Silicone Devices: A Scalable DIY Approach for Fabricating Self-Contained Multi-Layered Soft Circuits using Microfluidics

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ABSTRACT
We present a scalable Do-It-Yourself (DIY) fabrication workflow for prototyping highly stretchable yet robust devices using a CO2 laser cutter, which we call *Silicone Devices*. Silicone Devices are self-contained and thus embed components for input, output, processing, and power. Our approach scales to arbitrary complex devices as it supports techniques to make multi-layered stretchable circuits and buried VIAs. Additionally, high-frequency signals are supported as our circuits consist of liquid metal and are therefore highly conductive and durable. To enable makers and interaction designers to prototype a wide variety of Silicone Devices, we also contribute a stretchable sensor toolkit, consisting of touch, proximity, sliding, pressure, and strain sensors. We demonstrate the versatility and novel opportunities of our technique by prototyping various samples and exploring their use cases. Strain tests report on the reliability of our circuits and preliminary user feedback reports on the user-experience of our workflow by non-engineers.

ACM Classification Keywords
H.5.2. Information Interfaces and Presentation

Author Keywords
Fabrication, Stretchable Circuits, Flexible Circuits, DIY, Ubiquitous Computing, Wearable Computing

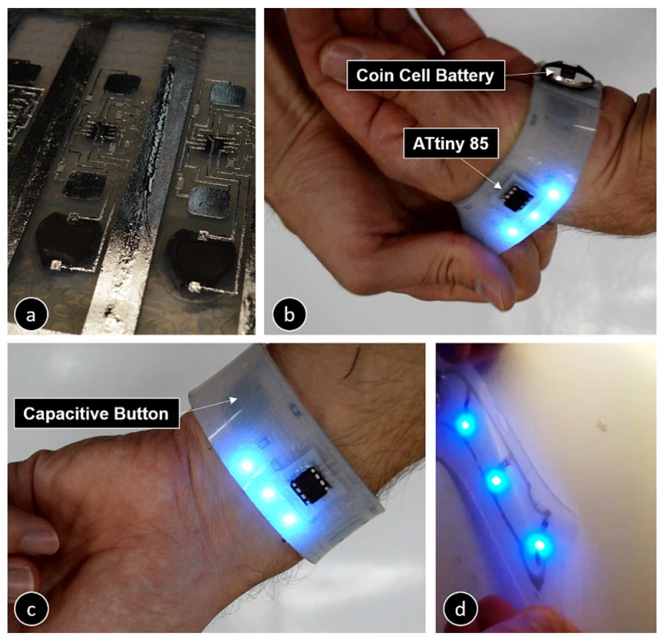

Figure 1. Silicone Devices use highly conductive liquid metal as conductors (a) and embed all components for input, output, processing, and power (b-c). Silicone Devices maintain their conductive performance while stretching (d).

INTRODUCTION
Inspired by work in material science, researchers explored DIY fabrication techniques, such as silkscreen [7] or inkjet printing [10] to enable non-experts to prototype flexible electronic circuits in lab settings. Recently, there is a similar trend for producing stretchable electronic sensors outside clean rooms, which are conform with curved objects [38] and the elasticity of skin [36, 37]. Examples include sensors, such as capacitive buttons, sliders, dials, proximity sensors, and EL-displays printed on Polydimethylsiloxane (PDMS) silicone and coated with poly polystyrene sulfonate (PEDOT:PSS) conductive ink [38] or injected with carbon black particles (cPDMS) [36]. While these individual sensors are stretchable, they are typically connected, using wires or copper tape, to a traditional rigid circuit board that controls, processes, and powers these sensors. Making self-contained devices stretchable is not yet supported by these techniques as they provide no means for integrating various types of ICs and multi-layered circuit designs with VIAs (Vertical Interconnect Access). Furthermore, high-frequency signals are not supported as the conductivity of PEDOT:PSS [38] and cPDMS [36] is suboptimal (respectively $350\,\Omega/\square$ to $500\,\Omega/\square$ and ca.$10\,M\Omega/\square$) and deteriorates further after stretching.

