Toolset for Printed Electronics

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Abstract

For several years there have been many efforts to employ ink jet technologies in the fabrication of consumer electronics. The potential of displacing large and expensive pieces of electronic fabrication equipment and processes with seemingly appropriately scaled inexpensive alternatives is attractive. However, of course, the devil is in the details. Feature size, accuracy, registration and materials all have severe impacts on design rules, processing, performance and the types of devices appropriate to the technology. In this article, we describe aspects of the jet-printing technology for large-are electronic device processing that have been developed at PARC. These aspects include fine feature patterning, multi-layer registration for thin-film transistor device fabrication, printing of solution processable semiconductor and conductive materials, and printer color filters. The focus of this work is to demonstrate the wide range of applications for jet printing in the area of device processing.. Examples of working proto types of displays, imagers and microfluidic devices produced through ink jet printing are given and we discuss the tools used to design these devices.

Introduction

It has been conjectured over the past several years that conventional integrated circuit (IC) fabrication methods may not be appropriate when applied to the manufacture of particular classes of devices. While conventional fabrication has been honed over decades for efficient mass production of devices consisting of massive amounts of sub-micron transistors, there are classes of device technologies which, while capable of being designed and manufactured, suffer from aspects of the entrenched IC manufacturing methods which limit ease of manufacturing as well the ability to achieve price targets. Two current examples which may significantly benefit from new and different fabrication approaches are large-area electronic devices[1], such as wall size displays, x-ray imagers or wearable electronics, and small devices which could be mass produced beyond what is capable today as in the case of RFIDs.

Our efforts toward exploring new modes of manufacturing and reducing costs have focused on advances in high resolution printing technology coupled with the maturing field of solution processable electronic materials. In particular, we have concentrated on ink-jet printing rather than other high-resolution printing methods, such as microcontact printing, due to the wide range of compatible materials and its ability to easily register successive material layers and existing structures. While inkjet printing possesses relatively large minimum feature sizes (~ 40 µm drops), the use of potentially higher resolution patterning for the initial layer is possible. Figure 1 compares feature size of relevant devices to the capability of several print patterning methods. The ability of inkjet printing to cover large areas while capable of producing features down to 10um is very attractive. Successful techniques reported thus far include screen printing for simple electronic signage and ink jet printing for the application of color filters for LCD displays as well as the deposition of organic LEDs.

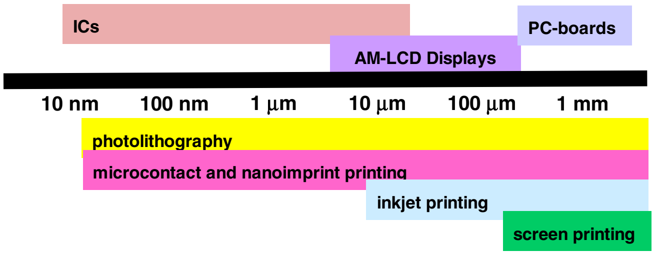

Figure 0 Chart displaying target technology and manufacturing methods against a dimension scale.

While the applicability of inkjet methods to printed electronics is promising, the ability to accurately register small drops on a substrate is not the only requirement for producing robust devices for consumer electronics. Each layer step in creating a working device requires the development of processes and knowledge of all the interactions of new materials and interfaces. In this paper we first discuss inkjet manufacturing issues and then a few of the processes developed at PARC which may prove to be significant in the development of printed electronics.

Ink Jet Issues

For ink jet technology to succeed as an alternative to photolithography for large scale device production, it needs to meet criteria which give it a significant advantage. Feature size, accuracy, repeatability, reliability, throughput, environmental and material compatibility as well as the ability to enable new capabilities all need to be weighed against the equipment cost to overcome the barriers for adoption. We discuss a few of these considerations here pertaining to current research capabilities but many performance attributes can only be established in a fully engineered production system.

While drop placement accuracy from ink-jet print heads is subject to the design and fabrication of the heads, local dynamics of the fluid-nozzle interaction contributes significantly to individual ejector drop accuracy and uniformity[2,3]. The electronic performance demands on materials suitable for electronic circuits tend to push the characteristics of the “electronic ink” from that of an ideal Newtonian fluid. This makes it very difficult for any single ink-jet technology (or any other patterning alternative) to meet manufacturing and performance requirements

