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NUCLEOS: TOWARD RAPID-PROTOTYPING OF ROBOTIC MATERIALS THAT CAN SENSE, THINK AND ACT

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ABSTRACT

Robotic Materials are materials that have sensing, computation and, possibly actuation, distributed throughout the bulk of the material. In such a material, we envision semi-conducting polymer based sensing, actuation, and information processing for on-board decision making to be designed, in tandem, with the smart product that will be implemented with the smart material. Prior work in printing polymer semiconductors for sensing and cognition have focused on highly energetic inkjet printing. Alternatively, we are developing liquid polymer extrusion processes to work hand-in-hand with existing solid polymer extrusion processes (such as Fused Deposition Manufacturing - FDM) to simultaneously deposit sensing, computation, actuation and structure. We demonstrate the successful extrusion printing of conductors and 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. Consequently, these printed devices are integrated into a sheet material that is folded into a 3-D, six-legged walking machine with attached electric motor.

INTRODUCTION

A common definition of robotics is “systems that combine perception, cognition and actuation”; hence, they can sense, think and act. In general, we design such systems using a lumped model whereby sensors, computers and actuators are components of the system in a design process that is discrete and siloed in nature. In other words, mechanical design, electrical design, software design, and control design, are all considered separately, as in robotic systems described in [1, 2]. The new field of “soft robotics” combines the function of sensors, actuators, and structure into compliant materials that appear “soft” upon interaction with the environment [3], yet, these systems are still designed primarily in the same siloed way.

Robotic Materials are materials that have sensing, computation and, even actuation, distributed throughout the bulk of the material, adding entirely new characteristics to the selection of materials for the design of smart products. The complexity of the resulting design space—we predict—will revolutionize design, demanding an end to siloed design practices. These materials will largely be polymer-based, 3-D printed and will evolve in