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Several researchers therefore explored DIY techniques for making circuits that embed electronic components directly in a stretchable substrate [18, 8]. These techniques use gallium based liquid metal alloy conductors, such as EGaIn or Galinstan, which have much greater conductive properties (0.01 $\Omega/\square$ to 0.02 $\Omega/\square$) compared to cPMDS or PEDOT:PSS. Lu et al. [18], for example, uses a UV laser cutter to selectively evaporate areas of EGaIn between circuit traces. Scaling this approach to arbitrary complex circuits with multiple layers is hard as it is unclear how to evaporate EGaIn without also cutting into the elastomer and circuit layer below. Jeong et al. [8] explored a more manual approach in which stencils of circuit layers are patterned with a vinyl cutter and aligned and interconnected manually. Although accessible, this technique requires a high level of precision and is therefore error-prone when making advanced self-contained devices.

In this paper, we present a scalable DIY fabrication approach for making robust Silicone Devices, such as the interactive wristband shown in Figure 1b-c. These highly stretchable devices are self-contained and embed input and output sensors, microcontrollers, electronic components, a power source, and conductive traces to interconnect all elements. The approach scales to arbitrary complex devices and circuits as it supports multi-layered circuits, buried VIAs, and integration of various types of electronic components. The presented technique is also accessible as it uses a CO2 laser cutter, readily available for makers, interaction designers, and enthusiasts interested in prototyping sensor-based systems. Silicone Devices use gallium based liquid metal alloys (further referred to as "liquid metal"), such as Galinstan, as a conductor in tiny silicone channels which makes them extremely durable (Figure 1a). Besides its superior conductive properties, liquid metal maintains its fluidic performance within the silicone channels. Stretching therefore does not permanently alter the conductive properties and Silicone Devices only break when liquid metal escapes as a result of extreme forces that tear the silicone.

As Silicone Devices are highly stretchable, reliable, and self-contained (Figure 1d), our approach enables easy prototyping of sensor-based systems that support true integration in fabrics, textiles, and on top of skin. Especially in the HCI community the self-contained nature of Silicone Devices is important as it allows for building interactive prototypes that closely approximate the look-and-feel of the final product. Silicone Devices also bring sensors, such as heart rate or blood pressure sensors in close contact with the skin which makes our approach ideally suited for prototyping health monitoring devices.

The primary contribution of this paper is a scalable DIY fabrication approach for prototyping self-contained stretchable devices that integrate components for I/O, processing, as well as power. Specifically, we contribute:

(1) A DIY workflow to realize arbitrary complex stretchable electronic devices that seamlessly embed components for input and output, processing, and power. Our approach supports building multiple circuit layers interconnected with stretchable buried VIAs. The only machinery that is required, is a CO2 laser cutter which is commonly available nowadays (e.g. in FabLabs and Makerspaces).

(2) A toolkit of basic input sensors, such as touch, pressure, proximity, sliding, and strain sensors that are consistent with our workflow and seamlessly blend in Silicone Devices. Our toolkit shows maker enthusiasts how to embed and combine these sensors when fabricating custom Silicone Devices.

(3) The presentation of a set of sample Silicone Devices, and an exploration of the use cases enabled by our novel fabrication technique.

Our evaluation validates the behavior and reliability of Silicone Devices under variable strain configurations and show that they can be stretched for more than 100% after which the circuit immediately returns to the initial conductive properties upon release. Finally, preliminary user feedback reports on the user-experience of our workflow by non-engineers.

RELATED WORK

This work draws from, and builds upon previous DIY fabrication techniques for making stretchable and flexible sensors and circuits as well as prior work in material science for making high-end stretchable circuits.

