All-Printed Electronics: Materials, Devices, and Circuit Implications

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Abstract

Digital printing has garnered significant attention in recent years as a pathway to ultra-low-cost electronic systems. In particular, given the low viscosity requirements of inkjet printing, this has been a leading candidate technology for realization of all-printed electronic devices. We have developed inkjet-compatible materials for a full range of electronic materials, including printed conductors for interconnects and antennae, dielectrics for capacitors and transistors, and semiconductors for active devices. Using various combinations of nanoengineered particles and organic materials, we have realized fully printed transistors, diodes, and passive components with performance approaching the requirements of various applications including displays, sensors, and low-cost RFID tags. We review our materials technology, report on advanced devices fabricated using these materials, and discuss the implications of the same on the viability of fully-printed circuits.

Introduction

In recent years, there has been great interest in the use of printing as a means of realizing ultra-low-cost electronic systems. Since printing offers a method for fabricating electronic systems using fully-additive processing techniques, it is expected to result in a substantial reduction in process complexity. This in turn will lead to a large reduction in cost per unit area for circuit fabricated using printing technology when compared with circuits fabricated by conventional means. Of the various printing technologies that are in widespread use, digital printing techniques based on inkjet technology have generally received the most attention for printed electronics applications due to the low viscosity requirements of the same. This ensures excellent material compatibility with a wide range of electronic material inks.

Given the low cost per unit area of printed electronics, various applications have garnered substantial interest as potential deployment points for printed electronics. In particular, three applications that have received tremendous attention are displays, sensors, and RFID tags. In this work, we review the application-specific material and device requirements of printed electronics as they relate to these applications, and discuss the state of the art of printed electronics technology being developed by us for the same.

Application-Specific Requirements

The main consequence of a fully-printed process flow is a reduction in the overall process complexity. A typical fully-printed process flow reduces the total number of process steps in a typical fabrication process by up to 60%. This in turn results in a dramatic reduction in cost per unit area. Depending on the assumptions made with regards to process throughput, capital expenditure, and raw materials costs, the overall cost reduction in printed electronics relative to conventional subtractive processing is 2 to 3 orders of magnitude. Interestingly, the cost per transistor in printed electronics is actually not cheaper than the cost per transistor in silicon, since silicon transistor densities are orders of magnitude higher than that achievable using any existing commercially viable printing techniques. This cost structure has two consequences. First, ideal applications for printed electronics are applications where form factor is relatively independent of transistor count (e.g., displays, some sensors, and RFID tags operating at lower frequencies). Second, the real benefits of printed electronics derive from a reduction in process complexity; therefore, there is tremendous need to drive towards a fully-additive, all-printed solution, which in turn places constraints on material needs and device structures.

Displays

Displays are a tremendous driver for printed electronics [1]. Since display form factors are determined by the viewing requirements and transistor counts typically do not determine display size, this application fits well within the cost paradigms of printed electronics. Additionally, since the incumbent technology is amorphous silicon, the performance requirements are certainly within the realm of those achievable using printed materials. Devices required for display applications include transparent conductors, low-resistance conductors, transistors, and capacitors, in addition to the display element itself. The display element (LCD, OLED, etc.) will not be discussed here. Based on the other needs, it is clear that material needs include transparent conductors and low-resistance metallic conductors, printable semiconductors, and printable dielectrics. For display applications, there is also generally a benefit resulting from moving towards all-transparent electronics, since this allows the use of larger electronics within sacrificing display brightness or aperture ratio; this in turn allows the use of lower-performance parts [2].

Sensors

The drive towards printed sensors is determined more by form factor issues than by cost. Since sensors on plastic are desirable for various consumer packaging applications including product content monitoring, there is generally interest in development of sensors that are printed directly on plastic. In particular, there is interest in gas / vapor / fluid sensor for monitoring of product quality within a package [3]. In turn, this defines materials / device needs including the need for printed sensing elements as well as printed circuitry for processing the signals produced by the sensing elements.