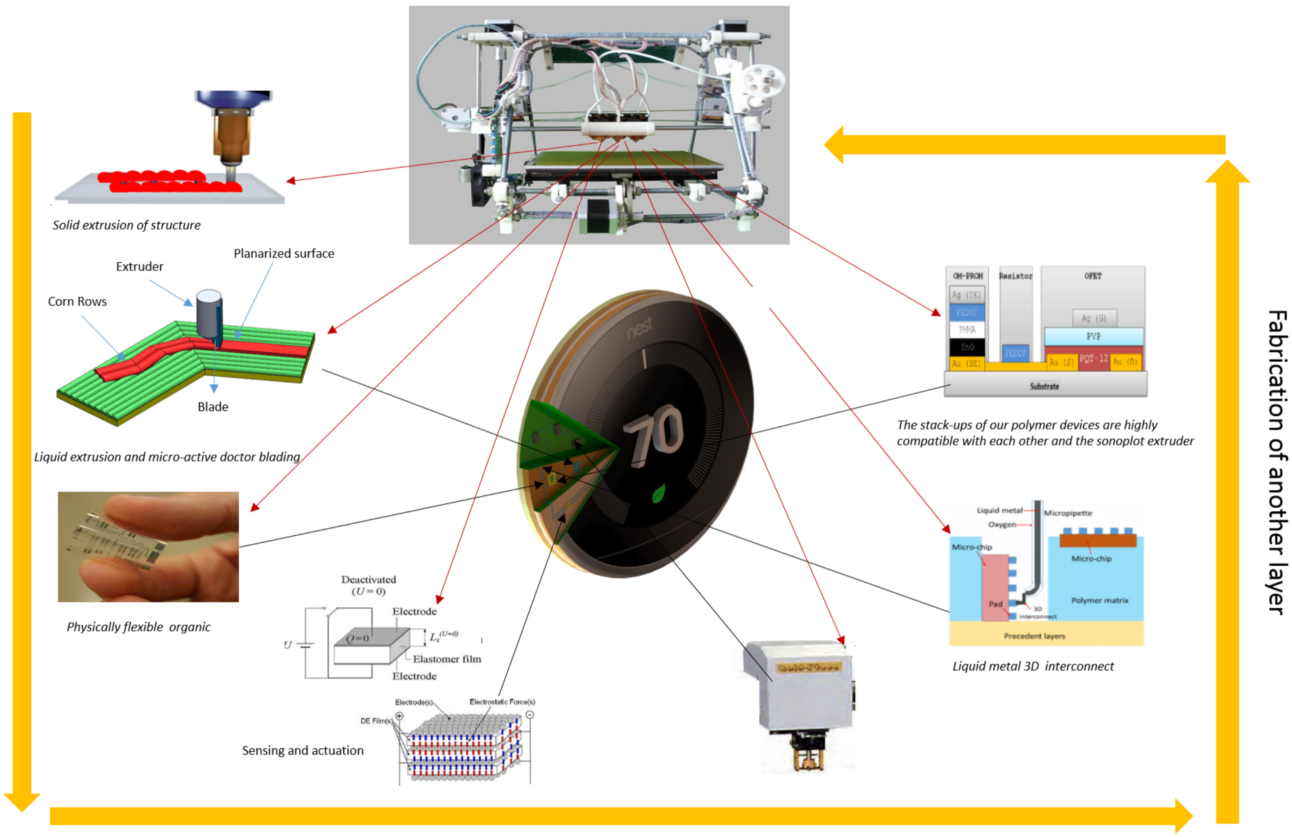

FIGURE 1. CONCEPTUAL VIEW OF THE CRITICAL COMPONENTS OF THE 3-D POLYMER PRINTER FOR SMART PRODUCTS

concert with the artifacts they will enable; ushering in a new era in co-design of smart products from "designer polymers."

The synthesis of polymers around World War II enabled a new era for the types of things designers could design. More recently, the 3-D printing revolution democratized prototyping by removing the knowledge barrier designers needed to produce an instantiation of their design. But neither of these innovations had a direct impact on the design process, itself. The way designers design was not changed. We believe the age of robotic materials will usher in a new golden era of design in which materials and products will be designed holistically with unified design methods that integrate both form and function across the hardware/software interface. This will enable the advancement of co-design to fully embrace the convergence of electrical, mechanical, and software design.

This paper represents an important step in our prior work on lithography-based Structured Computational Polymers [4], an all-polymer form of robotic materials, for the rapid and mass-customizable realm of low-cost 3-D printing of entire smart products. Building on our neuromorphic architecture implemented from polymer electronic materials [5, 6], we have demonstrated the first results of a four-year project to bring fully-integrated robotic materials to life with potentially low-cost additive manufacturing. While we report here only passive devices converted to 3-D printing, the range of devices we have previously demonstrated 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.

Over the years, several researchers have developed active and passive 3-D printed electronic components using inkjet printing technology [7]. While many of these efforts have produced impressive results, we believe the energetics of inkjet printing of polymer semiconducting devices and the coffee ring effect are not good for long-term success with high-performance devices. At the micro-level, inkjet-printed semiconducting devices look like the "craters on the moon" with planarity levels that produce passable but sub-optimal films insufficient for high-performance transistors and other components [8, 9]. Alternatively, we are 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 an extension of the prior work which constructed synthetic neurons with lithography [4] or with discrete components [10] to make robotic materials, or structured computational polymers. We extend this prior work along the lines of [11], which explored the preparation of a printable substrate through planarization and subsequent spraying of conductive materials. Here, we report on early results of a new, highly-integrated project [Fig. 1] to produce a complete 3-D printer that will eventually produce complete smart products containing distributed sensing, neural computation and actuation throughout the bulk of formed material without the use of inkjet printing that produces suboptimal films. We also demonstrate the successful extrusion-printing of capacitors to match the impedance to 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. Finally, the electronics are integrated into a sheet of composite materials, which can be folded into a six-legged walking robot similar to the design of Fearing [12].

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 [13–15]. Also, several groups in the soft robotics space have demonstrated complete robotics systems based on polymers [16, 17]. Others also reported the biomimetic jellyfish robot [18] created with an ionic polymer metal composite and an all-polymer foot [19] capable of climbing walls, mimicking the ability of a gecko or spider foot. However, the proposed designs 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 a number of research groups have demonstrated fabrication of "electronic skin" from polymeric materials [20, 21]. Additionally, they are typically fabricated using lithographic processes.

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

A side-effect of the thermoplastic 3-D printing process are the "corn rows" of adjacent extrusions that occur, as in Fig. 2(a) and (e). The solid extrusion fuses enough in the "four-connected

