ShrinkyCircuits: Sketching, Shrinking, and Formgiving for Electronic Circuits

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ABSTRACT
In this paper we describe the development of ShrinkyCircuits, a novel electronic prototyping technique that captures the flexibility of sketching and leverages properties of a common everyday plastic polymer to enable low-cost, miniature, planar, and curved, multi-layer circuit designs in minutes. ShrinkyCircuits take advantage of inexpensive prestressed polymer film that shrinks to its original size when exposed to heat. This enables improved electrical characteristics though sintering of the conductive electrical layer, partial self-assembly of the circuit and components, and mechanically robust custom shapes - including curves and non-planar form factors. We demonstrate the range and adaptability of ShrinkyCircuits designs from simple hand drawn circuits with through-hole components to complex multilayer, printed circuit boards (PCB), with curved and irregular shaped electronic layouts and surface mount components. Our approach enables users to create extremely customized circuit boards with dense circuit layouts while avoiding messy chemical etching, expensive board milling machines, or time consuming delays in using outside PCB production houses.

Author Keywords
Creativity support tools; DIY; Prototyping; Sketching; Electronics; Fabrication; Sustainability design; Education

ACM Classification Keywords
H.5.m. Information interfaces and presentation (e.g., HCI): Miscellaneous

INTRODUCTION
The ability to envision, prototype, and construct electronic and computational interfaces using low-cost and accessible materials has been transformative to not only professional practitioners within HCI and Design and K-12 students as an educational tool but more recently as a catalyst within the emerging online maker communities. This "maker movement", as it is often called, is radically transformative — affecting a broad range of fundamental and critical cultural themes such as education, manufacturing, healthcare, and the economy, to name just a few [1-6]. One primary new element of this movement has been its ability to empower individuals and communities to imagine, design, collage, make, and share new, often interactive, physical artifacts and objects [7, 8]. It is the promise of this new opportunity for creative innovation that continues to inspire and proliferate this movement. We have already observed the impact of how these sharing resources and tools can inspire learning and empower personal creativity. However, there remains a rich landscape of opportunities to bring the benefits of tangibility and playfulness to elaborate and robust hardware design. In this paper we describe the development of ShrinkyCircuits, a techniuqe that captures the flexibility of sketching and leverages properties of a common everyday plastic polymer to enable prototyping circuits of differing complexity and diverse design (Figure 1).

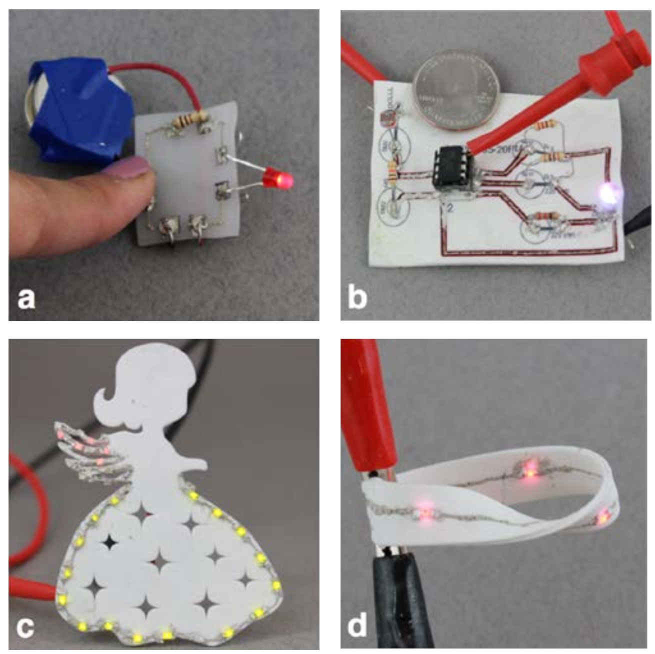

Figure 1. Different types of ShrinkyCircuits. a) A LED circuit with a physical switch and through-hold electronic components. b) An Eagle generated design with a microcontroller and through-hole components. c) A LED circuit board with fine cutout details made with a low-cost vinyl cutter. d) A Möbius strip LED circuit.

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MOTIVATION

Drawing and sketching have played a critical role within the development of user interface design [9, 10]. In particular, we have seen sketching bringing interesting elements to hardware prototyping, sparking creative innovations within the maker community[9, 11-20]. The familiar form factor and the ease of use of the conductive pen have made it the predominant circuit-sketching tool. While the existing conductive pen methods are sufficient for simple designs, their delicate and often unreliable nature severely limit the complexity and application-base procedure [8, 21]. The final designs of such conductive pen and paper-based approaches are far from robust, as the paper folding and creasing often break the electrical connections. Lacking any rigid structure, most sketched paper circuits cannot be used in any real system even as a rough prototype.