DIY Fabrication of Flexible Circuits and Sensors

To make flexible circuits and sensors in DIY lab environments, researchers experimented with copper tape [27], conductive paint [20], and conductive ink[1] to manually add interactivity to thin-film substrates. To speed up this process, conductive traces can be added on substrates using an off-the-shelf inkjet printer filled with silver nanoparticle ink [11], a screen printing hobby kit, or by milling copper traces. To avoid using such specialized equipment, Varun et al. [2] present Printem, a special multi-layered film to produce flexible circuits by printing a circuit mask on top of the film in regular black ink. This mask selectively cures the copper gilding foil below the mask after exposing the film to UV light. As such, only the circuit traces remain attached to the top layer after separating the layers.

These DIY production techniques have been used to produce compatible flexible sensors, such as PyzoFlex [29], a pressure sensitive foil. PyzoFlex consists of piezoelectric material sandwiched between a layer of driving and sensing electrodes. The piezoelectric material develops an electrical charge proportional to the change in mechanical stress. A similar layered construction with a different sensor layout resulted in the FlexSense system [30] which accurately reconstructs the deformation of an A4 sensor surface. The surface integrates 16 piezoelectric sensors of which readings over time are integrated in a machine learning algorithm. As RFID antennas are convenient to print on substrates, the PaperID [15] project investigates using passive RFID tags for recognizing gestures. This was realized by monitoring low-level channel parameters of the RFID communication using machine learning techniques to identify user interactions, such as touch, sliding, turning, swiping, and movements of tags or hands. To enable laypeople to reconfigure touch sensors in different shapes, Olberding et al. [23] positioned electrodes in a star and three shape which makes sensor sheets more tolerant for

[1] https://www.circuitscribe.com

cutting with scissors. Similarly Dementyev et al. [4] present a tape with embedded electronics that can be cut at a certain length to rapid prototype proximity sensing.

Besides input sensors, researchers also explored techniques for making thin-film output sensors. FoldIO [24] supports actuated bending of paper by covering a printed resistor with polyethelyne tape. Perumal and Wigdor [2] as well as Coelho et al. [3] demonstrate how to integrate a speaker in a substrate using a thin-film coil with an electromagnet behind. Alternatively, piezo speakers can be integrated in paper to realize a paper headline [32]. PrintScreen [25] shows how to prototype thin-film EL-displays in a specific shape by printing the conductor below the dielectric using silver ink and the conductor on top in PEDOT:PSS based translucent ink.

To facilitate using these novel technologies by non-engineers, several software design environments have been developed. Midas [31] routes circuit traces between conductive pads. PaperPulse [28] facilitates prototyping self-contained paper devices using an advanced routing algorithm that interconnects components and a processing unit. FoldIO [24] builds on top of these ideas by supporting interactive origami-like 3D folding structures and Lo et al. [17] contribute techniques to route conductors in more aesthetic shapes. Finally, the LightTrace [35] tool contributes an algorithm to evenly light up a large number of LEDs along specific paths.

DIY Fabrication of Stretchable Sensors

Inspired by research in material science as well as DIY techniques for making flexible sensors, several researchers investigated prototyping methods for stretchable sensors. iSkin [36] shows how to prototype silicone touch sensors by laser patterning sheets of PDMS and carbon-filled PDMS (cPDMS). By sandwiching a perforated layer of PDMS in between two pads of cPDMS, iSkin sensors support light and firm touches using respectively capacitive and resistive sensing. Stretchis [38] contributes a DIY technique for making stretchable EL-displays and buttons. A stretchable dielectric is realized by mixing phosphor particles in PDMS. This layer is then sandwiched in between two translucent electrodes which are produced by screen printing translucent PEDOT:PSS ink on PDMS. While the previous two approaches are suitable for prototyping individual sensors, they are still wired to external processing and power units. Silicone Devices, in contrast, are self-contained and seamlessly embed all components for sensing, processing, and powering devices. Furthermore, our technique supports high frequency signals, such as serial communication, PWM, I2C, and audio signals, as liquid metal has a conductive performance between $0.01\,\Omega/\square$ to $0.02\,\Omega/\square$, which is orders of magnitude better compared to PEDOT:PSS and cPDMS, used in earlier approaches [36, 38]. Finally, our liquid conductor significantly better endures strain as circuits always self-heal.

