The Prospects of Inkjet Printing for Displays and Sensor Tapes

J.H. Daniel, A.C. Arias, T. Ng, B. Russo, B.S. Krusor, Palo Alto Research Center, Palo Alto, CA, USA

Abstract

When fabricating electronic devices, an all-additive solution-based process would have the lowest cost and complexity, because it employs the lowest number of processing steps and it consumes the least amount of process material. However, there are still many challenges on the way to achieving electronic circuits by such processes. Here, we present inkjet printing approaches to fabricate displays and sensor circuits.

Introduction

Printing methods enable the direct fabrication of electronic circuits on flexible substrates and open up the opportunity for roll-to-roll processing which is promising for lowering the manufacturing cost.

Recently, printing methods have been explored in various fields of electronics. For display fabrication, screen printing was used to pattern the active-matrix backplane in a liquid powder display [1]. Roll printing, based on a gravure-type printing method, was explored for resist printing to replace photolithography in the fabrication of a liquid crystal display (LCD) [2]. Radio frequency identification (RFID) tags have been printed using a variety of printing methods and low-cost sensor applications are finding increased interest [3,4].

Here, the focus will be on inkjet printing for fabricating flexible display backplanes used in electrophoretic displays and flexible printed sensors for detecting explosions in the battle field.

Inkjet Printing

Amongst several printing methods, inkjet printing has the advantage of variable digital data printing and non-contact material deposition. It is also well suited for prototyping and materials research because of the small amounts of material consumed. Inkjet printing has been explored for a variety of electronic applications such as for the patterning of large-size color filters in displays or as an alternative to photolithography [5,6]. Organic semiconductors have been deposited by inkjet printing, particularly for organic light emitting diode displays and for pixel transistors in active-matrix backplanes [7-9]. Within these applications, there are still many challenges in optimizing the printing processes. Printing inks have to be formulated to be reliably jettable, which requires optimization of the ink viscosity and surface tension. The solutions must also exhibit stability to prevent clogging of the inkjet nozzle and the inks should be tuned to show reduced coffee stain effects upon drying of the printed drops.

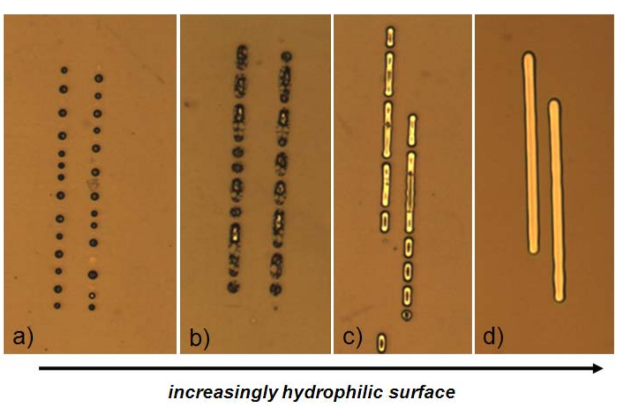


Figure 1. *Inkjet printed silver on a polymer surface with increasing surface energy (from a - d). In a), the ink is repelled and in d) continuous lines are formed with a width of 40-50 µm.*

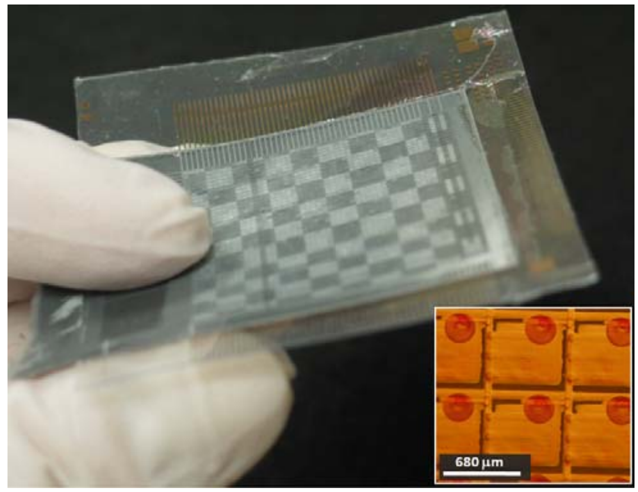


Figure 2. *Flexible electrophoretic display with printed active-matrix backplane. The inset shows a close-up image of the printed pixel circuit. The pixel TFTs are based on the organic semiconductor PQT-12.*