Inspired by a rich body of prior work, our goal is to maintain the affordance of sketched circuits while addressing the limitations commonly encountered by circuit design, fabrication, assembly, and deployment. This paper presents a low-cost, flexible approach to physical prototyping that affords a sketch-like rapid iteration method that:

(1) Enables more complex structural designs (i.e. multi-sided and multi-layered circuits)

(2) Manifests a wide range of form factors including non-planar, irregular, and curved

(3) Provides a mechanism for miniaturization,

(4) Improves the electrical conductivity of the overall circuit sketched with a conductive pen

(5) Enables partial self-mounting of circuit components, thus decreasing prototyping time

(6) Creates a robust final product that can be deployed and evaluated in everyday contexts outside of the typical fragile laboratory setting (i.e. allows for testing such systems in situ)

Our solution uses a novel technique where users can draw circuit designs free form with a conductive pen on a large piece of prestressed polymer film. The prestressed polymer film will relax and shrink to its original size when exposed to heat. There are numerous advantages to this approach including achieving the six goals we detailed above and providing additional benefits that we will describe. In this paper, we detail our approach to sketching, designing, making, and deploying a wide variety of working circuits using this technique through a series of examples.

RELATED WORK

Crafting and Sketching Electronics

Injecting craft in electronic making is an important element in DIY practice and hacking. Projects such as Kit-of-No-Parts and Scrapyard Challenge encourages participants to explore circuit making by combing everyday objects in creative ways [19, 22]. Makers of any electronic skill level can learn to build circuits in a tangible and engaging manner using commercially available electronic Tookits such as LittleBits and Snap Circuits. Hudson et al. investigated created physical interfaces from cardboard, thumbtacks, tin foil, and masking tape [23]. Jacoby et al. set up a storytelling platform for children by providing them to paint with conductive ink [8]. Saul et al. designed various functional electronic products by printing electronic connections on paper, folding them into desired shapes, and incorporating electronic component into the products [13]. Commercial products such as the Lilypad Arduino allow users to easily integrate electronics into their craft projects [24]. Inspired by this body of work, our fabrication method maintains the tangible and playful manner of electronic crafting, but also aims to create circuits that are more robust and reliable.

Prototyping Electronics

Prototyping circuits is a major element in electronic prototyping. PCB's are often the preferred electronics platform for integrating into hardware products due to their compact size and robustness. However, prototyping circuit boards is not an easy task, and it is often one of the major bottlenecks in creating the final electronic product[25, 26]. If the user does not have access to expensive PCB printing machines or the time and funds to send the design to a vendor, they commonly resort to a method involving DIY chemical etched PCB. Although this DIY PCB method enables users to have the freedom to customize their PCB's, the process is lengthy and potentially unsafe[27]. Electronic products such as Arduino serve as a platform that allow users to customize a more robust circuit board according to their applications, but the predefined trace lines still take away the creative freedom. To address the difficulties in prototyping electronics, our ShrinkyCircuits utilize an easy, safe, streamlined fabrication method to customize and prototype more reliable circuits that can be easily integrated with larger systems.

Applications of Prestretched Polymers Films

Prestressed polymer films have been used to realize many engineering and scientific applications. In 3M Research, engineers use shrink film polymer substrate to create conductive traces smaller than 50μm [28]. In microfluidics, prestressed polymer enables researchers to create channels that are tens of microns by first etching wider channels into the polymer sheet with inexpensive lithographic equipment, and then shrinking them [29, 30]. Using a similar method, Odom et al created large arrays of 200nm-features by shrinking the master template [31]. These arrays of nanofeatures have huge implications in various areas such as nanophotonic single-particle sensors, long-range optical communications, and high-density solar cells [31]. The malleable and shape shifting nature of polymer also enables makers to create customized products by applying moderate amounts of heat or light [32]. Our ShrinkyCircuits process utilizes the technology enablement and crafting nature of prestreched polymers to provide an innovative way for sketching and prototyping complex circuit designs (i.e. multi-sided and non-planar) with robust electrical and mechanical properties.