Also related to our work are the recent explorations towards interactive tattoos that have to withstand limited strain of the human skin [16, 37]. These tattoos are first prepared on flexible tattoo paper after which they are transfered to skin using water. Skintillates [16] realizes pushbuttons and strain gauges by screen printing silver ink on tattoo paper. SkinMarks [37] achieves thinner interactive tattoo sensors by screen printing PEDOT:PSS ink.

Conductive thread also provides a means to integrate circuits in stretchable substrates, such as textiles. These kind of threads can be integrated during the weaving process [26] or sewed into the fabric at a later stage [1]. Devendorf et al. [5] show how to make stretchable textile displays by coating conductive threads with thermochromic pigments.

Closest to our work, are a number of projects in the material science community that aim to eliminate customized hardware setups and clean room environments for fabricating soft matter electronics. Lu et al. [18] experimented with laser patterning circuit traces in a film of EGaIn between two layers of PDMS. Although metal alloys cannot be patterned with a CO2 laser cutter, the authors discovered that the liquid metal evaporates when the surrounding vaporized silicone polymer exerts sufficient pressure on the EGaIn. However, this work does not support multi-layered design or integrated components which are essential for fabricating self-contained devices. Later, Lu et al. [19] contributed a technique for prototyping microfluidic stretchable circuits with embedded components by selectively evaporating EGaIn with UV micromachining. This technique, however, requires an expensive UV laser cutter and does not directly support multi-layered circuits as it is unclear how one would selectively evaporate EGaIn without cutting into the thin layer of elastomer that isolates them from circuit traces below. Furthermore, the technique requires uniform dispersion and magnetic alignment of z-axis ferromagnetic microparticles which is not evident in DIY settings by novices.

Engineering Stretchable Circuits

Finally, there is a large corpus of related work presenting techniques for producing stretchable circuits in cleanroom environments that did not yet transfer to the HCI/maker community. Here, we discuss the most relevant articles that inspired this work.

Microfluidic circuits have been engineered by patterning silicone channels directly and filling them afterwards with liquid metal. Such channels are often patterned using direct-write laser machinery [13] or photo lithography [12, 33]. Filling channels afterwards with a pressure pump and syringe, however, is a tedious and error-prone process. Therefore, researchers explored optimizing the geometry of the cavities for liquid injection [33] and by depositing metals, such as gold on the inner surface, to facilitate injection [12].

Instead of injecting channels, material scientists also explored encapsulating liquid metals with casting silicones using masks [8, 9, 14]. Jeong et al. [8] as well as Kramer [14] created a mask out of coper foil by means of chemical etching. Later Jeong et al. [9] presented a more accessible technique that used a plotter to cut vinyl masks. However, manual alignment of multi-layered designs as well as manual production of VIAs using a knife is required. While Jeong et al. experimented with embedding basic components, such as LEDs, these circuits were only stretched 25%, as there was no technique to prevent components from moving within their compartments and causing short circuits.

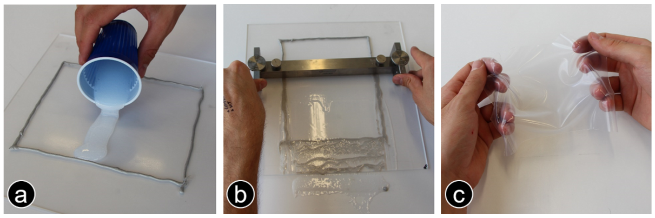

Figure 2. Prototyping a basic uniform thin-film layer of silicone: (a) casting PDMS in a mold prototyped with silicone sealant, (b) blade coating both silicones at the desired thickness, (c) the final uniform thin-film sheet of silicone.