RFID Tags

The size of RFID tags operating at 13.56MHz is largely determined by the antenna size. As a result, printed electronics may fit well in this space from an economic perspective [4]. To realize printed RFID tags, materials / device requirements include printed transistors and potentially also printed diodes, printed capacitors, and printed high-Q inductors. This in turn defines material needs including printed low-resistance conductors, dielectrics with low-dispersion at 13.56MHz, and high-mobility printed semiconductors.

Technology Status: Printing

From the analysis above, it is evident that the advantages of printed electronics are generally predicated on a cost-per-unit-area basis. From this perspective, it would be expected that traditional high-speed analog techniques such as screen printing, gravure printing, flexographic printing, or offset printing would be the most promising candidates for printed electronics. State of the art digital printing techniques still lag behind these techniques in terms of throughput, and therefore in terms of cost per unit area calculated on a raw throughput basis.

It turns out, however, that digital printing dominates all demonstrated printed electronic circuits to date. Indeed, it is likely that digital printing will be the first commercially realized printed electronics platform; certainly companies such as Plastic Logic are exploiting digital printing techniques for materials deposition, if not for patterning [5]. Digital printing is promising for printed electronics for several reasons:

1. Digital printing allows the use of small volumes of material. This is particularly attractive given the high cost of many printed electronic "inks"
2. Digital printing allows rapid pattern re-design. This is also attractive, given the nascent nature of the field
3. Most importantly, viscosity requirements for many digital printing systems are significantly lower than that required for most traditional analog printing techniques. This is tremendously important, since the use of binders in inks will degrade electronic performance; as a result, most printed electronics "inks" consist of active material plus solvent only; this limits viscosity to <10cP
4. Digital printing can correct *in situ* for substrate distortion

For the above reasons, digital printing is likely to be the first printing technique to be used in printed electronics applications. The down-side to digital printing, of course, is the relatively poor reliability in terms of drop placement accuracy, head firing, etc. As a result, question marks certainly remain with regard to manufacturing viability of digital printing; recent progress in head specifications in terms of characteristics and reliability reported by several inkjet head manufacturers suggests that these concerns are certainly being addressed, at least to a degree.

Technology Status: Materials & Devices

Based on the applications above, we have been pursuing a program aimed at developing materials, devices, and circuits targeted at the above needs. Here, we review our progress towards development of fully-printed low-cost electronic systems.

Printed conductors and passive components

As discussed above, there is a need for printed conductors for interconnection in all the aforementioned applications, as well as for formation of passive components for printed RFID applications. To achieve low-resistance, we have exploited the substantial melting point reduction that is exhibited in metallic nanoparticles [6]. Organic-encapsulated metallic nanoparticles are synthesized and solubilized to form an ink. This is printed and sintered at plastic-compatible temperatures. Through appropriate design of the nanoparticle, this temperature is sufficient to fuse the nanoparticles to form high-conductivity metals. Using this process, we have fabricated both interconnects and passive components, as shown below [7].

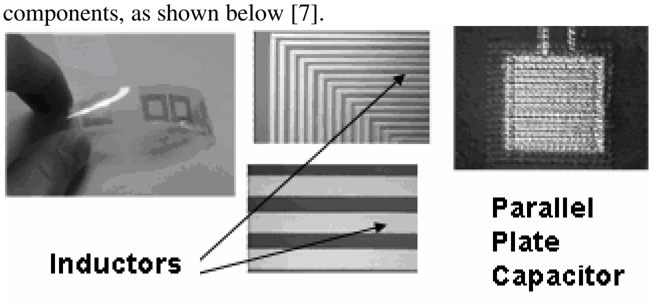

Figure 1: Printed passive components formed using nanoparticle inks

Printed transistors

Printed transistors are fabricated using the metal nanoparticles above in conjunction with various printed semiconductors and dielectrics. A conventional bottom-gated transistor structure is typically use. All layers are printed [8].

