Printing Techniques and Plastic Electronics for Paperlike Displays

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Abstract Heading

Plastic electronic materials and high resolution printing methods may be important technologies for new classes of consumer electronic devices that are lightweight, mechanically flexible and bendable, and which can cover large areas at low cost. This paper summarizes some of our recent work in this area. It focuses on the materials and patterning techniques that we used to produce plastic active matrix backplane circuits for a type of paperlike display. It also presents some strategies for encapsulating and enhancing the bendablity of these devices.

Introduction

Organic materials and printing techniques that are capable of patterning them have the potential to play essential roles in two different classes of future electronics systems: ultrahigh density circuits that incorporate molecular-scale switching elements and new types of circuits that are lightweight and mechanically flexible. This latter area will be important not because of its potential for achieving high speed, density, etc. but because the circuits can be rugged and bendable, and because they can be printed rapidly over large areas at low cost. These features can be difficult to achieve with the brittle inorganic materials and sophisticated processing techniques that are used for conventional electronics. Bendable plastic circuits will enable new devices – electronic paper, wearable computers or sensors, disposable wireless ID tags, etc. – that complement the types of systems that existing silicon-based electronics supports well (e.g. microprocessors, high density RAM, etc.). This field is relatively new (i.e. there are no entrenched technologies) and it relies on new patterning techniques and organic materials.

Progress in flexible electronics is driven by (i) organic or otherwise unconventional materials that can be deposited on flexible supports, (ii) low cost, high resolution patterning techniques that can be used with these materials and substrates, (iii) component geometries that explore the (often unusual) properties of these materials in new ways, and (iv) approaches to take advantage of the unique characteristics of these printed circuits in devices. This paper provides a brief overview of some of our recent work on these materials and systems, with a focus on applications in electronic paperlike displays. It begins with an overview of the layout of the circuitry for these displays and of its integration with the electronic inks. The printing and fabrication techniques are then discussed; measurements of the electrical characteristics of the transistors in the circuit illustrate their performance and their suitability for electronic paper. We conclude by highlighting the advantages and disadvantages of the fabrication methods and by assessing their potential application to devices that are more advanced than the one described here.

Circuit Layout and Design

The circuit for the prototype display consists of a square array of 256 transistors distributed over an area ~0.5x0.5 ft^2.[1] Figure 1 shows a detailed view of the gate and source/drain levels in a unit cell. The smallest features are the source/drain electrodes and the distance that separates them. In order to achieve the necessary switching speeds and current outputs for this application, the separation (i.e. transistor channel length) is ~10 µm and the electrodes and the wires that connect to them are ~10 µm wide; the width of the channel is ~100 µm. The transistors can be built with the source/drain electrodes beneath the organic semiconductor (bottom contact; as illustrated in Figure 1) or they can be constructed with these electrodes on top of the semiconductor (top contact).

The completed display comprises a top electrode of indium tin oxide (ITO) and an unpatterned layer of ‘electronic ink’ laminated onto this backplane circuitry. Each transistor functions as a switch that locally controls the color of the 'ink', which is based on technologies developed for electrophoretic image display systems.[1,2] Applying a voltage to a column (gate) and a row (drain) electrode activates the transistor located at the position where these electrodes intersect. Electric fields build up between the ITO and the electrodes (i.e. pixel electrodes, which are connected to the transistor source electrodes) that connect to pads that spatially define the pixels. These fields cause changes the color of the pixel, as observed through the ITO. Coordinated control of the transistors is achieved with external circuitry connected to the ITO layer and to pinouts that lead to the column and row electrodes.

