DESIGNER POLYMERS: ADDITIVE MANUFACTURING OF SMART MATERIALS AS A COMPLEMENT TO INJECTION MOLDING

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Abstract

This paper presents the idea of "designer polymers" – these are polymers that can be custom formulated to include sensing, computation, and actuation infused throughout the bulk of the material. Designer polymers are useful in the design and fabrication of smart products and we believe they will revolutionize the co-design of complex products. The co-design of smart products involves the simultaneous design of, for example, hardware and the software that executes during the functioning of the device. In our quest to develop designer materials, we have explored a variety of fabrication methods, including insert-molding and 3-D printing, or additive manufacturing.

Introduction

"Designer Polymers" are mass-customized polymer materials that have polymer sensing, computation and, even actuation, distributed throughout the bulk of the material which enhance the design of smart products for which the new materials are co-evolved. Designing custom materials that specifically enhance the function of engineered products could revolutionize the design process to create new capabilities functionality and sustainability. These advanced materials, dubbed "designer polymers," will largely be polymer-based, "4-D printed" (combining 3-D form with an extra dimension of function), and will essentially enable the co-design of functional materials with new, advanced smart products that take advantage of the new material capabilities.

3-D printing has made accessible rapid fabrication and creation of meta-materials for almost any design idea for anyone. Also polymers have for decades made available fabrication of many products for designers. Yet despite these advances, the design process itself has largely stayed unchanged. We believe that "Designer Polymers" will revolutionize the design process for such products in such a way that it will be carried out holistically with unified design methods that integrate both form and function across the hardware/software interface to achieve 4D-printing, i.e. the ability to co-design will enable convergence of electrical, mechanical and software design.

Our prior work [1] in the area of lithography-based Structured Computational Polymers, has enabled us to present in this paper an important step: all-polymer form of robotic materials, for the rapid and mass-customizable realm of low-cost 3-D printing of entire smart products, as an extension of injection molding. Injection molding and 3-D printing and aren't really competing technologies so much as they are complementary. Both can theoretically be used for manufacturing and both can technically be used for rapid prototype generation. Building on our neuromorphic architecture implemented from polymer electronic materials [2, 3], we have demonstrated fabrication of fully-integrated robotic materials with low-cost additive manufacturing. The devices we have previously fabricated include transistors, memristive devices, sensors and actuators that span the full range of devices necessary to realize the neuromorphic circuits for user-defined robotic materials. In this paper, only passive devices converted to extrusion printing are reported.

Over the years, many works have explored developing active and passive 3-D printed electronic components using inkjet printing technology. For example, [4] has contributed to production of significant results, but many such techniques are not suitable for fabrication of durable high-performance polymer semiconductor devices. Because of the inherent energetic process at the micro-level, inkjet-printed semiconducting devices look like the "craters of the moon" with planarity levels that produce passable but sub-optimal films insufficient for high-performance transistors and other components [5, 6]. We are also developing liquid polymer extrusion processes to work hand-in-hand with existing solid polymer extrusion processes, such as FDM, to simultaneously deposit sensing, computation, actuation and structure at the same time.

This paper is built upon of our prior works which constructed synthetic neurons with lithography [1, 7] to produce *robotic materials*. We have extended these prior works along the lines of [8], which explored the preparation of a printable substrate through planarization and subsequent spraying of conductive materials. The early results of a new, highly integrated project [Fig. 1] are reported upon, which intends to produce a complete *Form + Function 4-D Printer* that will eventually bring to life complete smart products containing distributed sensing, neural computation and actuation throughout the bulk of formed material. A particular strength of our project is the avoidance of inkjet printing in favor of liquid extrusion printing, which avoids the energetic "craters of the moon". Here, we demonstrate single-layer extrusion-printing of capacitors and resistors to filter and impedance-match the signal to a new, higher-performance organic transistor design that solves the cascading problem previously reported and is more amenable to liquid extrusion printing technology. The planar-printed polymer electronics is integrated, by folding, into a 3-D, six-legged walking robot based on the design of [9].