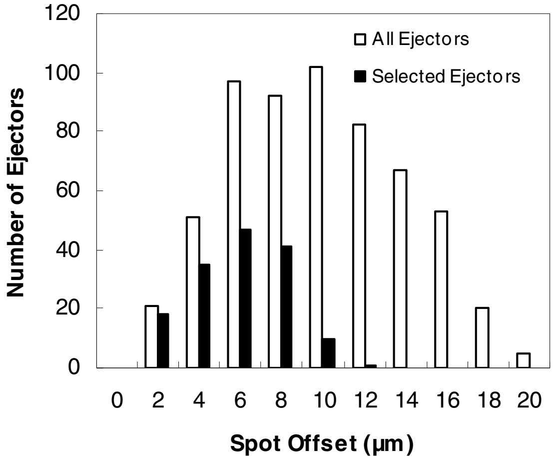

Figure 2 Histogram of spot placement offsets for wax ink jet. Large spread is due to variations in the manufacturing of the printhead and performance limitations introduced in the current printing application. All ejector spots are shown in the unfilled bars. The solid bars represent 152 optimized ejectors selected for +/-5µm drop placement accuracy

in an all additive process. To this end, we have initially focused the jetting of wax as a replacement for photolithography coupled with low-temperature processing of vapor deposited materials.

Deposited wax is potentially an ideal material for an ink jet fabricated etch mask since its thermal phase change behavior lends itself to the control of the solidified spot size.[4] By adjusting the print-head temperature, the wax viscosity can be tuned with the driving waveform to produce droplets of a controlled size. With a given droplet temperature, printing speed and target substrate temperature, the solidification dynamics can be controlled. The coalescence behavior of drops with previously deposited drops results in well behaved, smooth edge wax lines when formed in the printing direction.

We use commercial print heads from Xerox designed for the printing of pigmented wax ink at operating temperatures up to 150ºC. While specifically designed for ejecting wax at elevated temperatures, the all stainless steel construction also allows for the printing of a wide range of solvent-based inks down to room temperature. The head has 1236 nozzles designed to print 8.5" CMYK documents with minimal lateral travel and a natural ejector spacing of 37.5 DPI. Our prototype printers are equipped with *in situ* machine vision alignment and drop placement calibration to enable the selection of ejectors for the desired accuracy of spot placement and registration to existing patterns (Figure 2). In this way, the printer software can compensate for changes in print-head performance and manufacturing defects. The trade off is that printing is done with a reduced set of ejectors, though the number of resulting ejectors is generally more than most commercial print heads in use today in electronics applications.

The ejected wax droplets form minimum line features ranging from 40 to 60um wide depending on the wax and substrate temperature along with the substrate material's surface characteristics.

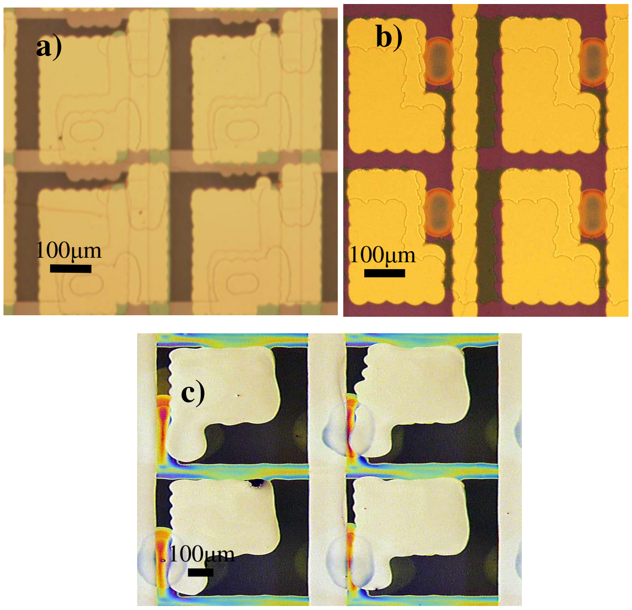

Figure 3 Examples of incremental application of ink jet printing to transistor driven backplanes. Micrograph a) shows result of ink jet wax etch mask applied to low temperature a-Si arrays on PEN. Micrograph b) shows jet printed semiconductor ploymer, PQT, and wax mask defined electrodes. Micrograph c) shows a TFT array of printed silver nano-particle electrodes and PQT with spun on ploymeric dielectric on glass.