Moreover, the surface tension of the inks, together with the surface energy of the print substrates, has to be well coordinated to obtain the desirable print features. In Fig. 1, an example of the dependence on the surface energy of the substrate of a jet-printed pattern is shown. Here, two parallel lines were printed with a silver nanoparticle ink. The lines break up into individual droplets on a hydrophobic (low surface energy) surface (Fig. 1a). When the surface energy is increased by treatment with ozone, the lines become increasingly continuous. An optimum point is achieved where the printed lines remain narrow and continuous after drying of the ink.

With our custom-built inkjet printing systems, we achieve a drop placement accuracy of +/-5 µm and we have printed lines of ~40-50 µm width with 10 µm spacing.

Printed Active-Matrix Pixel Circuits

Fig. 2 shows an electrophoretic display with a printed flexible active-matrix backplane and electrophoretic film from E-Ink Corporation. Since the electrophoretic ink has bistable characteristics, the image remains visible after disconnecting the driver electronics. The pixel circuit of 50x50 pixels was fabricated on a 5 mil thin polyethylene naphthalate (PEN) substrate with process temperatures not exceeding 160degC. The inset in Fig. 2 shows a close-up photograph of printed pixels. The pixel pitch was

680 µm (37ppi) which is adequate for poster-type displays that are viewed from a distance. The pixel circuits were fabricated in an all-additive solution process in which the metal for the gate- and data-layer and the organic semiconductor for the pixel thin-film transistor (TFT) were deposited by jet-printing. A polymer gate dielectric was deposited by spin-coating. The process resulted in pixel arrays with good consistency regarding the feature definition and with good registration between the layers. For the metal layers, silver nanoparticles were printed from solution and subsequently sintered. The pixel transistors are based on the polythiophene semiconductor PQT-12 and PVP (polyvinylphenol) gate dielectric. Transistor Ion/Ioff ratios of ~10^5 – 10^6 and a mobility of ~0.02-0.08 cm^2/Vs are achieved, which is sufficient for driving reflective display media with a moderate refresh rate [10].

Although much progress has been made with printed displays, challenges still remain. One is the achievement of higher resolution. Another is the integration of conventional driver circuits.

Field-shielded Printed Pixels

The maximum display resolution is affected by the pixel fill factor (ratio of pixel pad area to total pixel area) which in turn is limited by the minimum printed line and gap width. This is illustrated in Fig. 3. Higher fill factors can be achieved with field-shielded (multi-layer) pixel designs in which the data bus lines and the TFT are at least partially covered by a top-layer pixel pad (Fig. 4a). A multi-layer pixel design requires additional processing steps including via formation in a top layer dielectric which covers the data bus lines. Others have formed vias in printed circuits using solvent printing [8]. The concept shown in Fig. 4b is based on a continuous layer of negative acting photopolymer as the top layer dielectric. Contact vias are formed in the layer by jet-printing opaque silver features that server as photomask. The photopolymer is then exposed to light that crosslinks the un-masked areas and subsequently the silver metal mask is removed together with the un-crosslinked regions that form the vias. The silver mask and the un-crosslinked polymer are removed in a single process step. After formation of the via holes, the conductor for the via connection and the top layer pixel pads are inkjet printed. Although this is not an all-additive process, it is a simple approach that uses the same printer for depositing the metal conductors and for printing the metal mask. A field-shielded pixel design will enable the fabrication of printed pixel arrays with 200 µm pixel pitch without further reducing the printed line width of ~50 µm.