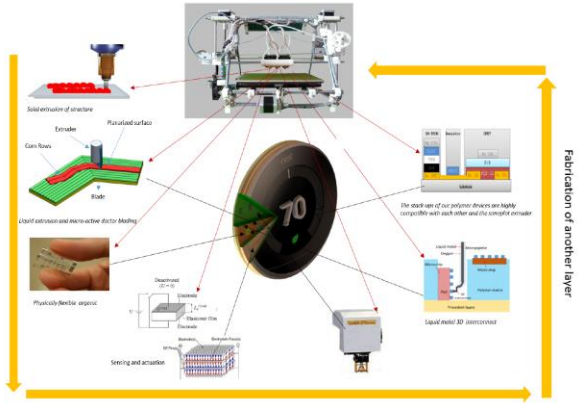


Figure 1: Conceptual view of the critical components of the 4-D polymer printer for smart products [21]

Prior Work

The prior papers reported on 1-D and 2-D materials for actuation and computation using polymers as the flexible constituents. Semi-conducting, conducting, and ferroelectric polymers have been used as sensors and actuators for contraction and expansion [10,11]. Also, several researches in the soft robotics space have demonstrated complete robotics systems based on polymers [12]. All of those concentrate only on the sensing ability of their material and do not address cognition nor actuation aspects. As such, our proposal differs starkly with the aforementioned designs. Recently several research groups have demonstrated fabrication of "electronic skin" from polymeric materials [13, 14]. Additionally, they are typically fabricated using lithographic processes.

4-D Printing and co-Design

We refer to the fabrication of smart polymer materials through additive manufacturing as "Form + Function 4-D Printing." One example of Form and Function, is the Tupperware Flat Out container [Fig. 2] where 'Form' represents the container shape and 'Function' represents the container inflating and deflate (mechanical design only), but not co-design.

Robotics commonly defined as "systems that combine perception, cognition and actuation"; hence, they can sense, think and act via their sensors, processors and actuators. The design process for such systems are generally broken into separate paths for electrical, control or mechanical designs [15, 16]. More recently, "soft robotics" combines the function of sensors, actuators, and structure into compliant materials that appear "soft" upon interaction with the environment [17], still they are designed in the same way. The co-design of smart products refers to the simultaneous design of hardware (electrical, control and mechanical) and the software that executes during the functioning of the device. Therefore, augmenting co-design, form and function will lead to "Form + Function 4-D Printing and co-design", one example of this, is the "Plain2Fun" where it is possible to print electrical circuits on the surface of ordinary objects. Plain2fun represents a design and fabrication pipeline enabling users to quickly transform ordinary objects into interactive and functional ones [18]. Another example is acheiving the co-design of neuromorphic architectures using printed synthetic neural networks (electrical design and software design). The approach presents the development of a flexible polymer meta-material that embeds a neuromorphic architecture for computation based on printable organic semiconductors with intrinsic pressure sensing co-designed with an algorithm to compute the centroid of pressure [19].

Figure 2: Tupperware Flat Out container

Component Capabilities

As mentioned previously, the point of this paper is to report initial efforts to pave the way for 3-D printing of entire smart products. These include the planarization of solid extrusion of (thermoplastic) structural layers, the smoothing of parallel liquid extrusions, the liquid extrusion of multilayer capacitors, and the performance of a low-impedance organic transistor capable of cascading signals from one stage to the next.

Substrate Preparation

As can be seen in Figures 3(a) and 3(e), a drawback of thermoplastic 3-D printing process is the "corn rows" of adjacent extrusions that occur. They are created because solid extrusion fuses enough in the “four-connected-sense” i.e. top, bottom, left and right, to form a rigid material with about 75% of the strength of native material. Yet, the surface roughness is extremely high for polymer electronics as it provides no uniformity for the semiconducting films. A StrataSys FDM machine exhibits a surface roughness of about 70 μm. We have demonstrated that we can smooth this type of surface with the polymer CyEPL to the degree necessary for high-quality polymer electronics: a planarity of 1–2 μm. This was achieved using demonstrated this with a StrataSys Dimension Elite FDM machine by printing a flat substrate, as shown in Fig. 3b). Multiple layers were deposited to develop a thermally stable substrate. Figure 3(f) illustrates the boundary between the planarizing CyEPL polymer (left) and the bare ABS material (right). The dramatic smoothing is evident at the edge of the material and the profilometry shows planarity with CyEPL as good as 1:69 μm. One can imagine it is like scraping cream with a blade over rough surface of a toast and the resulting surface of that toast becoming more planar than before. This process is repeated with *n* structural layers m intelligent layers, their planning and interaction of these complex layers is a subject of development and future research.