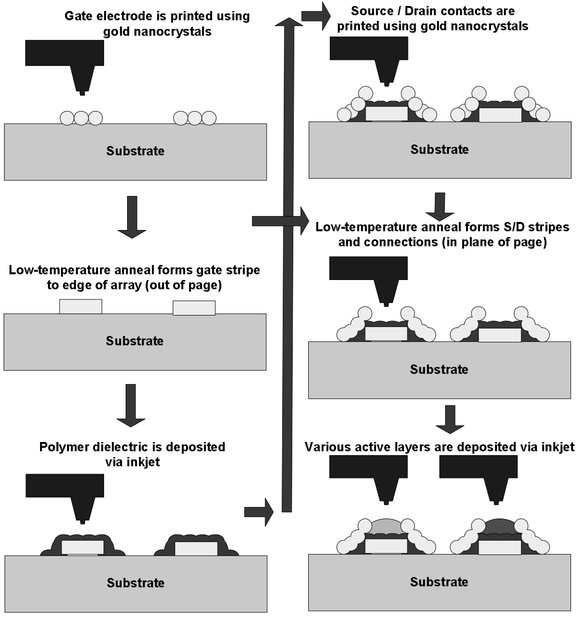

Figure 2: Process flow used to fabricate printed transistors

Various types of printable semiconductors are used, including various printable organic semiconductors and nanoparticle-based inorganic semiconductors. A key feature of our process is that all printed layers are converted during the process into insoluble form.

This allows multiple layers to be printed over each other without causing significant solvent-interaction problems. Thus, the nanoparticles are converted into insoluble metal, polymer dielectrics are crosslinked to make them insoluble, and organic and inorganic semiconductors are thermally converted into insoluble forms.

Among organic semiconductors, we have focused on various oligothiophene and pentacene derivatives. Mobilities as high as 0.2cm^2/V-s have been achieved. Operating voltages as low as 10V have been achieved by printing thin gate dielectrics (dielectrics as thin as 20nm have been achieved with high yield and no pinholes) [9].

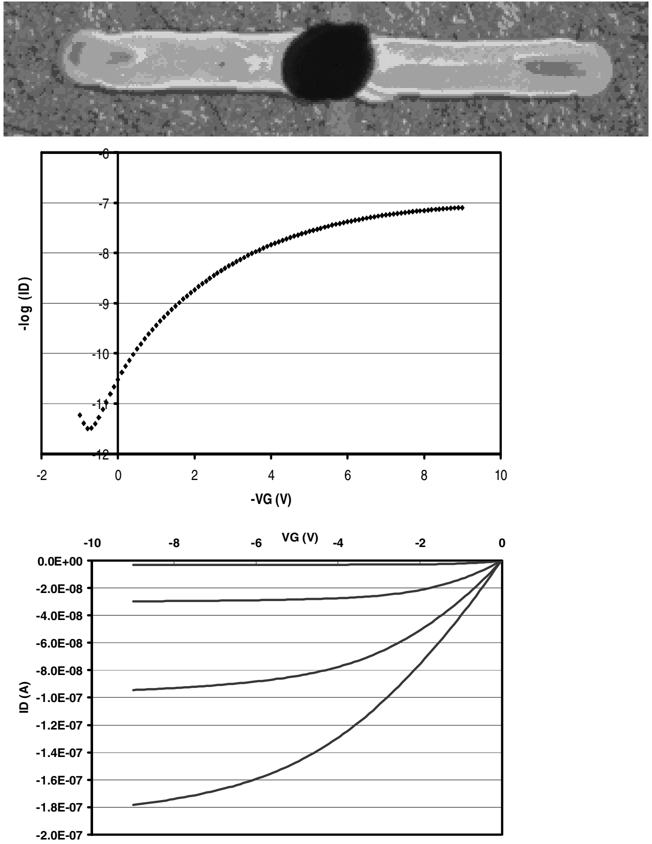

Figure 3: *Electrical characteristics of printed transistors formed using a soluble pentacene precursor*

Devices with inorganic semiconductor channels have also been realized using ZnO nanoparticles. Mobility as high as 0.2cm^2/V-s have been achieved, as shown below [10]. ZnO has the additional advantage of being transparent, making it highly attractive for use in displays.