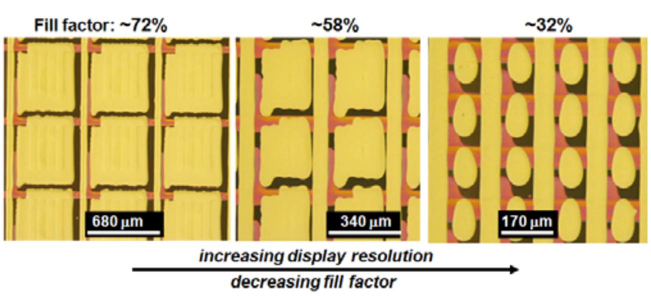


***Figure 3.** Printed pixel circuits with varying resolution. Towards smaller pixels, the pixel fill-factor decreases (at constant printed line width) due to the smaller relative pixel pad area.*

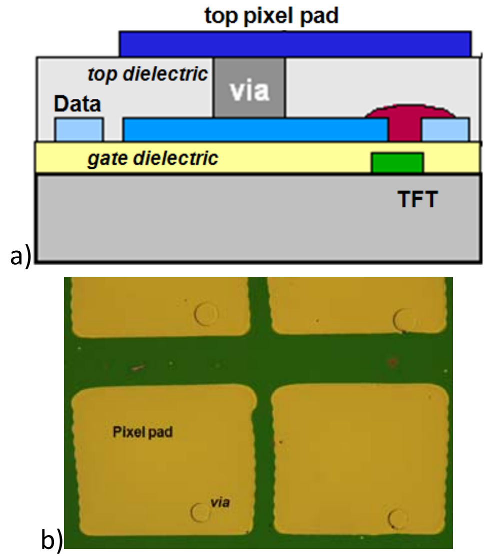


***Figure 4.** Field-shielded pixel design (a) and via process using a printing approach in which printed silver acts as a photomask for the via region (b).The shown top layer pixel pads function as a cover over the transistor region and the data bus lines.*

Connecting Driver Electronics

Because printed electronics is not capable of performing all the tasks to drive a display, conventional electronic circuits such as bus drivers and video signal processors, etc., have to be integrated to form a full display. Pick-and-place technologies may be used to attach integrated circuits onto the same flexible substrate that contains the printed circuit. Fig. 5 shows an approach in which inkjet printing is used to form electrical connections between a printed electronic circuit and an integrated circuit with a ball-grid contact pad array. After attaching the integrated circuit to the substrate, a polymer is molded over the integrated circuit and its contacts (here, solder balls). The molding step forms a polymer ramp between the substrate and the contact level. In an optimized process, the top surface of the contacts remains free of polymer. Conducting lines are then inkjet printed over the polymer ramp to connect the printed circuit with the integrated circuit. Because in inkjet-printing the print head does not touch the print surface, it is possible to print over such topographies. Also, due to the digital nature of inkjet printing, the printing process can compensate for placement inaccuracies of the integrated circuits.

Printed Sensors

Printing technology is also promising for inexpensive sensor devices and currently we are developing printed sensor tapes to detect blast events on the battlefield. It has been shown that traumatic brain injury (TBI) caused by blast events is cumulative and early detection is important. The goal is to attach flexible printed blast sensor tapes to a soldier's helmet and to record events that can cause TBI over a period of 7 days. The sensor tapes include accelerometers, pressure sensors, acoustic sensors, light sensors and printed organic electronics to record and store the sensor signals.