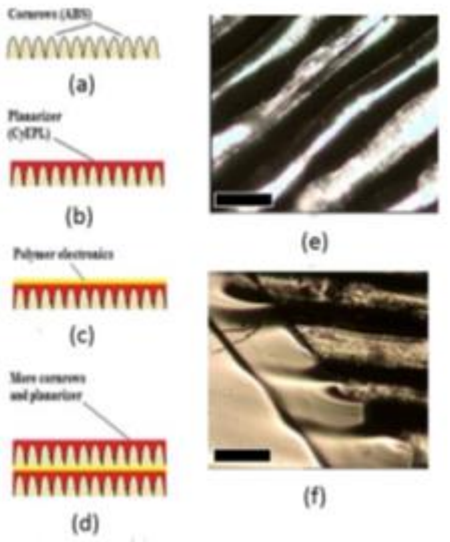


Figure 3: (a-d) Planarization process (e-f) Surface characteristics [21]

Line Smoothing

As mentioned above, inkjet printing is not capable of producing the highest quality thin films. We have chosen a different and more generic approach that is derived directly from a process common in polymer electronics: blade coating. In our process, we locally blade coated the viscous layers into a uniform thin film by physically smoothing with a rigid blade at the local level. As an example, we smoothed the corn rows that result from liquid extrusion of polymer semiconductors, as shown in Fig. 3(b). Fig. 3(c) demonstrates the ability of local blade coating to maintain precise, localized films using an Ultimus V precision dispenser and Nordson robotic stage. The dispenser laid five adjacent rows of PMMA and then we used our prototype microactive doctor blade to smooth the corn rows of a 3 μm film. The resulting profilometer plot is revealing a surface roughness of 100 nm.

Transistor Performance

We have previously fabricated a prototype of low voltage, p-type double-gate organic field effect transistors (OFET) using DNTT through a conventional lithographic process [20]. The device structure can be seen in Fig. 4(a). This transistor is also used for amplification [Fig. 4(b)]. The fabrication process included thermal evaporation of golden electrodes, as well as the organic semiconductor. CVD-deposited biocompatible Parylene served as the dielectric, as well as top and bottom encapsulation and substrate layers. The channel length of width of the p-type devices were 5 μm and 10 μm, respectively.

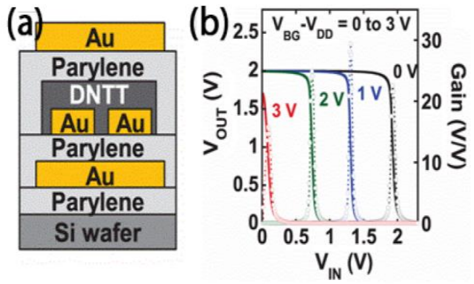


Figure 4: (a) Transistor Structure (b) Amplification characteristics [21]

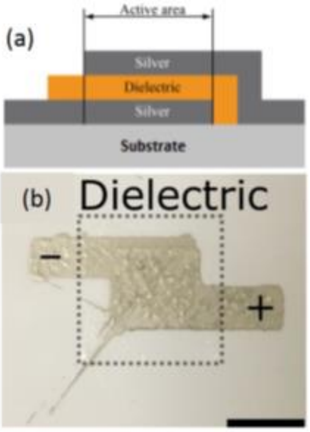


Figure 3: (a) Capacitor layout (b) Printed [21]

Printed Capacitors

A capacitor consists of two plates (electrodes) enclosing a dielectric. Capacitor layout is shown in Fig. 5(a). Here, the capacitor electrodes are printed using a solid extrusion FDM printer with PE873 Stretchable Silver Conductor

(DuPont, USA) for printed electronics purposes. The dielectric of the capacitors is PE773 Stretchable Encapsulate for Wearables (DuPont, USA) and was printed using the same printer. The capacitors are printed as shown in Fig. 5(b). The capacitance was in the range of 12-58 pF with an active area of 25mm2. Fig. 6 shows a printed low pass filter.

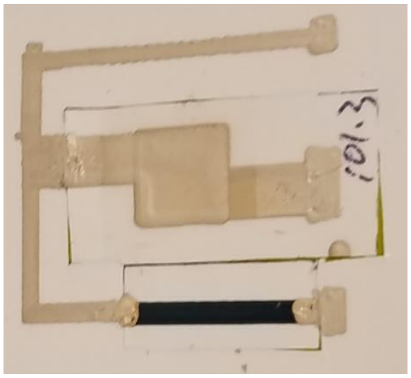


Figure 6: (a) Printed Low Pass Filter.

