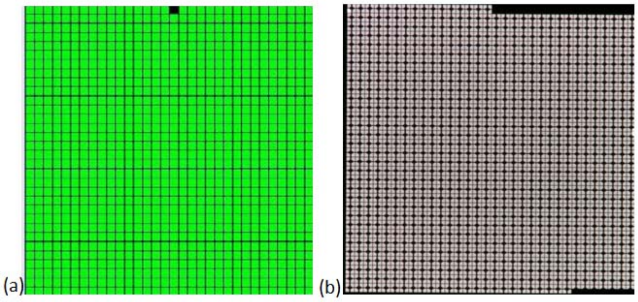

Figure 11 a. Transfer-printing yield map b. Photograph of uniformly illuminated monochrome AMOLED display.

Testing of the fabricated displays has shown that they have unique performance characteristics that cannot be achieved using conventional TFT approaches [7, 8]. The luminance efficiency after transmission through the backplane, including the relatively thick planarization polymer, was measured to be 20 cd/A. The contrast ratio (white field vs. black field) exceeded the measurement limit of 100,000:1. Individual pixels were operated without problems at a driving voltage of 16 V (Vgs of 6.5 V) and pixel currents of 20 µA (> 20,000 nits in the OLED emission area). When the display was uniformly illuminated with an average pixel current of 2 µA, the standard deviation of the individual pixel currents was measured to be 1.9%. The small current variations randomly distributed across the display were imperceptible to the viewer and constitute a mura-free display.

The AMOLEDs with transfer-printed ICs showed improved hysteresis characteristics compared to AMOLEDs driven by LTPS-based TFTs [7]. For both types of displays the current density was rapidly increased from ~0.5 mA/cm^2 to ~3 mA/cm^2, and rapidly decreased from ~6 mA/cm^2 to ~3 mA/cm^2. For the LTPS-TFT display, the current overshoots by 10-20% while the transfer-printed pixel-IC driven display overshoots by less than 1%. The LTPS-TFT display settled to within ±0.5% of the target current density in > 5 seconds while the transfer-printed IC driven display meets this target within 0.05 seconds. More recently [8], the displays have been operated with 2 µs switching times (on and off), which represents 500 kHz pixel switching frequency.

Color AMOLEDs have also been fabricated by incorporating thin film color filters into the display architecture [8].

Conclusions

AMOLED displays using transfer-printed IC backplanes have been demonstrated. The luminance, contrast ratio, uniformity, controllability (hysteresis) and switching speed of the resultant OLED displays were comparable to or better than the performance of commercially available LCD displays. The transfer printing process has demonstrated high yields. The next challenge is to demonstrate that this technology can scale-up to larger AMOLED displays.

Figure 12. Photograph of operating OLED with video input.

Acknowledgements

The work presented here was partially supported through an NSF SBIR Phase II program on flexible display backplanes (NSF IIP- 0712017). The authors express their appreciation for the help given to them by the fabrication and test staff at Semprius and Eastman Kodak Company.

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