3D Printed Electronics

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Abstract

PARC has been a leading innovator in printed electronics with over a decade of experience in large area electronics, application of novel and current printing technology to industrial applications and the printing of electronic circuits and devices. We are currently applying this knowledge to the concept of printing multi-material 3 dimensional objects with electronic and/or mechanical functionality. The concept is to develop capability and provide means of manufacturing functional objects which may be difficult to manufacture or even not be manufacturable by other means.

In this paper, we will outline the creation of a rapid digital manufacturing system and considerations for building such a "printer" with the ability to integrate a structural material with functional electronic materials. The printer incorporates inkjet and extrusion techniques on the same platform, along with an in-line UV-curing lamp. This platform enables a wide processing window for structural and electronic materials; i.e., it is capable of patterning inks with viscosity ranging from 1 to 25000 cP The printer has been optimized to yield smooth printed features (down to tens of microns) without implementing pressure-leveling steps.

Introduction

The last decade has experienced significant interest and progress in the creation of alternative manufacturing technologies driven by the capabilities engendered with digital control. 3D rapid prototyping equipment has progressed to the point that one can envision applications where high value customized products are additively printed into existence in a viable business.

In addition, the field of digital, additively printed functional electronics has also developed significantly. While early applications focused on the use of printed field-effect transistors (FETs) for active-matrix backplanes to drive displays (primarily reflective displays), many recent examples have addressed printed sense-and-record systems. Such systems require not only printed transistors (to form logic circuits for data processing), but also printed sensors, memories, and power sources.

PARC has developed printed complementary field-effect transistors printed using an ink-jet technique.[1,2,3] These FETs are based on organic semiconductors, metal nanoparticle conductors and polymeric dielectrics. Printing both p- and n-type semiconductors enables circuits with a simpler design, lower power consumption and improved aging characteristics when compared with unipolar circuits.

a)

b)

c)

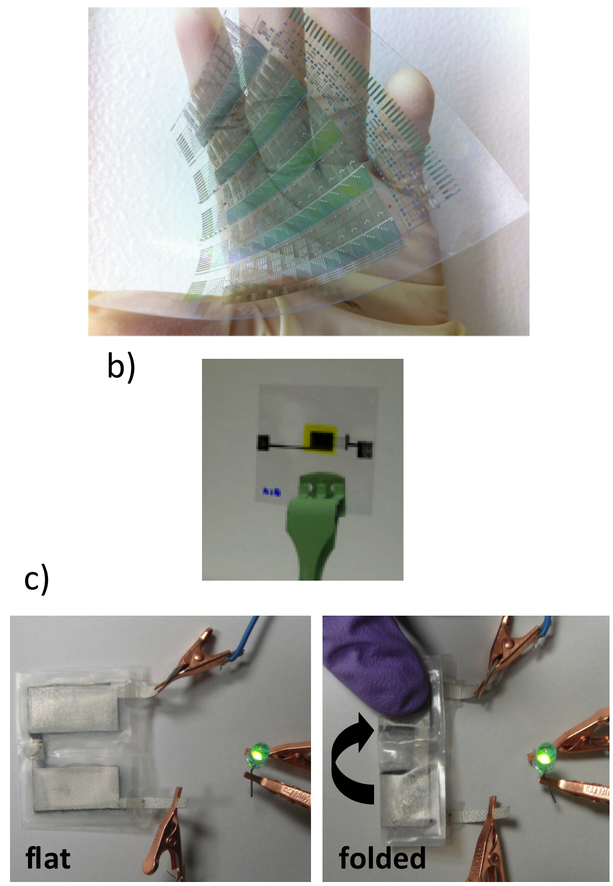


***Figure 1**. Examples of printed electronic components. a) printed decoder for memory addressing fabricated from ink-jet printed complementary organic field-effect transistors [1] b) example of a printed sensor, an ink-jet printed bulk-hetereojunction photodiodoe for high-illumanance detection [3] c) A stensil-printed alkaline electrochemical cell, shown powering a green LED when flat and folded over to a bend radius of 3 mm.[8]*

For these devices design rules and characteristics have been extracted and used to develop simulations, which then assist in the design of new circuits, such as decoders, and shift registers[1,2,3,4].