SYSTEM DETAILS AND FABRICATION PROCESS

We selected prestressed thermoplastic polymer sheet as our dielectric substrate to take advantage of its interesting mechanical properties. Prestressed thermoplastic polymers, such as polyolefin and polystyrene, will shrink to a predetermined size when they are exposed to heat. In this paper, we chose to demonstrate our novel fabrication process using a commercially available, inexpensive ($0.55-$1.90/sheet), readily available prestressed thermoplastic polymer more commonly known as Shrinky Dinks™. There are three major benefits to using a shrinkable polymer as the dielectric substrate for prototyping electronic circuit boards.

First, circuit boards with small features and footprints can be created while by sketching at the larger scale prior to shrinking. This is due to the fact that all features drawn on the dielectric will shrink to 40% (+/- 2%) of their original size once heated. This is particularly beneficial to applications such as wearable or mobile electronics, where PCB real estate is a precious resource.

Second, the traces are more conductive and reliable via two mechanisms. First, the conductive ink is sintered when the Shrinky Dink is heated and thus forms a solid conductive trace, which is a well-known technique for improving the conductivity of traces created by conductive pens. In addition, the metallic particles in the conductive ink condense as the substrate shrinks to 40% of its original size, thus ensuring a higher metal-to-metal contact ratio within the trace volume. Due to these two factors, traces that are conductive and reliable can be created simply by drawing a line with only a single pass on the substrate.

Finally, the electronic components can be easily and securely loaded on the circuit board to enable partial component assembly. Prior to the shrinking process, holes are cut or punched into the substrate and through-hole components are loaded into the holes. The holes in which the electronic components are inserted then decrease in size during the heating process, and tighten around the leads of the components. Because of the shrinking substrate, the conductive ink surrounding the electronic components forms mounds that envelop the leads. These mounds act as solder on a PCB, and they provide a reliable conductive and mechanical connection.

Mechanical and Electrical Properties

Shrinky Dinks™ are made of thermoplastic polymer sheets of polystyrene that have been preheated and stretched. When they are heated up to their glass transition temperature again (approximately 100°C), they relax and shrink back to their original size. This results in a dramatic in-plane uniform reduction in size, which ranges from 50%-60% depending on the prestressed strength.

For this study, we used Shrinky Dinks™ for Inkjet Printers, and we observe a 60% +/- 2% shrinkage in these particular Shrinky Dinks™ polystyrene sheets. Although there is no observable difference within one sheet of polymer [31], there were minor variations (+/- 2%) between different sheets. The sheet-to-sheet variation did not pose major problems in the circuit fabrication in this study.

The glass transition temperature that is required for shrinkage is easily achieved with a range of household appliances, such as toaster ovens, craft heat guns, incandescent and infrared lights [32]. The relatively safe and easy usage of Shrinky Dinks™ has made it a popular children's toy as well as a novel and reliable tool for scientific discovery[29-31].

We also performed studies on the increase in conductivity by cutting out five long, thin polymer strips (uniform in size, 28cm x 0.5cm) and coating them with one layer of the conductive ink. Prior to heating, the samples have an average resistance of 11.48Ω, which equates to a resistivity of 0.205/square. After heating the five samples at 100°C for five minutes, the strips shrunk to 11cm x 0.2cm and the resistance reduced to an average of 1.4Ω (0.0255/square). The net result is an increased conductivity of 800%. In contrast, a 22-gauge wire of the same length (11cm) has a resistivity of 0.4Ω. This demonstrates that heating the polymer substrate resulted in an 8 times reduction in resistivity, but the traces are not as conductive as a piece of wire (in this example our final trace is 29% conductive as a 22-gauge wire of equal length). If higher conductivity is needed for the circuit, user can deposit more conductive ink on the traces prior to heating. However, a thin line drawn with a conductive pen on the polymer substrate was sufficiently conductive for most DIY electronic applications and provided the necessary mechanical structure to maintain these electrical characteristics. To examine the physical effect of heating have on the silver conductive ink, we took scanning electron micrograph (SEM) pictures of the silver-ink-coated polymer strips before and after heating. Figure 2a shows that the silver ink patches were not well connected prior to heating. Figure 2b shows that the silver ink was well connected after heating, thus forming a better conductive path.

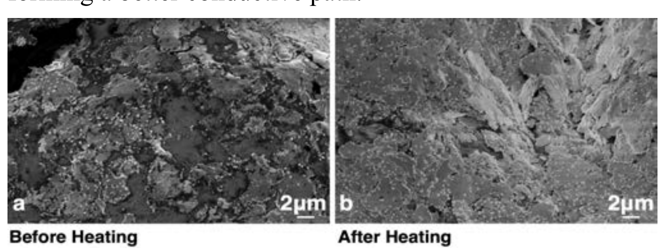

Figure 2: Scanning electron microscopy (SEM) pictures of the conductive silver ink on a polymer substrate. a) Before the silver ink and the substrate are heated. b) After the silver ink and the substrate are heated.