Fig. 6 illustrates the concept of a helmet mounted sensor tape. The tape may be designed in branches so that sensors are positioned in several locations on the helmet. Light sensors may be positioned near the eyes, acoustic sensors near the ears and

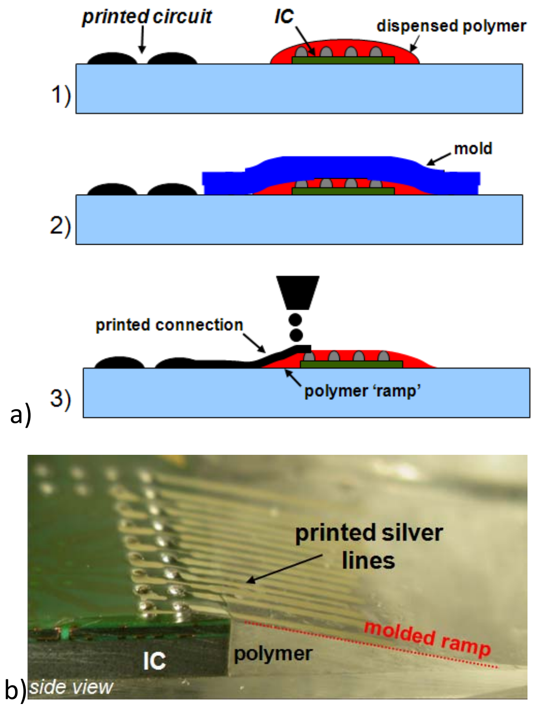


Figure 5. *Formation of connections between printed electronics and a conventional integrated circuit (IC). A molding process forms a polymer ramp over which conducting traces are jet-printed to join the circuits (a). In b), a close-up photograph is shown of a ramp with silver lines.*

acceleration sensors may occupy three approximately orthogonal locations for 3-axis acceleration sensitivity. Fig. 6b emphasizes that a printed sensor tape may have a more complex shape to enable stretching or conformal attachment to a variety of different surface geometries.

Low-voltage Transistors

In contrast to the display backplanes (which require relatively high voltages to drive the electrophoretic medium), low-voltage operation is essential for the sensor tape. This is in part because the tape is operated by a thin-film battery and high voltages are more difficult to achieve. Moreover, it is due to the fact that the tapes are mounted close to the human body and only low voltages are permitted.

In order to achieve low-voltage transistor operation, a high gate capacitance is required. This can be achieved with thin dielectric layers and materials with high dielectric constant. Amongst several approaches, we have explored atomic layer deposition (ALD) of a hafnium oxide (HfO_2) gate dielectric due to its high dielectric constant. Fig. 7 shows the transistor curve of a TFT with a bi-layer gate dielectric consisting of HfO_2 (100nm) and a low-surface-energy polymer. The low-surface energy polymer improves the molecular ordering of the organic semiconductor PQT-12. The HfO_2 was deposited over the jet-printed silver gate layer at 150degC in a Savannah series ALD system by Cambridge Nanotech. Traditionally, ALD deposition is regarded as a slow process and it therefore would be in contradiction to a printing technology which favors fast and low-cost processing. However, recently approaches to increase the throughput of ALD have been

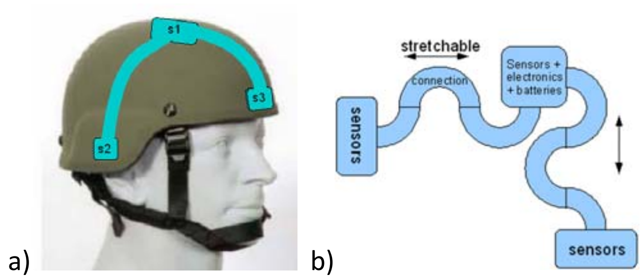


Figure 6. *Concept of a flexible sensor tape attached to a helmet for measuring blast events (a). In b), a stretchable version of the tape is depicted.*

reported using web or large-batch processing [11]. The combined gate capacitance of the bi-layer dielectric was around 40nF/cm^2 which is significantly higher than ~15nF/cm^2 which is typically achieved with the PVP polymer dielectric. The TFT of Fig. 7 shows a good mobility and an on/off ratio of 10^4-10^5 within a 10 V gate voltage swing.