In order to create highly functional sensing systems, other printed devices are needed such as those for sensing environmental stimuli, recording data, and powering these systems. For example, ink-jet printed bulk heterojunction photosensors based on polymer blends can be used for light

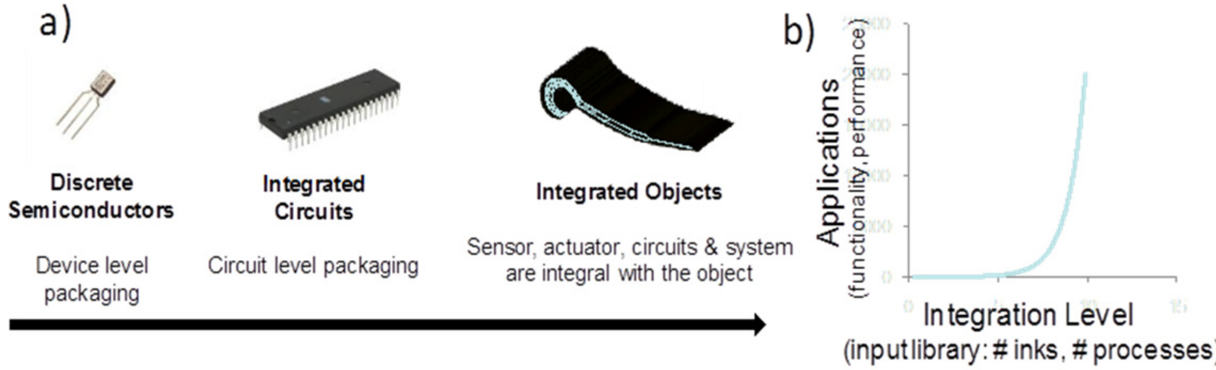


Figure 2. *a) Integrated objects viewed as a further level of integration. b) We expect the number of addressable applications for 3D printing to increase significantly through the inclusion of additional inks and processes.*

sensing,[5] printed metal-oxide thermistors have been used for temperature sensing and devices incorporating piezoelectric polymers have been used for sensing applied pressure.[6] Through modification of the polarization of a ferroelectric polymer dielectric, printed field-effect transistors can be used as memory devices.[7] In order to power these devices for mobile applications flexible printed batteries have also been developed.[8] In addition to fabrication of these separate elements, printing is a compelling approach for the integration of such devices into more complex functional systems. Examples include using printed inverters to amplify the signal produced by flexible sensors,[9] using printed logic circuits to address memory elements,[3] active matrix arrays for displays,[10] and powering circuits using a battery formed from an array of printed electrochemical cells.[11]

The central theme of this work is to suggest a new manufacturing capability based on additive printing of both structural and electronic materials, taking advantage of materials and processes for both 3D printing and printed electronics, enabling digital production of electromechanical parts directly from solid model CAD assemblies. Our intentions are to significantly enhance the functionality of printed mechanical objects, by enabling 3D printers to include functional electronic materials as well as structural materials. The vision is ultimately for a complete, functional integrated object to exit the printer eliminating any and all manual assembly. We imagine a platform capable of including many different materials, components and processes in a single manufacturing system, allowing for the production of a vast array of objects covering many application areas (see figure 2). Incorporation of appropriate design tools will ideally enable the system to be broadly used through a distributed manufacturing model.

Objects manufactured using additive methods, such as 3D printing, are typically purely structural, having little inherent electronic functionality. This generally makes additively manufactured objects more useful as individual parts to be incorporated into more complex systems, rather than directly as functional items. Broadening the scope of additive manufacturing to include not only the deposition of structural materials, but also of functional materials (in particular materials with electronic functionality) should enable monolithic objects to be produced with embedded electronic and mechanical functionality using a single, additive digital manufacturing system. In addition to allowing the direct fabrication of useful functional objects, such an integrated system will also benefit substantially from automated Design for Manufacturability (DfM) tools which will help optimize the process and design of the end product.

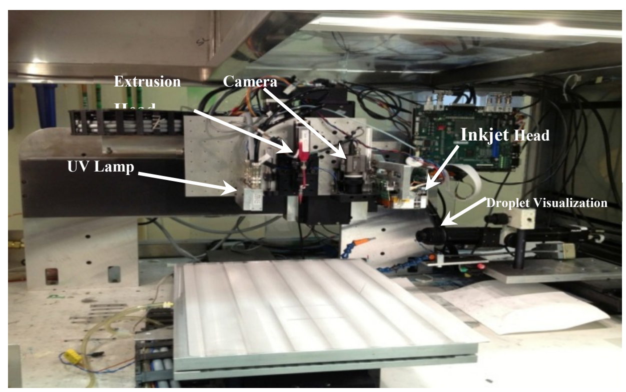


***Figure 3**. Initial 3D high accuracy printing system intended to demonstrate 3D multi-functional object fabrication.*

Printing System

This initial work has focused on integrating the two most important materials that will be necessary for creating functional electromechanical parts – a structural material (we are currently working with a UV curable polyurethane gel, - 25000 cP) and a conductor (a nanoparticle silver ink - 10 cP) to make electrical connections, using extrusion and ink-jet printing processes. Figure 3 displays the beginning of an integrated fixture which includes inkjet, extrusion and UV curing capability. Future systems could then integrate other materials (such as semiconductors), components (such as integrated circuits and sensors), and processes (such as chip assembly and laser processing).