Fabricating with ShrinkyCircuits

The following three basic steps serve as building blocks for many variations of ShrinkyCircuits:

1. **Sketch**: Sketch the desired circuit on a piece of ShrinkyDinks™ polystyrene sheet (Shrinky Dinks for Inkjet Printers, amazon.com) with a regular pen and determine the placement of the electronic components. If through-hole components are used, cut holes on the polymer sheet so that the components can be inserted later.
2. **Trace**: Trace the circuit with a conductive pen (CircuitWriter™ Precision Pen, $21.25). Simply draw a thin line for traces and pads (in any shape) for the electronic components. The lines drawn with conductive pens with only one pass often appear to be too thin or not uniformly filled. With the ShrinkyCircuit fabrication technique, the traces do not need to by refilled the conductive ink will connect in the shrinking process The circuit can be drawn on both front of back of the polymer sheet. The two sides can be connected by drawing a dot on the edge if needed.
3. **Heat**: Heat up the assembly with a toaster oven set to approximately 100°C or with a crafting heat gun (PaperSource Embossing Heat Tool was used in this study, $23.95). Remove the assembly from the heat once the substrate has shrunk (usually after 3-5min).

The resulting ShrinkyCircuit is ~40% of its original footprint and nine times thicker. This increased thickness provides increased structural support making the assembly more durable and easier to handle. The electronic component mounting steps are slightly different for each type of component, and they will be discussed in following sections.

When sketching the circuits in Step 1, the user should calculate the size of the original circuit from the desired size of the end product. Based on our measurements, a user would sketch the circuit 2.5 times the desired final size. We will later show an automated process to achieve the desired size by simply scaling a circuit layout prior to tracing using common image scaling techniques.

DESIGNING WITH SHRINKYCIRCUITS

ShrinkyCircuit is an extremely versatile circuit prototyping method and can be used to create circuits of many difference shapes and form. The aforementioned fabrication procedure can be easily extended to create a plethora of different circuit types. In the following sections we describe six simple variations to the basic fabrication procedure and discuss the benefits and limitations through a series of examples.

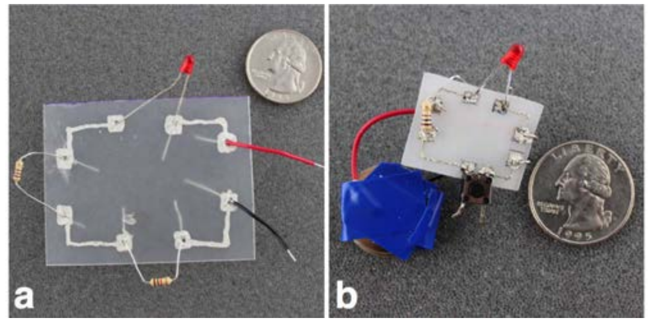

Figure 3: ShrinkyCircuit with through-hole components. a) Components are loosely held in place prior to shrinking. b) Components are "self-soldered" onto circuit board after the substrate shrinks.

Through-hole Components

Clearly, most circuits will require additional through-hole components to be added. This can be done using the same basic fabrication procedure mentioned previously with an added hole-cutting and component mounting step. Before drawing the circuit onto the polymer substrate, cut or drill holes that are slightly bigger then the component leads on where they are to be inserted. After the circuit is drawn on, insert the components leads into the holes (Figure 3a). Subsequent to heating, the through-hole electronic components would all be securely loaded on the board as the conductive ink wraps and the substrate around the leads during the shrinking process - therefore, no additional soldering is necessary (Figure 3b). Please note that components with no flexible leads would not shrink conformably with the circuit and therefore should be inserted after the heating step.

For even a moderately complex circuit (i.e. 4 thorough-hole components), the entire process from sketching, tracing, and loading electronic components, to shrinking the polymer substrate, can be completed in 10 minutes or less. Except for the 5-7 minutes of waiting time during the final heating process, the time required to build a through-hole ShrinkyCircuit is comparable to circuit breadboarding. However, unlike breadboarding, the result of this process is a robust circuit board with "self-soldered" electrical components.