Sensor amplifier

Pressure, acoustic and acceleration sensors based on piezoelectric readout were chosen for the sensor tape because of the requirement for low power and because of the relatively simple readout method. Piezosensors generate a voltage when mechanical stress is applied. This voltage is then amplified and further processed. Polymer piezoelectric materials such as PVDF or PVDF-TrFE copolymer are particularly suitable because of their mechanical flexibility, their ease of processing and because of their high signal voltage.

As shown in Fig. 8, the sensor signal is amplified by an inverter circuit. In Fig. 8a, the response curve of a printed inverter is shown. This inverter was fabricated with p-type TFTs using organic semiconductor material from Flexink, Ltd., and a thin evaporated Parylene gate dielectric. At the driving conditions shown in the figure, the inverter had a gain of ~2.

The inverter was combined with a pressure sensor made from a suspended stainless steel membrane with a sensor layer

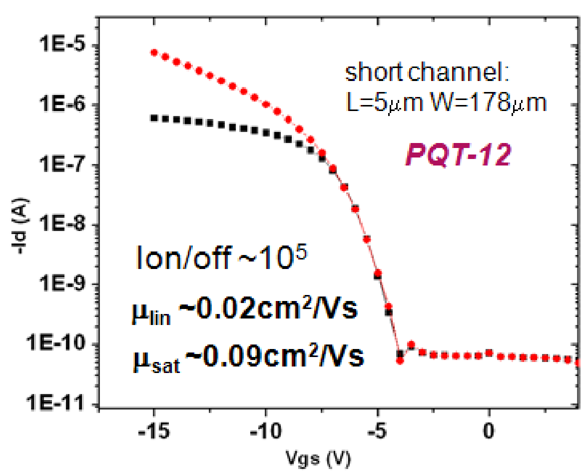
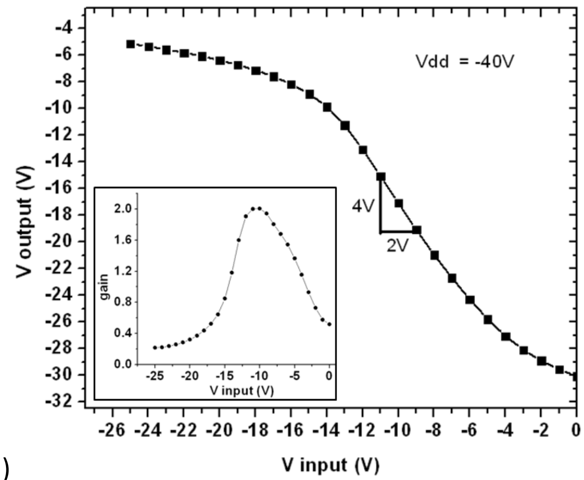


Figure 7. *Transistor curve of a low-voltage TFT with HfO_2 based gate dielectric. The HfO_2 layer is deposited by ALD over a jet-printed transistor gate. Together with a hydrophobic surface coating, a gate capacitance of ~40nF/cm^2 is achieved. The semiconductor is solution-deposited PQT-12.*

a)



b)

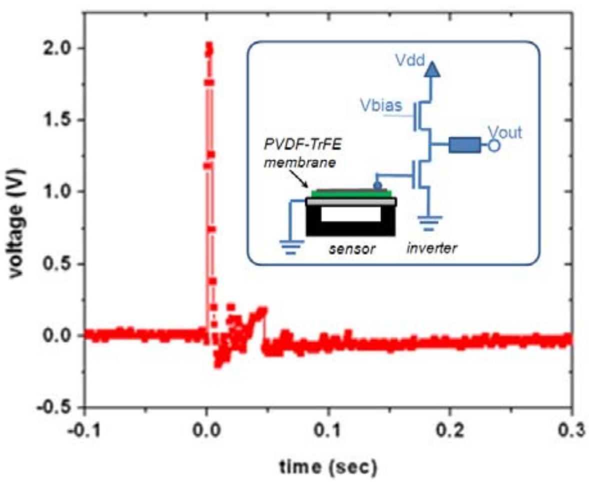


Figure 8. Inverter curve (a) and signal of a piezoelectric sensor with printed inverter (b).The pressure sensor consists of a suspended steel membrane with spin-coated PVDF-TrFE sensor film.