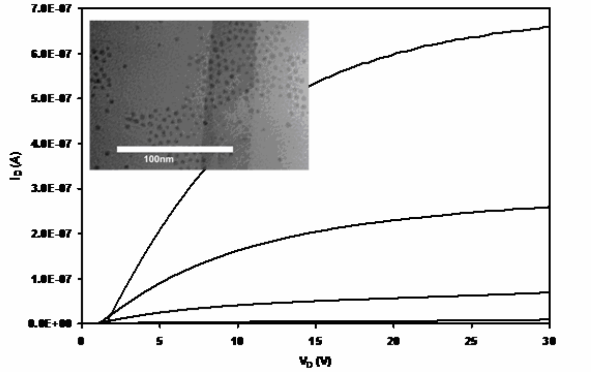

Figure 4: *Output characteristics of a ZnO nanoparticle-based thin film transistor with mobility >0.1cm^2/V-s, despite large contact barriers.*

Gas sensors

By exploiting the chemical sensitivity of organic materials, we have also realized gas sensors. Arrays of individual sensing transistors are deployed on the same substrate. This is conveniently achieved using inkjet printing. By functionalizing individual chemicals to be sensitive to different materials and deploying them into an array, highly specific sensors may be realized [11]. The resulting sensor forms an "electronic nose", in which specificity is obtained by pattern matching to the cumulative response of multiple (individually non-specific) sensing elements, as shown below.

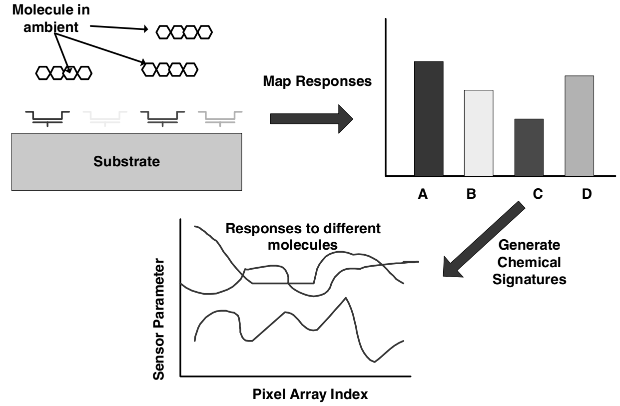

Figure 5: *Schematic illustration of electronic nose operation, showing use of pattern matching to achieve selectivity via individually non-specific sensor elements*

The response of a sample array sensor to different analytes is shown below.

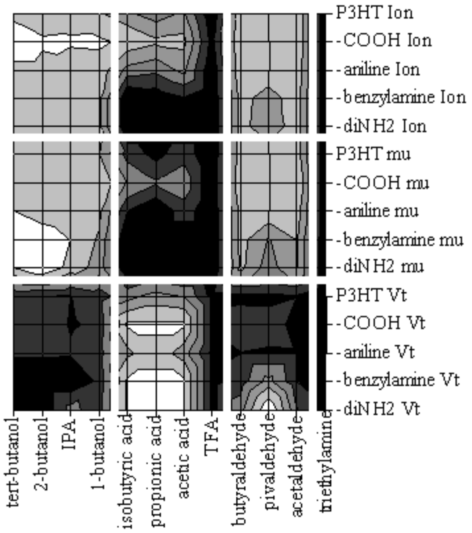

Figure 6: *Array response of various printed sensors (horizontal axis) to various vapors (vertical axis)*

Conclusions

In this paper, we have discussed our development of various printed electronics technologies targeted at meeting the needs of various optimal applications for printed electronics. While several concerns remain, particularly related to stability and reliability, the potential for printed electronics is strong, and progress will continue, driven by development of new materials and processes designed to exploit the opportunities that exist at the intersection of economics and engineering through the benefits of printing.

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Author Biography

Vivek Subramanian received his PhD in electrical engineering from Stanford University in 1998. He co-founded Matrix Semiconductor that year. Since 2000, he has been with the EECS Department at the University of California, Berkeley, where he is an Associate Professor. Recent awards he has received include the Rappaport Award for the best paper in an IEEE journal, the IEEE Device Research Conference best paper award, and the UC Berkeley EECS Department distinguished teaching award.