Approaches to Manufacturability

The use of jetted wax as an etch mask has enabled an incremental approach to printed electronics development where conventional vacuum–deposition techniques can be used solely or in combination with new solution deposited material. Figure 3 shows optical micrographs of a range of display backplane arrays produced by printed etch masks (Fig. 3a) to all additive printed processing (Fig. 3c). These examples illustrate potential limitations to produce fine features and control critical overlap with relatively large drop features. Processing techniques available from conventional manufacturing can be applied with jet printing, for

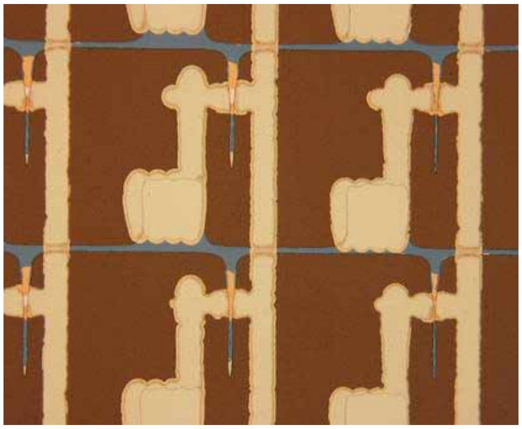

Figure 4 Under-etched gate and channel regions along with self aligning technique using backside exposure resulting in 10 - 15µm channel lengths from 45um wax mask features

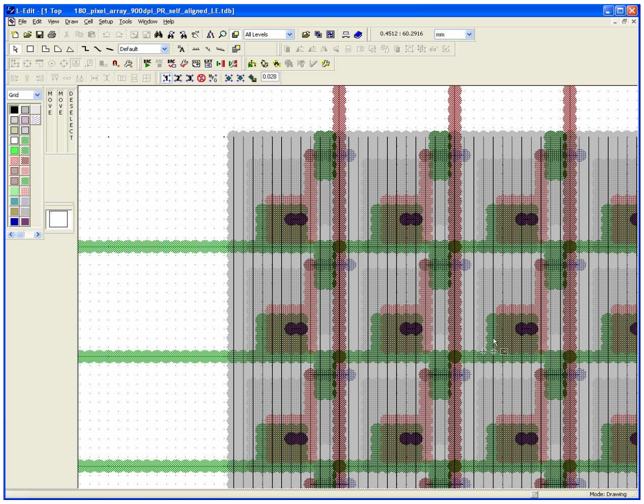

Figure 5 Example of a standard IC layout tool for the design input to our inkjet printers. The resulting device array fabricated by ink jetted wax mask is shown in figure 3a.

example under etching to define short channel lengths, combined with backside exposure for self-aligned contact electrodes, are illustrated in Figure 4..

Short channel lengths are crucial for enhanced current switching ability, particularly with semiconductor materials with low mobilities, like polymer semiconductors and a-Si. Other groups have demonstrated methods of surface energy modifications coupled with photolithography to define small gaps[5,6] as well as the defining of narrow conductive lines by laser curing of jetted UV curable conductive ink[7]. However, there are few options to having this sort of control in all printed electronics other than small drop features and, perhaps more importantly, very precise drop placement. Another way we have approached the drop accuracy problem is to ensure that the pattern for any one layer in each pixel is printed with the same ejector so that ejector to ejector drop placement variation is minimized within the pixel.

Another challenge to the realization of polymer electronics is the apparent susceptibility of many of the current organic materials to environmental degradation. Moisture, oxygen and other constituents in the air have been shown in various degrees to affect the performance of transistor operation over time[8,9]. This necessitates prompt application of barrier layers to the newly formed and exposed materials and/or additional processing prior encapsulation of the sensitive semiconducting layers.

We have developed a one-step process for mitigating environmental effects with the jetting of polymer blends[10,11]. A blend consisting of polythiophene semiconductor and PMMA is jetted on to a dielectric surface. The blend phase separates with the poythiophene preferentially depositing on the dielectric surface and the PMMA separating towards the free surface. The PMMA acts as a protection layer greatly inhibiting environmental effects until a final passivation material can be applied in a later process step.

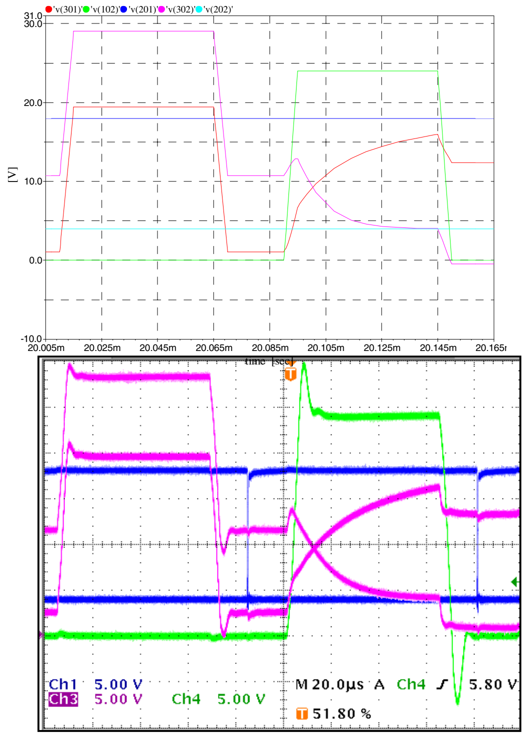

Figure 6 a) Simulated pixel array performance plot from an s-Si display design and b) the measured performance of the array.