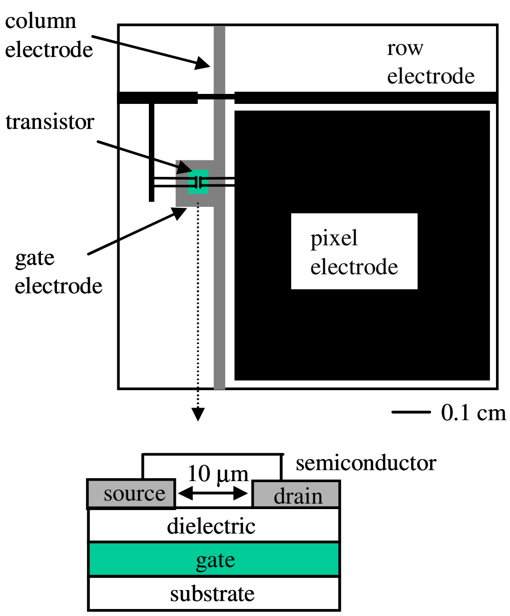

Figure 1. Unit cell

A transistor can switch a pixel if it provides sufficient 'on' current to switch the pixels (~1 μA at 80 V), and small enough 'leakage' and 'off' currents to avoid unwanted switching (~30 nA at 80 V). In addition to these static characteristics, the driving scheme demands that the total capacitance associated with each pixel is sufficiently small to allow for millisecond switching times. This requirement places limits on the area of overlap of the gate with conductors on the source/drain level and the transistor channels; it stresses the need for fine features.

Printing and Integration

The electrical requirements of the transistors in the display circuit and the moderate to relatively low mobilities of organic semiconductors (i.e. <~1 cm^2/Vs) demand high resolution patterning for the source/drain level of the circuit. We have developed procedures for using microcontact printing for this application.[2-4] The techniques are attractive for plastic electronics because of their compatibility with reel-to-reel processing, their operational simplicity, their ability to pattern high resolution features on plastic substrates and their potential for patterning large areas at very low cost. This approach uses high resolution rubber stamps and 'ink's of molecules that form self-assembled monolayers on the surface that is printed. For the systems described here, we used a solution of hexadecanethiol (HDT) in ethanol as the 'ink' and a thin gold film on plastic as the substrate that we printed on. Figure 2 gives a schematic illustration of the process. The printed HDT acts as a resist for acqueous-based etching of the substrate. Removing the HDT after etching leaves a pattern of a conducting gold. The transistors can be completed by depositing organic semiconductor on top of electrodes formed in this fashion on a substrate that supports the gate and gate dielectric. Alternatively, these electrodes can be patterned on an elastomeric, conformable support that can then be physically laminated against a different substrate that is patterned with the semiconductor, the gate and the gate dielectric.[5] This latter lamination procedure is illustrated in Figure 3. It has the advantage that it automatically encapsulates the circuit at the neutral mechanical plane of the resulting structure. It also separates the deposition and patterning steps for the source/drain electrodes from the other components of the circuit.