ShrinkyCircuit can also support rapid changes to a circuit design. While rerouting traces with ShrinkyCircuits requires crafting jumpers and breaking traces, ShrinkyCircuits do enable individual components to be easily swapped. Replacing damaged LEDs, changing resistor values, capacitors and similar electronic components can be done by simply pulling the component with a moderate force and inserting a new component back into the holes. This component swapping is possible because the holes created by the conductive ink melt and compress around the original leads, and therefore the holes are of the perfect size for a snug fit around the same component. Throughout our studies with ShrinkyCircuits, we observed consistently snug and secure electrical connections over several component swaps without any physical deformation to the holes. Even after repeated swaps when we encountered loosening in the electrical connection, it was straightforward to simply apply a small amount of additional conductive ink around the connection.

Surface Mount Components

One important feature of PCBs is their compactness, which is often achieved by using small surface mount components. Surface-mount components can be loaded into ShrinkyCircuits by slightly modifying the basic procedure described earlier. When using surface mount components, the circuit is again directly sketched on the polymer substrate, but this time without cutting any holes for through-hole components. To prepare for the loading of surface-mount components, appropriately sized gaps are drawn to accounting for the shrinkage that will occur. After the design is sketched, the polymer substrate is heated and shrunk without the surface mount components loaded. The surface mount components are then simply glued on with conductive epoxy (i.e. MG Chemicals 8331 Two-part Silver Conductive Epoxy, $42.95). This adhesive process is similar to traditional surface-mount component soldering processes and yield remarkable similar results. To swap out components, the old component could be pried out with a razor blade and another component can be reloaded using the conductive paste. Although the number of step of the surface-mount ShrinkyCircuit is same as soldering on a PCB, the ShrinkyCircuit board is quicker to make and significantly safer due to the absence of dangerous chemical handling in the process.

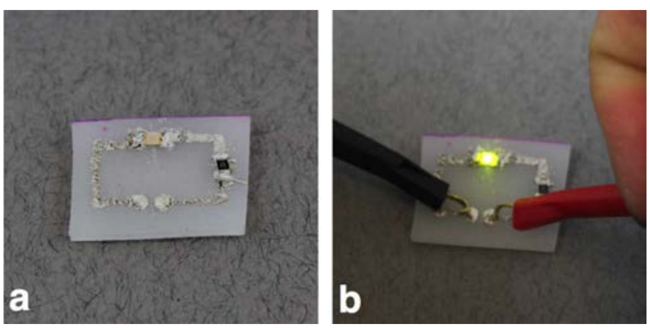

Figure 4: ShrinkyCircuit with surface-mount components. a) Circuit board after the components are loaded with conductive epoxy. b) The ShrinkyCircuit under operation.

Using PCB Layout Software Tools

Sketching ciruits is fast and flexible. However, as circuit designs become more complex, it is often more convenient to use a PCB layout software, such as Eagle as a design tool. Designs in Eagle can be easily and quickly prototyped with ShrinkyCircuits. First, the Eagle layout is printed onto the polystyrene polymer sheet with an inkjet printer (HP PhotoSmart C4780 was used in this study). Next, holes are cut out for inserting any through-hole components. The printed trace markings (red lines in Figure 5) are then traced over with a conductive pen, and the through-hole components with flexible leads are inserted (Figure 5a). After the assembly is heated and shrunk, IC holders can be inserted to house the IC of choice (Figure 5b).

To demonstrate this process, an RGB LED circuit with a photodiode and DIP footprint ATtiny85 Microcontroller was fabricated. For demonstration purposes, this circuit is designed to blink red, blue and green when the photocell detects light (Figure 5c).