Design for Printed Electronics

One particularly attractive trait of digital fabrication is the potential for rapid changes to designs affording shortened development cycles and custom variations to circuits. This need has proved to be crucial in the effort to expand a rich materials and processing base for organic electronics. Also, as a consequence of need to produce features that are composed of single drops, an important requirement is recognized for electronics designers to have appropriate layout tools which take into account the fundamental droplet feature.

Due to the inherent ability to design for features at the drop level as well as print direction and resulting drop sizes of differing materials on varied surfaces, a different approach from traditional IC layout is required. We have developed a method and set of rules by which circuit designers can use integrated circuit layout tools for which they are well familiar. This has enabled realistic multi layer visualization, functional simulation as well as on the fly rendering of the printed circuits from digital files. Figure 5 shows the pixel design rendered in a popular IC layout package. Thus we are able to vet designs by visualization and performance simulation prior to fabrication for a-Si devices as well as for organic semiconductors. The spice models of both polythiophene and a-Si have been used to predict performance. In the case of a-Si as seen in figure 6, the comparison of the simulation to the measured device is as good as seen with conventional a-Si.

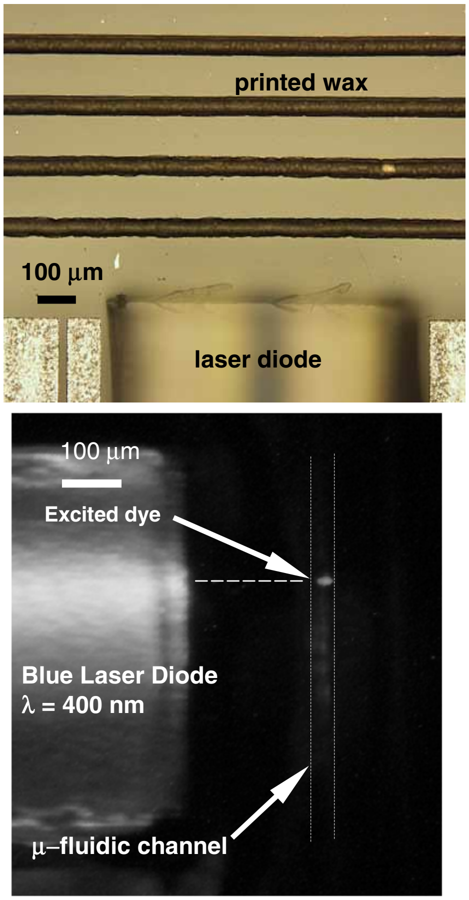

Figure 8 Wax line defined fluidic channels (top) aligned to existing flip chip bonded GaN blue laser. Laser excitation of florescent dye in channel (bottom).

Additional Opportunities

The particular capabilities of ink jet as applied to digital fabrication techniques offers the potential for the rethinking of device design and manufacturing modalities as can already be seen with the adoption of inkjet to the manufacture of LCD color filters, OLED displays and 3D model prototyping [12].

One aspect with specific potential is the capability to align the droplet placement accurately to existing features or system components. Figure 7 shows example where fluidic channels were formed by first depositing stacked multi-drop wax lines on a glass substrate in close alignment with a flip chip bonded Gallium Nitride blue diode laser. The wax lines serve as a mold for the subsequent application of PDMS. The solidified PDMS is then removed, allowing access and removal of the wax. The PDMS is then reapplied to the diode substrate assembly; the fluidic channels remain in close alignment with the laser diode output. Figure 8 shows the excitation of a dye solution within the microfluidic channel.

The non-contact, aligned patterning aspect of the jet printed wax allows for the opportunity to develop new fabrication methods for of micro-electromechanical systems. This is just one example which illustrates accurate alignment and fabrication of the MEMS structure to an existing optoelectronic device on a non-planar surface

Summary

Several methods by which inkjet manufacturing methods have been applied to form working electronic circuits and fluidic structures serve as examples for its capability and flexibility. Examples of inkjet printed wax masks to soluble organic polymer semiconductor and nano-particle conductive materials to three-dimensional structures have been exhibited. Issues concerning inkjet accuracy as applied to the formation of electronic circuits and design methods have been discussed.

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Author Biography

Steve Ready obtained his degree in Physics from the University of California at Santa Cruz in 1984. He then joined Xerox Palo Alto Research Center and has since studied the role of hydrogen in amorphous, polycrystalline and crystalline silicon, contributed to the development of large area amorphous and polycrystalline silicon imaging arrays for optical and x-ray applications, and is presently working on the development of organic semiconductor materials and devices.