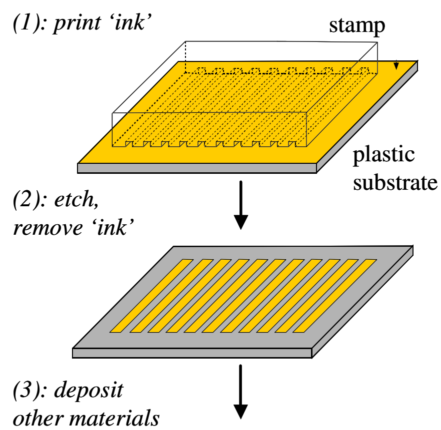

Figure 2. Printing procedure

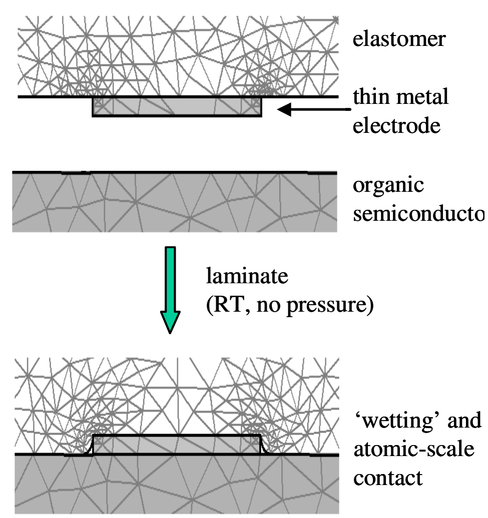

Figure 3. Lamination procedure

Results

Figure 4 shows an image of a printed flexible circuit formed according to the procedures described above.[1] In this case, the circuit uses the bottom contact design. Figure 5 shows a magnified view of a similar circuit built using the lamination procedures outlined in Figure 3.[5] In this case, the circuit is substantially waterproof; the image shows a circuit immediately after removal from a water bath. In both circuit designs, the electrical properties of the transistors are good. Figure 6 shows the current-voltage characteristics of a laminated device before and after immersion in stirred soapy water for 3 hours.[5] The on/off ratios of similar devices can be as high as 10^5-10^6, their effective mobilities are typically 0.1-0.5 cm^2/Vs and they can be designed to achieve 'on' currents that satisfy the requirements for electronic paper display systems. The high operating voltages are designed to match the high voltage requirements of the electronic inks.

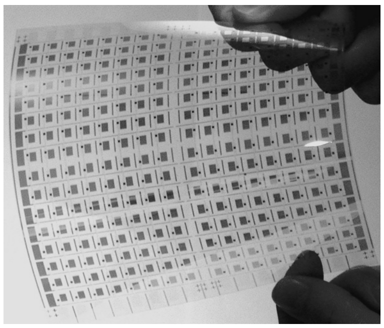

Figure 4. Printed plastic display circuit

Figure 5. Laminated plastic circuit

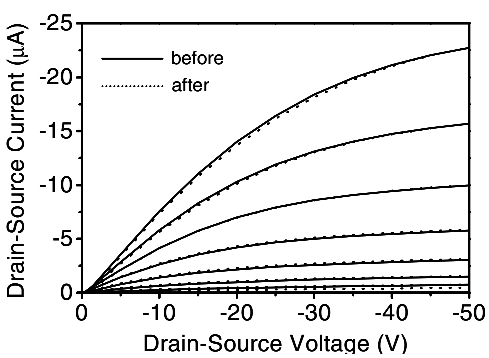

Figure 6. Transistor characteristics

Bonding the circuits to sheets of microencapsulated electrophoretic ink produces the displays. Figure 7 shows an image of one such display. Its total thickness is ~1 mm; the ink is reflective and it masks the drive circuit, which lies behind the ink layer. Coordinated control of the organic transistors is achieved with a small silicon-based circuit mounted on the backside of the display. The appearance and operation of the display is not affected by bending.

Figure 7. Electronic paperlike display

Conclusion

The sophistication and flexibility of the patterning procedures, the high level of integration on plastic substrates, the large area coverage and the good performance of the organic transistors are all important featuers of the printed plastic display circuits described here. Although these circuits do not support a large enough number of pixels to be useful for consumer applications, many of the processing approaches and materials can be extended to systems with more pixels and/or higher resolution.

The types of flexible circuits described here are also compatible with non-electrophoretic 'inks'. We demonstrated, for example, their use in small flexible displays that use thin layers of polymer dispersed liquid crystals (PDLCs).[6] Other groups have also explored this combination. The Sarnoff/Penn State group used photolithographically defined organic circuits and flexible substrates to drive small PDLC displays.[7] The Philips group reported small, ridid PDLC displays with many thousands of pixels and backplanes of photolithographically defined organic transistors on glass substrates.[8] These and other efforts, taken together with our own work, strongly suggest that the technologies required for commercially viable, printed paperlike displays may be available soon. For this reason, as well as many others, we believe that printed flexible electronic systems display a bright future.

References

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Biography

John A. Rogers received the B.A. and B.S. degrees in Chemistry and in Physics, respectively, from the University of Texas at Austin in 1989. He earned S.M. degrees in Physics and in Chemistry in 1992, and the Ph.D. degree in Physical Chemistry in 1995, all from M.I.T. From 1995 to 1997, he was a member of the Harvard Society of Fellows. John is currently Director, Nanotechnology Research at Bell Laboratories. His research interests include high resolution printing techniques and materials for plastic electronics.