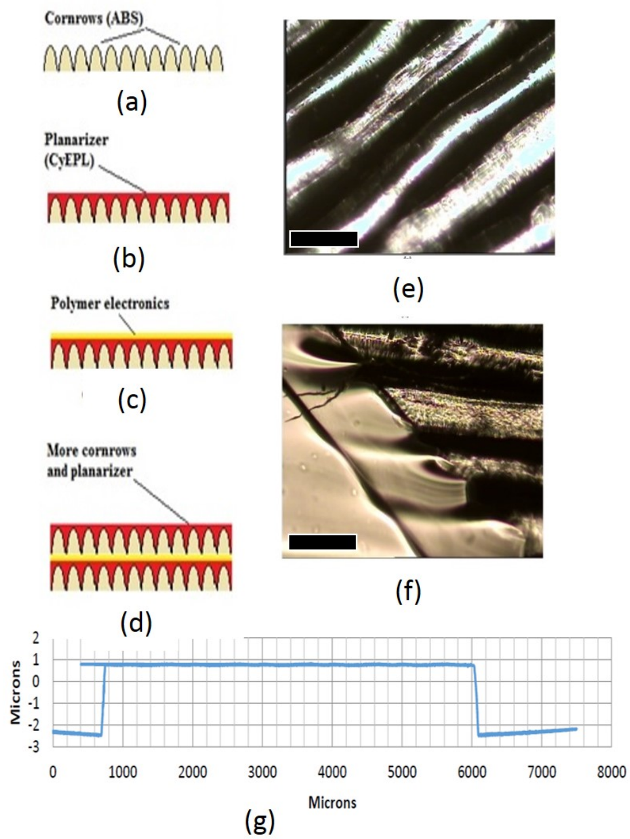

FIGURE 2. (a-d) PLARIZATION PROCESS (a) CORNROWS (b) PLANARIZATION (c) POLYMER ELECTRONICS (d) MULTIPLE PRINTING (e-f) SURFACE CHARACTERISTICS (e) SCANNED SURFACE (f) LEVELED AND UNLEVELED SURFACE SCALE BAR: 1 mm (g) SURFACE FLATNESS:PROFILOMETER PLOT OF LOCALLY DOCTOR-BLADED SET OF FIVE PARALLEL TRACES OF PMMA.

sense" (top, bottom, right, left) 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 [22].

We demonstrated this with a StrataSys Dimension Elite FDM machine by printing a flat substrate, as shown in Fig. 2(b). Multiple layers were deposited to develop a thermally stable substrate. Figure 2(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.

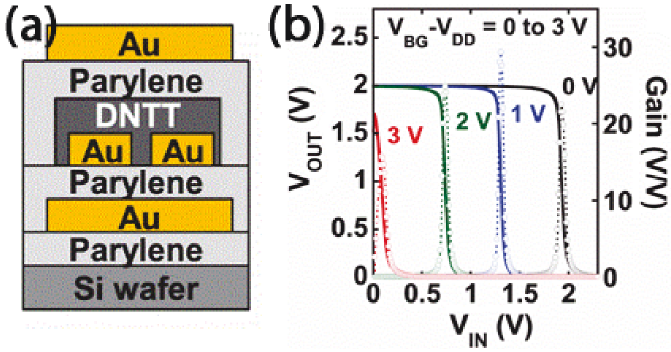

FIGURE 3. (a) TRANSISTOR STRUCTURE (b) AMPLIFICATION CHARACTERISTICS [23]

Finally, the process is repeated with *n* structural layers and *m* intelligence layers. The area of planning for these complex layers and their interaction is both a subject of development for this project and for future research.

Line Smoothing

As mentioned above, inkjet printing is a highly energetic process that we feel 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. 2(b).

Fig. 2(c) and (g) 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 dinaphtho[2,3-b:2',3'-f]thieno[3,2-b]thiophene (DNTT) through a conventional lithographic process [23, 24] The device structure was composed of Parylene 60 nm, Au 30 nm, Parylene 60 nm, DNTT 30 nm, Au 30 nm, Parylene 60 nm, and Au 30 nm [Fig. 3(a)]. This transistor is also used for amplification [Fig. 3(b)]. The fabrication process included thermally evaporated gold source, drain, and gate 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. The transistor is tested with and without light, showing different response to illumination [Fig. 4].

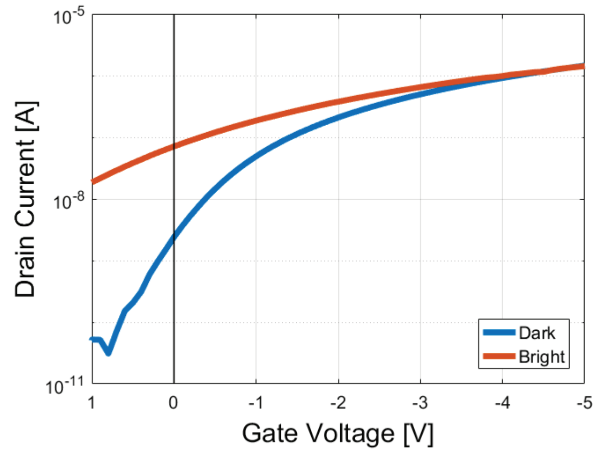

FIGURE 4. THE RESPONSE OF THE TRANSISTOR TO ILLUMINATION: 2.4nA (DARK). 71nA (BRIGHT)

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 the 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 25 mm^2.The capacitance versus frequency plot is shown in Fig. 5(c). The results are limited by our equipment where the used bandwidth was up to few KHz.