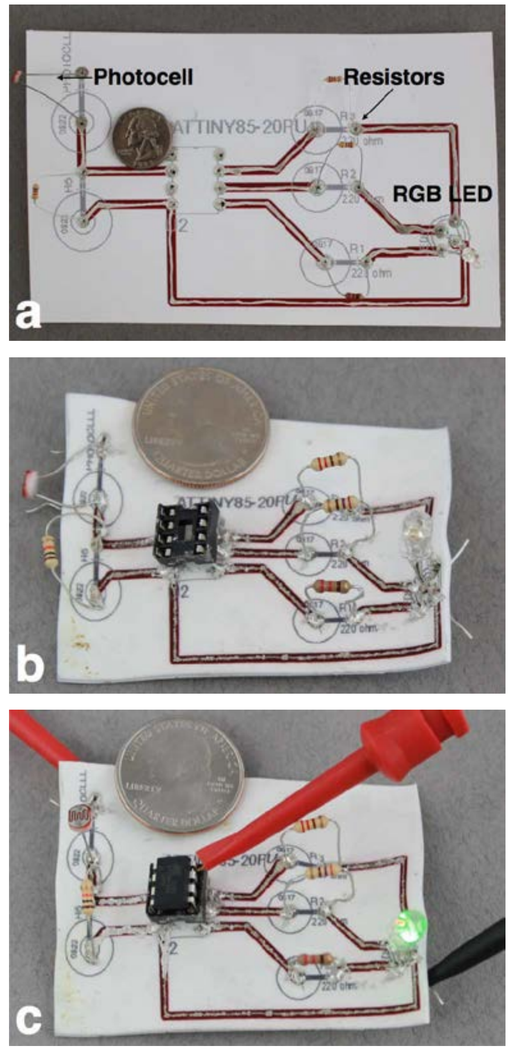

Figure 5: A ShrinkyCircuit designed using Eagle PCB software. a) Electronic components loaded on a circuit printed on polymer sheet with inkjet printer. The electrical connections are traced with a connective pen. c) IC holder is inserted into the shrunk circuit after the polymer substrate is heated. d) The ShrinkyCircuit under operation.

Crafting Uniquely Shaped ShrinkyCircuits

In addition to providing benefits similar to that of a PCB, the cardstock-like nature of the prebaked polymer sheet also brings an element of craft to ShrinkyCircuit. It is often very expensive to purchase PCBs of non-rectangular shapes from vendors and very labor-intensive to mill out special shapes with a 2D CNC mill. This is a problem that cannot be easily solved by making homemade DIY PCBs since most purchasable boards are rectangular. These thick and rigid boards can be cut into different shapes with a saw, but creating fine features is nearly impossible. This poses a problem for designs that often need circuit boards with small and irregular form factors, such as wearable or mobile applications.

ShrinkyCircuit can easily overcome this difficulty since it can be cut into the desired shape easily with a pair of scissors in its preheated state. For small features or complicated shapes, a low-cost craft vinyl cutter (i.e. Silhouette Cameo Electronic Cutting Tool, $259.38) can be used to cut the polymer sheet. In our study, we demonstrate this by cutting out an angel figure with fine features on its wings and skirt (Figure 6a). We then sketched an LED circuit on the cutout, heated up the substrate, and loaded the surface-mount LEDs (Figure 6b). The electrical power pads are drawn on the back of the angel to reduce clutter on the front. The versatility of this fabrication method not only brings a playful quality to advanced circuit making, it also provide makers the freedom of creating any board shapes that fit their products.

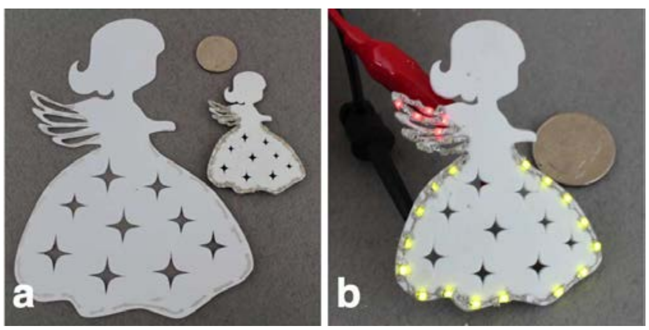

Figure 6: ShrinkyCircuit cut with a low-cost vinyl cutter. a) Polymer substrate prior to shrinking. b) ShrinkyCircuit under operation.

Multi-layer Circuits

Multi-layer circuits are essential in applications where horizontal space is precious. In PCBs, multiple layers of circuit board can be stacked up vertically and connected using vias. Multi-layer ShrinkyCircuits can be made using a similar process. By inserting a conductive material (i.e. wire, resistor leads) into multiple layers of polymer sheets, the layers will be guided to shrink together during the heating process. In this study, a two-layer ShrinkyCircuit was created to demonstrate this concept. Two striped wires were inserted into two polymer sheets with pre-cut holes (Figure 7a). The circuit design was drawn on with a conductive pen, with pads drawn around the wires on s both layers. The whole assembly was then heated up in an oven to shrink the substrates. The two layers were automatically connected electrically in the resulting circuit as both layers connected securely to the wires with conductive ink forming mounds around the wires. The resulting circuit is shown in Figure 7b.