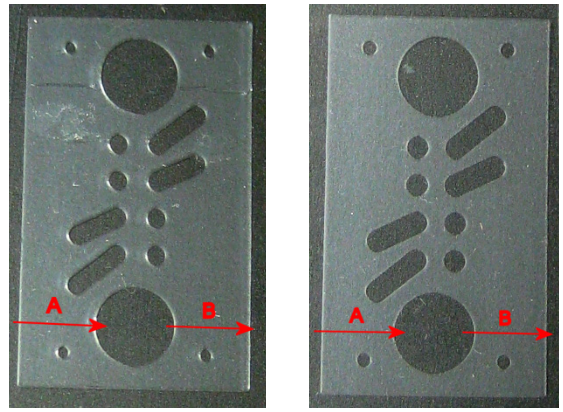
Results and Discussions

In order to extend printed electronics work into freeform 3D fabrication of embedded electronic systems we have integrated inkjet and extrusion printheads on one platform, enabling the use of a wide range of materials. The inkjet printhead is better suited for less viscous inks, and it provides higher resolution than the extrusion Auger valve. On the other hand, the extrusion technique is preferred as increasing ink viscosity may be favored for application of structural materials. The silver conductor line are currently deposited through the inkjet printhead. On top of the polyurethane structural material, the printed conductor lines were typically 35um in width and 1 um in thickness. The polyurethane extruded through a 27 gauge tip typically showed line width of 200um and thickness of 100um. Both the printed Ag conductor and the polyurethane gel were photonically dried and cured by the in-line UV lamp, allowing for repeatable, layer-by-layer fabrication of parts.

One of the major challenges with digital 3D printing is to produce smooth features. To create flat and smooth printed surfaces, some printers use a roller to apply pressure for leveling and merging neighboring lines and layers. This extra step adds complication to the system and increases printing time. Here we performed optimizations to the material application by extrusion in order to eliminate this step. The polyurethane gel allows reflow before UV curing, and thus is capable of yielding smooth surfaces with roughness less than 5%. In addition, by adjusting the extrusion starting and stopping conditions provides another control of feature flatness. In Figures 4 and 5, the extruded layer initially shows a pile-up of materials at the end of a printed line. This pile-up is due to the slow time response of the viscous gel ink, which does not retract immediately back into the nozzle and results in extra materials being deposited at the end of nozzle travel. In order to mitigate this effect, the printer control software is set to stop extrusion at various distances away from the intended edge. It is shown in Figure 5 that the best profile is obtained with a distance of 1 mm.

Conclusions

Taking advantage of both 3D printing and printed electronics, we are currently developing a printing system capable of seamlessly integrating electronic functionality into 3D objects. This system uses both ink-jet and extrusion methods, enabling a wide range of structural and functional inks to be used. Photonic curing allows for a continuous, automated, layer-by-layer approach for building up these integrated objects with embedded electronic functionality.



Delta ending distance = 0.0 mm

Delta ending distance = 1.0 mm

Figure 4. *Printed polyurethane parts, for which the extrusion nozzle was turned off at different distances from the edge.*

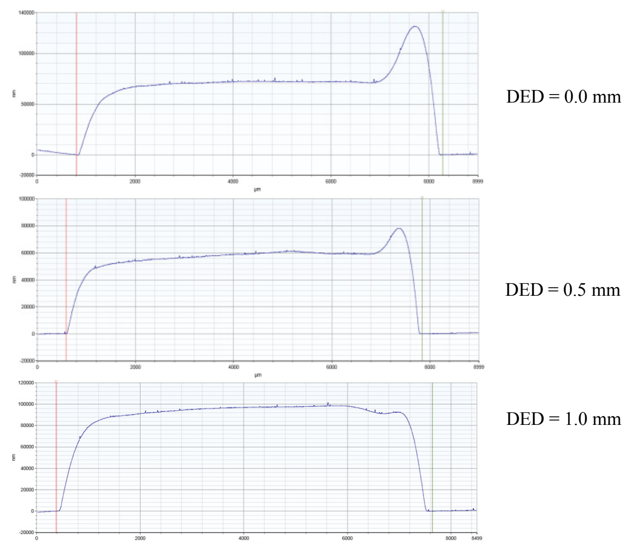


Figure 5*. Cross-sectional profiles of line A in Fig. 4. The printed features show a smoother surface when the extrusion nozzle is stopped farther away from the edge. DED means Delta Ending Distance, or the distance from the intended edge.*

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Author Biography

Steve Ready obtained his degree in Physics from the University of California at Santa Cruz. He then joined Xerox Palo Alto Research Center and has since studied the role of hydrogen in amorphous, polycrystalline and crystalline silicon and has contributed to the development of large area amorphous and polycrystalline silicon imaging arrays for optical and x-ray applications. Recently he has designed and developed several high-accuracy inkjet printers for printed organic electronics and documents.