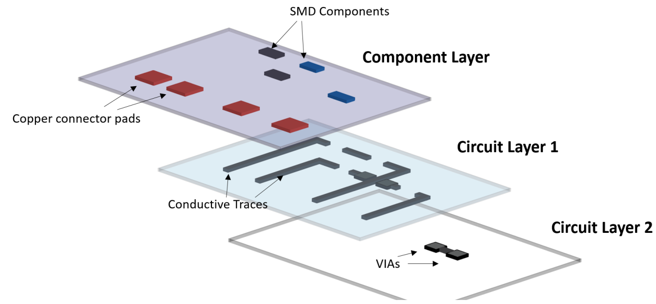

Figure 3. Silicone Devices always consist of at least 2 layers: a component layer and one or multiple circuit layers.

BACKGROUND ON MATERIALS

Silicone Devices are made of flexible and stretchable casting silicone, often referred to as Polydimethylsiloxane (PDMS). Casting silicone typically consists of two parts, the silicone rubber and a curing agent. When combined, the silicone hardens in the casted shape but remains flexible and stretchable. Many types of PDMS exist with varying characteristics, such as curing time and temperatures, viscosity, and hardness. In this work, we use platinum-based poly-addition casting silicone, which is an easy-to-process polymer that cures at room temperature within 15 minutes, and has a hardness of Shore A 15[2] and a viscosity of 5000mPa.s. Curing at higher temperatures is not feasible as our liquid metal conductors expands at higher temperatures which could introduce gaps in the uncured silicone. Liquid metal as well as silicone can, however, withstand very high temperatures once cured.

Casting silicone to a certain thickness or into a desired shape requires a mold. We prototype molds using silicon sealant as it is versatile and allows for rapid prototyping of custom shapes (Figure 2a). To make a uniform thin-film layer of silicone, PDMS is casted while the mold is still malleable. Both silicones are then blade coated at the desired thickness (Figure 2b). In this step, we use a manual blade coater[3] which is a tool consisting of a blade, of which the height to a flat surface below, can be adjusted precisely. Sliding the blade over a flat surface will scrape away the excess coating, leaving a uniform layer of coating at the desired thickness. After removing the excess silicone sealant and the casting silicone that floats over the mold, the uniform film of casting silicone cures while the silicone sealant acts as a custom mold. One could fabricate a DIY version of a blade coater at predefined heights using a 3D printer or laser cutter.

Our circuits, made of silicone, integrate channels of liquid metal as conductors. Liquid metal, such as EGaIn (eutectic gallium-indium) and Galinstan (gallium-indium-tin) are often used as stretchable electrical wiring in high-end electronic systems [34]. Gallium based liquid metal alloys instantly form a thin surface skin consisting of Ga_2O_3 oxides when exposed to air. In this state, liquid metal acts as an elastic gel-like material. However, when applying a critical surface stress, the surface skin breaks and the liquid metal flows readily [6]. In contrast to cPDMS and PEDOT:PSS conductive ink, for which stretching non-reversibly affects the conductive properties, liquid metal always self-heals. While both EGaIn and Galinstan are compatible with our technique, Galinstan is used in all prototypes presented in this paper.

As shown in Figure 1, IC components are seamlessly embedded in silicone. As silicone does not bind to the packages of these components, ICs could move within their compartments during stretches and liquid metal could work itself along the phalanges of the IC and potentially cause a short circuit. Therefore, we coat the packages of ICs with a silicone primer (BISON Silicone Primer) to ensure the silicone has a strong binding with the IC package which prevents components from moving.

FABRICATION WORKFLOW

Our Silicone Devices consist of multiple layers depending on the complexity of the circuit. When the circuit design is non-planar, additional layers are introduced and interconnected using VIAs. As shown in Figure 3, Silicone Devices always consist of at least two layers: a component layer, which integrates all IC components, and one or more circuit layers, which interconnect the ICs and integrate additional conductive pads to seamlessly embed sensing and interactivity (see Section "Stretchable Sensor Toolkit").