consisting of spin-coated PVDF-TrFE copolymer. Top electrodes on the sensor layer were deposited by jet-printing of a conductor or by sputter deposition through a shadow mask.

The sensor signal upon applying pressure was measured with an oscilloscope via a 20 MΩ resistor on the inverter output (Fig. 8b).

Summary and Conclusions

Printing methods are being explored for a variety of electronic applications, mainly with the goal of lowering fabrication costs. The specific application determines the requirements for materials and device performance. Here, active-matrix pixel circuits as well as electronics for blast sensor tapes was developed using inkjet printing.

Inkjet printing has several advantages compared to other printing techniques and the value of inkjet printing is particularly apparent in the prototyping and development phase of devices where rapid changes of designs and of materials systems are desirable. Also, the ability to print onto substrates with surface topography enables novel processes.

For manufacturing the developed devices at low cost, inkjet-printing may be combined with roll-to-roll processing.

Acknowledgment

The authors would like to thank Steve Ready at PARC for building the inkjet printing systems, the Xerox Research Center of Canada for providing PQT semiconductor, Dupont Teijin for the PEN substrate material and Measurement Specialties for the PVDF-TrFE polymer. We also thank Ritwik Bhatia, Jill Becker and Ganesh Sundaram at Cambridge Nanotech, Inc. for growing the ALD films. Part of this project was funded by DARPA (W81XWH-08-C-0065).

References

[1] H. Maeda, et al., “A 10-in. Printed Flexible Active-Matrix OTFT Array for QR-LDP-Based Motion Picture Displays”, SID 08 Digest, 23.2, p 314.

[2] Y.-G. Chang, et al., “Design Parameters of Roll Printing Process for TFT-LCD Fabrication”, SID 08 Digest, 43.1, p 637.

[3] Y.J. Chan, et al., “Printed RFID: Technology and Application”, IEEE Intern. Workshop on Radio-Frequency Integration Technology, 2005, 141

[4] T. Unander, et al., “Printed touch sensor for interactive packaging and display”, IEEE Polytronic 2007 Conf., p12

[5] J.H. Souk, et al., “Inkjet Technology for Large Sized Color Filter Plates”, SID 08 Digest, p 453

[6] W.S. Wong, et al., “Amorphous silicon thin-film transistors and arrays fabricated by jet-printing”, Appl. Phys. Lett., 80, 610 (2002)

[7] M. Bale, et al., “Ink-jet printing: The route to production of full-color P-OLED displays”, J. of the SID, 14/5, 2006, 453

[8] H. Sirringhaus, et al., “High-Resolution Inkjet Printing of All-Polymer Transistor Circuits”, Science, Vol. 290 (2000) 2123

[9] A.C. Arias, et al., “All jet-printed polymer thin-film transistor active-matrix backplanes”, Appl. Phys. Lett., 85, 3304 (2004).

[10] J. Daniel, et al., “Flexible Electrophoretic Displays with Jet-Printed Backplanes”, SID 09 Digest, 44.3, 660.

[11] D.H. Levy, et al., “Stable ZnO thin film transistors by fast open air atomic layer deposition”, Appl. Phys. Lett., 92, 192101 (2008)

Author Biography

Jurgen Daniel received a degree in physics from the University of Erlangen-Nuremberg (1994) and his PhD in electrical engineering from the University of Cambridge, UK (1999). Since then he has worked at the Palo Alto Research Center in various areas, including MEMS, displays, flexible printed electronics and photovoltaics.