Jet-printing of Active-Matrix TFT Backplanes for Displays and Sensors

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Abstract

The fabrication of electronic circuits by jet-printing can eliminate photolithography and offers the potential to reduce manufacturing cost. Techniques used to fabricate amorphous silicon and polymer semiconductor thin film transistors (TFT) by subtractive and additive jet-printed are described. TFT backplanes patterned entirely by jet-printing on glass and flexible substrates, with application to flat panel displays and x-ray imagers, are described.

Introduction

The interest in low cost large area transistor backplanes has focussed attention on new processing techniques. Since neither flat panel displays nor large x-ray imagers need the sub-micron patterning capability of photolithography, in principle, simpler printing techniques could be used. Minimum feature sizes of ~10 microns, with ~20 micron address line-widths are often sufficient, particularly for the larger arrays, and many document printing techniques approach this patterning precision. However, printed electronics also require more accurate registration of different layers, and higher processing yields than document printing.

Several printing techniques to pattern electronic devices have been reported.[1-4] Contact printing uses a master in a drum or flat plate system, examples being screen-printing, gravure, offset and micro-contact printing. Jet-printing, on the other hand, requires no master, has digital control of ejection to provide drop-on-demand printing, and is also a non-contact process. There is active development of jet-printing for applications including OLED displays and color filter panels.[5,6] This paper describes the patterning of thin film transistor arrays with jet-printing. [7-11]

Jet-Printing Systems

One of the jet printing systems developed at PARC is shown in Figure 1. It comprises a piezo-jet print-head based on commercial Xerox technology with about 600 independently addressable ejectors. Other print-heads of similar type have also been used in these systems. The printer ejects down onto a heated substrate, which is mounted on an x-y translation system accurate to about 1 µm. Our largest printing system can print over an area of about 15” × 15”, and the printer can be scaled to a much larger area while maintaining the same precision. A single multi-ejector print-head provides fast printing, and a system with multiple print heads can, in principle, coat a substrate at a rate of at least 100m^2/hour, making it compatible with present display manufacturing times.

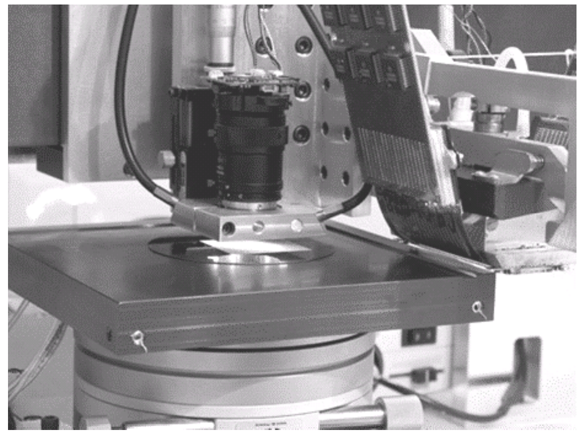

Figure 1. Photograph of the jet-printing system, showing the print-head, the alignment camera and the substrate holder.

The print-head allows ~40 micron features to be printed. This size is not limited by the printing technology but by the demands of document printing. A reduction by at least a factor 2 needs little new technology beyond a redesign of the print-head. Experimental jet-printing systems have demonstrated drop sizes of less than 5 microns, showing that reductions in feature size are possible.[12]

The printing system includes an electronic image-capture system, which is used for registration between the layers of the device. The printer locates alignment marks in previous layers and adjusts the drop ejection to provide approximately 5 µm alignment from one printed layer to the next. Such precise printing requires that the drops ejected from the head have accurate directionality. The print-head is positioned about 1 mm above the substrate so that a position error of 5 µm corresponds to a jetting direction error of ~0.25 degree. When the print-head or substrate moves, variation in the drop velocity gives corresponding errors in the drop position. However, commercial high performance print-heads can be normalized to give uniform drop velocity.

The ejection directionality is calibrated by printing a set of marks and using the computer vision system to locate the printed spot accurately. Ejectors that print to a specific tolerance can be selected, resulting in higher precision, although at the expense of lower throughput. The printing software also compensates for substrate misalignment. Using the alignment mark coordinates, the mask layer is digitally processed, repositioned, and aligned to the process wafer prior to printing the mask pattern, eliminating the need to manipulate optics or mechanically adjust a mask aligner and substrate.

Additive and Subtractive Processing

Since jet-printers can only print liquids, the conventional semiconductor device materials cannot be directly printed. There are two approaches to resolve this problem.

1. The jet-printer can print a mask layer onto a deposited thin film, replacing the photoresist used in conventional photolithography.[7,9,10] We call this approach digital lithography, and it is a subtractive process, since material is removed to form the pattern.
2. Suitable printable active materials can be found, which are liquids, solutions or suspensions. For example, polymer semiconductors can be deposited from solution at room temperature and in the ambient atmosphere. Printing solution-based active materials is an additive process in which the material is deposited and patterned in a single step.