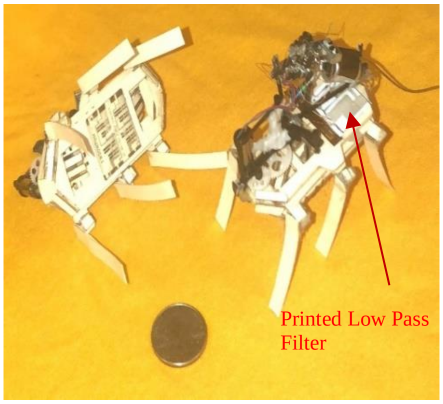


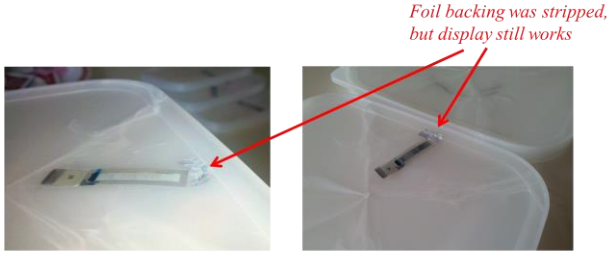
Figure 7: 3-D NUCLEOs Paperbot [21] folded up from *Designer Polymer* 2-D sheet material.

NUCLEOs Laminated Polymer Materials

NUCLEOs (Neuromorphic Computing on Laminated Electronic Organic substrate) is a six-legged walking robot built out of sheets of laminated, single-layer robotic materials that are folded into shape and driven by an attached motor [Fig. 7]. As a proof-of-concept, we built a NUCLEOs circuit out of the lithography-fabricated organic transistor that acts as a phototransistor and connected it to the external motor driver circuit. A circuit built of operational amplifiers to amplify the change in the drain currents and convert it to voltage to control the transistor driving the motor. With this circuit, the motor to drive NUCLEOs turns off without illumination (no light falls on the organic transistor) and turns on under illumination, effectively allowing NUCLEOs to chase a light spot [21].

Inset-Molded Polymers

The laminations are similar to insert-molded circuits we have fabricated using conventional polypropylene. As illustrated in Fig. 8, active eInk electronics paper displays were injection molded into conventional Tupperware lid forms and tested for survivability. The active eInk material survived and continued to function after the pressure and temperature of injection insert-molding. The eInk displays were great for low power consumption as they only required a power when updating the displays and maintained at almost a zero-power for the rest of the times. Another aspect of smart Tupperware is achieving picture tessellation and display around the corner that lead to a wrap-around display effect as shown in Fig. 9. An algorithm to tessellate the picture were developed to zoom in one picture and display every part with screen matrix.



Before Display Actuation

After Display Actuation

Figure 4: eInk displays insert-molded into Tupperware lids for survival tests using injection molding.

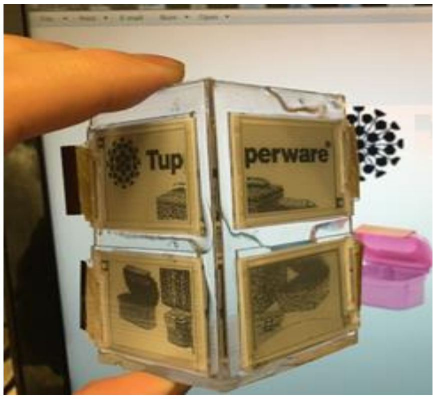


Figure 5: Glass-backed eInk displays molded into low temperature, two-part polymers.

Conclusions

Robotic Materials are materials that combine sensing, computation and actuation, distributed throughout the bulk of the material. This adds entirely new characteristics to the selection of materials for the design of smart products. We demonstrate the successful extrusion printing of capacitors to impedance-match a new, higher-performance organic transistor design that solves the cascading problem of the device previously reported and is more amenable to liquid extrusion printing. Therefore, these printed devices are integrated into a sheet material that is folded into a 3-D, six-legged walking machine with attached electric motor.

In summary, robotic materials will mostly be polymer-based, 3-D printed and will evolve in concert with the artifacts they will enable; a new era in co-design of smart products from designer polymers.

Acknowledgments

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