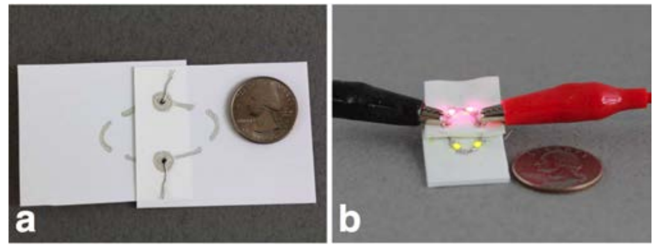

Figure 7: Dual-layer ShrinkyCircuits. a) Two polymer sheets are connected by inserting wires into precut holes. b) The daul-layer circuit can be powered by connecting to the exposed leads.

Non-planar Board Shapes

Perhaps one of the most powerful aspects of ShrinkyCircuits is the ability to easily explore the design space of non-planar, curved, and three-dimensional board shapes. This invites a rich landscape of possible new circuit designs that are better adapted for their final application, can be more densely packed, can be embedded into complex product form factors, or allow for new sensor and actuator placement strategies. The flexibility of the prestressed polymer sheet prior to heating enables the fabrication of non-planar, 3D circuits - something that cannot be accomplished using traditional PCBs. The fabrication process of non-planar circuits is also very craft-like, and affords rapid exploration of many possibilities with even a few simple, creative manipulations. To demonstrate the concept, three methods for making non-planar circuits are shown in this paper.

Angular ShrinkyCiruits

To make structures with angular connections, slots can be cut out from each polymer sheet. Figures 8 a) and b) illustrate this concept by showing two possible circuit configurations. For the structure in Figure 8a, the polymer sheets with the slot cutouts were first assembled, and then flattened temporarily to draw on the circuit. After the circuit was traced onto the sheet, the assembly was put back into its three-dimensional shape and heated up in the oven. The final step employed the standard approach for attaching the surface mount LEDs.

ShrinkyCiruits Frame

For the structure in Figure 8b, the circuit was drawn separately on four polymer strips, with connection pads drawn around the slot cutouts. The strips were then assembled and heated up. Again, the surface-mount LEDs were loaded after the heating process (i.e. when the structures were in their final three-dimensional shapes).

Folded ShrinkyCiruits

Non-planar ShrinkyCircuits can also be made by taking advantage of other conductive materials. Figure 8c shows a bow-shaped ShrinkyCircuit powered by the integrated conductive threads connected to a power supply. This structure was created by first drawing the circuit and cutting holes for inserting the through-hole components. The ends of the strip were then sewn together using conductive threads, thus forming the bow shape. After the electronic components were loaded, the assembly was heated up. The result was a rigid bow-shaped circuit that could be powered by connecting to the conductive threads.

Möbius ShrinkyCiruits

The Möbius strip LED circuit was fabricated by twisting a polymer strip and connecting the end with glue (Gorilla Glue All-Purpose Adhesive was used in this study). After the glue dried, a single line was drawn around the Möbius strip, leaving gaps for loading the LEDs. The Möbius strip was then heated up and the LEDs loaded onto the finished structure (Figure 8d).

Sculptable ShrinkyCircuits

The polystyrene substrate is somewhat malleable before it fully cools down from the baking process. By taking advantage of this property, functional objects with integrated ShrinkyCircuits can be molded. The flower-shaped tealight was made by first coloring a cutout using colored pencils, and then carefully folding up the petals as the shrunk substrate was taken out of the oven (Figure 8e). The nightlight was fabricated by first printing the desired pattern onto the substrate, and then loading the through-hole components into the precut holes. The curved lampshade-shape was created by bending the entire substrate before it fully cooled down (Figure 8f).

There are many different ways that ShrinkyCircuits can be made into interesting non-planar structures, and we only show a few of the possible examples with mechanical structures, conductive threads, and glue, in this paper. We envision a variety of additional ways users can potentially connect the polymer sheets by incorporating more materials and adhesives to create even more complex and novel designs and structures.

LIMITATIONS

Although ShrinkyCircuits provides tremendous new features and benefits to prototyping circuits, there are several limitations. With the self-soldered through-hole component process, heat sensitive components sometimes get damaged when the temperature of the oven gets over the storage temperature of the electronic component. This problem can be remedied by using components with higher temperature tolerance or heating the substrate with a heat gun. When using the heat gun to shrink the substrate, the user can control the amount of time and the direction (i.e. focus the heat onto the substrate but not the component) heat is applied to the heat sensitive components, thus avoiding damage to the components.

Another limitation with the through-hole component process is substrate warping in shrunk circuit boards. In addition to being an aesthetic and mechanical fit problem, the warping also distorts the alignment of the circuit. This is not ideal especially when it comes to loading tight tolerant parts such as DIP and SIP components. We believe that this problem is caused by the protruding leads of the electrical components that prevent the substrate from relaxing and conforming to the oven tray. A specially designed weighted "shrinking guide" may ameliorate this problem and help the substrate flatten evenly when it relaxes.