The additive and subtractive processes are illustrated in Figure 2 and compared to conventional photolithography. The combination of additive and subtractive jet-printing provides flexibility in the choice of materials and device structures.

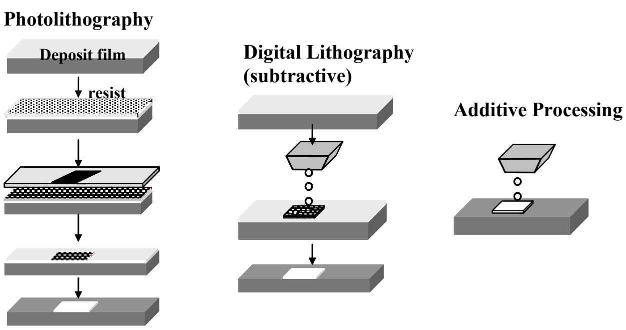

Figure 2. Illustration of the comparison between photolithography, digital lithography and additive printing.

Digital Lithography

The challenge for jet-printing of etch masks is to pattern device features with sufficient precision and reliability. Our technique achieves precise features by printing a molten wax which freezes on contact with the substrate. The feature size is controlled by the cooling rate, rather than surface energy interactions, so that consistent printing can be obtained on many different surfaces. Figure 3 shows an example of the printed wax mask and the resulting etched metal layer, for a design with a 340 micron pixel size. The process direction is vertical in the figure and as might be expected, more precise line edges are printed in the process direction than perpendicular. One of the design considerations in fabricating arrays is to choose the optimal print direction. However, parts of a single mask layer can be printed in orthogonal direction to optimize the printed line shapes.

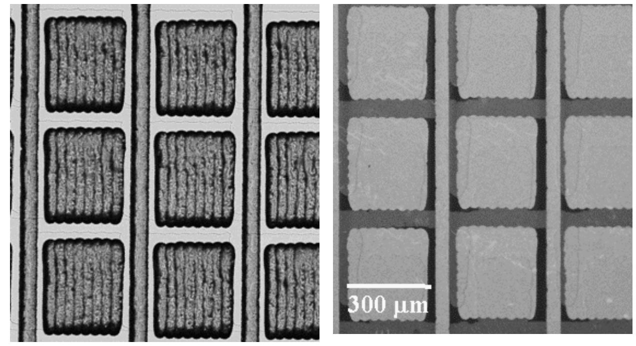

Figure 3. Photograph of the printed wax mask (left), and the resulting etched metal layer (right).

The wax mask technique allows patterning of arbitrary films on various substrates. Flexible substrates are interesting for possible roll-to-roll processing but also allow unbreakable or curved arrays. Jet printing may be an important enabler of processing flexible substrates, since jet-printing onto a roll system is used commercially for documents printing. Figure 4 shows a printed TFT array fabricated on PEN using digital lithography. We developed a 170C amorphous silicon process that gives mobility and leakage current comparable to conventionally processed a-Si TFTs.

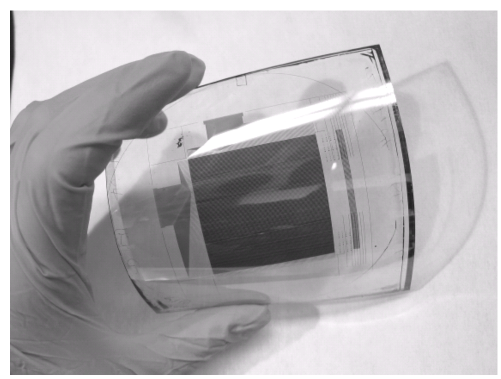

Figure 4. Photograph of a flexible printed amorphous silicon TFT array using a low temperature deposition process.

Additive Jet-Printed Polymer TFTs

Additive jet-printing requires solution-based materials and suitable metal, insulator and dielectric materials exist.[13] Our research has focused on additive jet-printing of polymer semiconductors for TFT arrays.[8,11] We fabricate bottom gate TFTs with coplanar source and drain contacts, in the structure illustrated in Figure 5. This structure was chosen because the metals and the dielectric layers can be completed before the semiconducting polymer is deposited, thus minimizing the possible degradation of the polymer from subsequent processing. The additive jet-printing process simultaneously deposits and patterns the solution-based polymeric semiconductor. The semiconductor is one of the polythiophenes, which so far have the highest mobility of the polymers.[14] An encapsulation layer (not shown in Figure 5) completes the TFT device fabrication. Our process uses subtractive printing to pattern the metal and dielectric layers, but additive printing of these materials is expected in the future.

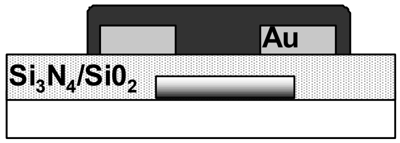

Figure 5. Schematic illustration of the polymer TFT structure used for additive printed devices.

A small region of a printed polymer TFT arrays is shown in Figure 6. The polymer is confined to the region of the gate electrode between the TFT contacts, and this is achieved by suitable control of the surface energy. Extension of the polymer beyond the gate electrode adversely affects the TFT performance since there is a higher leakage current in un-gated regions.