NUCLEOs ROBOTIC SMART PRODUCT

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. 6] (2-D printed). 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 [Fig. 7]. As shown in Fig. 4, when the transistor is unbiased ($V_{gs} = 0$), the difference in the drain currents under dark and bright conditions are around 30 times. A transresistance 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

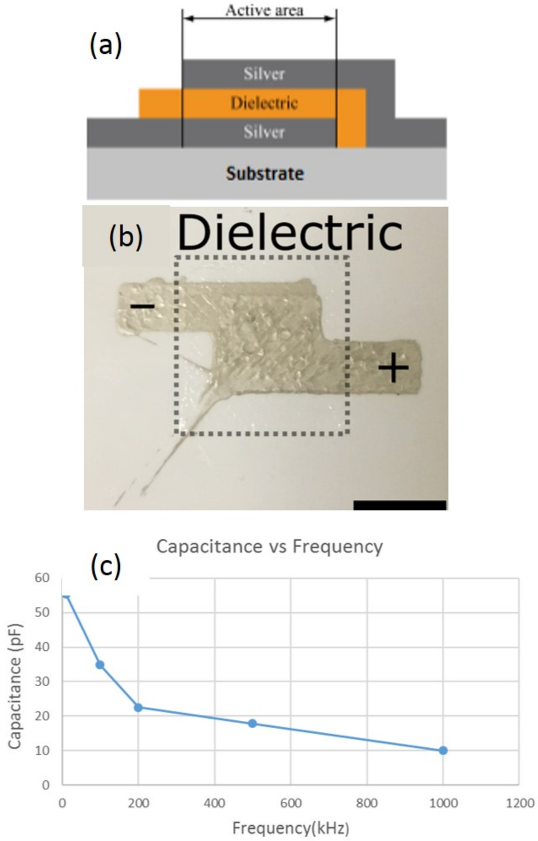

FIGURE 5. (a) ORGANIC CAPACITOR STRUCTURE LAYOUT. (b) A PRINTED CAPACITOR. SCALE BAR: 10 , (c) CAPACITOR FREQUENCY CHARACTERISTIC

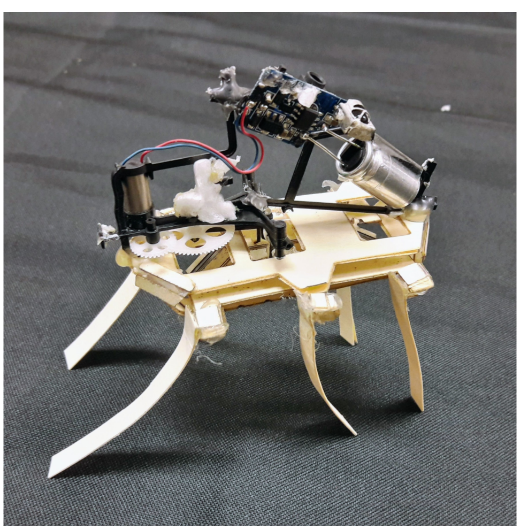

FIGURE 6. NUCLEOs PAPERBOT

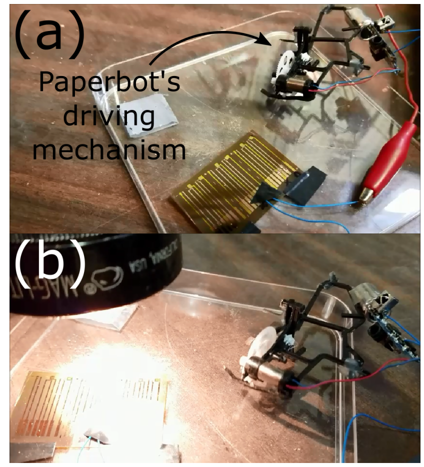

FIGURE 7. PAPERBOT: (a) TURNS OFF WITHOUT ILLUMINATION (b) TURNS ON WITH ILLUMINATION (Motor rotates)

turns off without illumination (no light fall on the organic transistor)and turns on under illumination [Fig. 7], effectively allowing NUCLEOs to chase a light spot.

CONCLUSION

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 summery, 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.

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