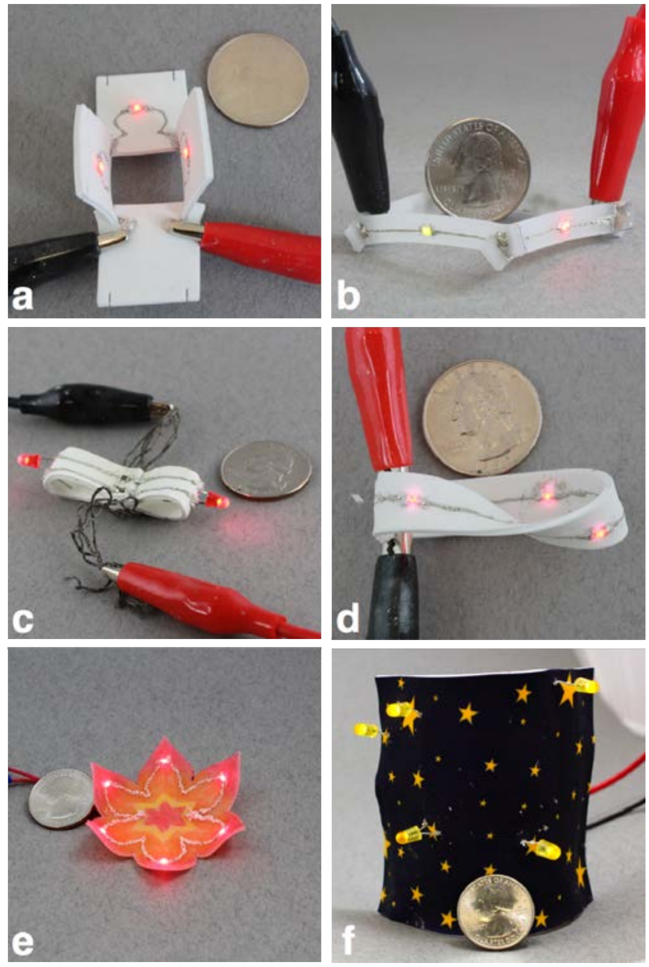

Figure 8: Non-planar ShrinkyCircuits. a) A box-like circuit held together by slot cutouts. b) A square frame held together with slot cutouts. c) A bow-tie circuit connected with conductive threads. d) A Möbius strip LED circuit. e) A flower-shaped tealight decorated with color pencils. f) A night light with patterns printed with an inkjet printer.

DISCUSSION AND FUTURE APPLICATIONS

The development of ShrinkyCircuit has big impact potential in multiple fields, including prototyping, education, scientific research, and electronic crafting. Schoolchilrdren and expert makers alike could utilize this fabrication process to create structurally complex circuits due to it safe (i.e. requires no toxic chemicals) and tangible nature. We would like to continue to investigate ways to improve the process to create more reliable circuits in new forms and at lower cost. Beyond shrinking the whole substrate, we plan to study methods for localized heating of the substrate in order to fold and shrink the circuit in a highly controllable manner. We believe that our technique can contribute to a wide array of engineering fields, including wireless communications with three-dimensional antennas, sensing-circuit-integrated microfluidic platform, and wearable devices. We would also like to explore the usage of ShrinkyCircuits for educational purposes by breaking down common circuits into stampable design elements, which would allow younger children to explore circuit making without drawing fine lines by hand for traces. We envision ShrinkyCircuit to be useful both in introductory science and art classes, where teachers can pique students' interest in circuits by exploring creative ways to incorporate electronics into multidimensional designs. With the exception of the bake step, every step is an opportunity for interactive learning and creativity for students of all ages. While older students could perform all the steps independent of their teacher's input, younger students could be supervised and assisted by their teachers where needed while still learning valuable lessons and skills.

CONCLUSION

In this paper, we have described our work on ShrinkyCircuit, a novel circuit prototyping technique that creates robust and reliable circuits. The ShrinkyCircuit process enables the self-soldering of through-hole component during the heating step, which further speeds up the circuit prototyping process. Moreover, non-planar ShrinkyCircuit can be crafted by mixing various construction methods and conductive mediums. The ShrinkyCircuit enables makes of all levels to freely construct functional, durable, and fully customizable circuits of various shapes, while reaping the benefits of a fun and tangible craft-like fabrication process.

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