Previous studies have shown that spin-coated films of polythiophene give TFTs with carrier mobility of about 0.1 cm^2/Vsec. Our studies showed that the printed TFTs have comparable performance to the spin-coated films, so jet-printing introduces no loss of device performance.

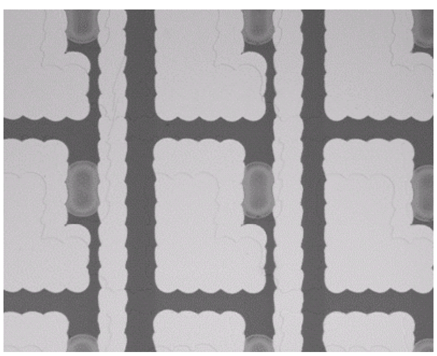

Figure 5. (Left) Photograph of part of a 128 x 128 pixel printed polymer TFT array.

Jet-Printed Backplane Prototypes

Small TFT backplanes have been fabricated to demonstrate that digital lithography and additive printing are a practical means to fabricate both a-Si and polymer active matrix arrays, and to understand the manufacturing issues. Since the TFT backplanes comprise metals, insulators and semiconductors, the patterning techniques must be versatile and the registration of the layers is critical to the performance. Lack of good registration neccessitates the design of larger overlaps between layers, which can lead to higher parasitic capacitance and reduced circuit performance.

We have developed printed TFTs for reflective displays and x-ray imager sensors. Figure 6 shows a reflective display made using a 128 × 128 printed polymer backplane and Gyricon media.[15] The design uses a 4 mask process with 3 layers fabricated by digital lithography, additive printing of the polymer and a spin-coated passivation layer. The electrophoretic cell is laminated to the surface. The display shows that the printing process can be used successfully for array fabrication. The array contains more defects than the equivalent photolithography process, and further work is needed to quantify the yield.

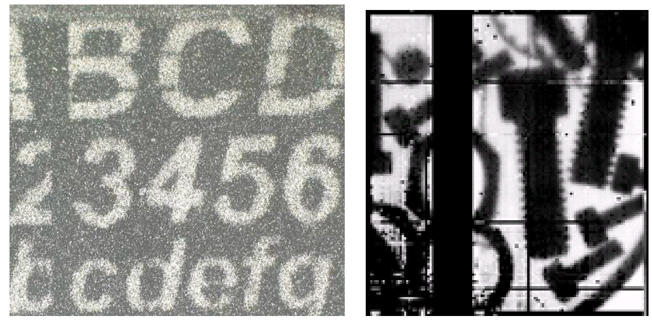

Figure 6. (left) Reflective display fabricated from a 128 x 128 printed polymer TFT array with gyricon media. (Right) X-ray image obtained from an amorphous silicon TFT sensor array fabricated using digital lithography.

Printed TFT arrays have also been made to demonstrate x-ray image sensors.[9] These are more complex structures since they includes an integrated photodiode light detector. The array uses 7 masks and is made by digital lithography with a-Si TFTs. The design uses a high fill factor structure in which the photodiode layer is deposited as a continuous film on top of the array. This approach is particularly useful for digital lithography, since it minimizes the need for fine feature patterning.

Figure 6 shows a portion of a 128 × 128 pixel image sensor arrays, and an example of an image obtained under x-ray exposure with a GdO_2S_2:Tb phosphor placed in contact with the sensor array surface. These arrays also have line and pixel defects due to processing faults, but otherwise show reasonable performance given their processing complexity.

Discussion

The larger feature size associated with present jet-printing technology limits the array performance in several ways, including minimum pixel size, addressing speed and feed-through charge. The pixel size of 340 microns is about as small as can be made with our present printing equipment and with a reasonably high aperture ratio. Reducing the feature size from 40 microns should give a corresponding reduction in the minimum pixel size, so that 20 micron lines would allow pixel sizes that cover most display and x-ray imaging applications.

Given the limitations of the printed feature size, it is important to use the design of the backplanes to optimize performance. One approach is to take advantage of the drop position accuracy of jet-printing. Patterned edges in different layers can be lined up within 5-10 microns, which is considerably smaller than the printed feature size. In the same way, the gap between two printed lines can also be ~10 microns. This capability is particularly advantageous since the channel of a TFT, as well as other design features, are determined by gaps rather than by the printed feature sizes. As we learn to use these properties of the jet-printing systems, the overall performance is expected to improve.

Another useful strategy is to design a 3-dimensional structure rather than one with a planar geometry. In a planar geometry the pixel elements compete for space, and design compromises must be made, including a reduced aperture ratio for the device element. In a 3-dimensional structure, the TFTs are in one layer, each interconnect line could have its own metal layer, and the device contact can take up the whole of the top surface. For example, the high fill factor design described above for the x-ray imager, has a continuous sensor layer on top of a mushroom metal. This design optimizes the sensor fill factor and gives extra space for the TFT and address lines.

Acknowledgement

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