Our fabrication workflow starts with a multi-layered circuit design, created in a standard design tool, such as GradSoft EAGLE, Adobe Illustrator, or Inkscape. In the remaining of this section, we present a streamlined workflow to convert a multi-layered digital circuit design, consisting of IC sensor pads, circuit traces, and VIAs, into a self-contained Silicone Device. We aim to describe the workflow and materials in order to make it reproducible for non-engineers. Key to our workflow is the precise processing of vinyl stencil stickers and silicone with a CO2 laser cutter to precisely buildup layers on top of each other. Precise cutting and alignment of multiple layers is achieved by positioning the workpiece at exactly the same position in the laser cutter. This is simplified by consistently aligning the same straight corner of the workpiece in the top corner of the honeycomb grid.

Our approach requires two identical buildplates which are, on all edges, at least 5 centimeters larger than the outline of the Silicone Device, perfectly flush, rectangular, disposable, and easy to process with a laser cutter. Acrylic sheets with a thickness of 3mm are used as buildplates for the prototypes in

[2]https://www.siliconesandmore.com/en/silicones-addition-transparent-15-fast.html

[3]http://webshop.mtv-messtechnik.de/mtv-universal-film-applicator-Model-UA-3000-220

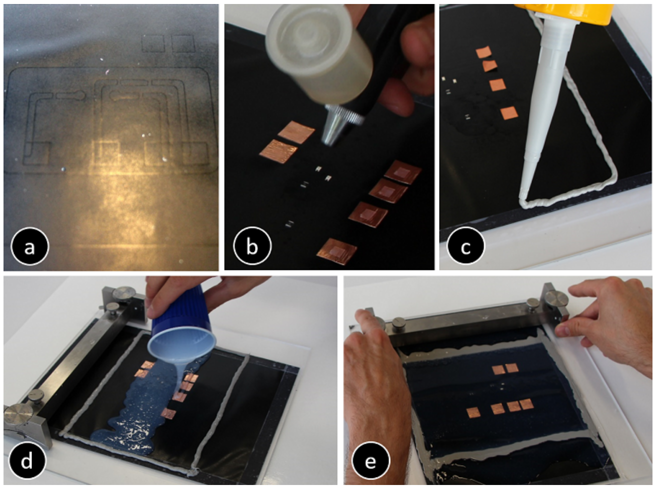

Figure 4. Fabricating the component layer: (a) engraving the positions of components, (b) populating the component layer and spray coating with silicone primer, (c) prototyping a mold with silicone sealant, (d) casting PDMS, (e) blade coating at the desired thickness.

this paper. Our workflow inverts the layup shown in Figure 3, and starts with producing the component layer on the first buildplate. Later, the component layer is transfered upside down on the second buildplate. Finally, the circuit layers are produced on the back of the component layer until we get to the last circuit layer (Figure 3).

Component Layer

Fabricating the component layer (Figure 3) starts with attaching a layer of vinyl upside down at the center of one of the buildplates using scotch tape. A few centimeters on every edge of the buildplate is left exposed and will be used to position the blade coater in the next steps (Figure 4a). The adhesive side of the vinyl is now facing the top and sticks to the IC components and silicone that will be casted on top. The buildplate is positioned in the top corner of a CO2 laser cutter and the traces of the first circuit layer are engraved to visualize the positions of all components (Figure 4a). Cutting through the vinyl is not recommended at this stage as casting silicone could leak through cuts. According to the engraved outlines, all ICs are positioned upright and pressed firmly with their contact pads onto the vinyl sticker (Figure 4b). Copper pads can be integrated in this layer to support external connections. Next, all exposed areas of the ICs are coated with a silicone primer, by means of spray coating. This ensures a strong binding between the IC package and the casting silicone (Figure 4b). Afterwards, we prototype a mold using silicone sealant (Figure 4c) and cast the PDMS (Figure 4d). Notice that only the contact pads of the IC and the bottom region of the package, remain accessible after casting for the circuit layers to build onto. While still malleable, both silicones are blade coated at the height of the thickest IC plus 250μm (Figure 4e). This additional thickness prevents ICs from piercing through the silicone during extreme flexing or stretching. If thinner Silicone Devices, or sockets for removable components are desired, one could cast only a part of the ICs at the expense of precise control of the thickness of the film which blade coating offers. We elaborate on this alternative approach in section “Stretchable Sensor Toolkit”.

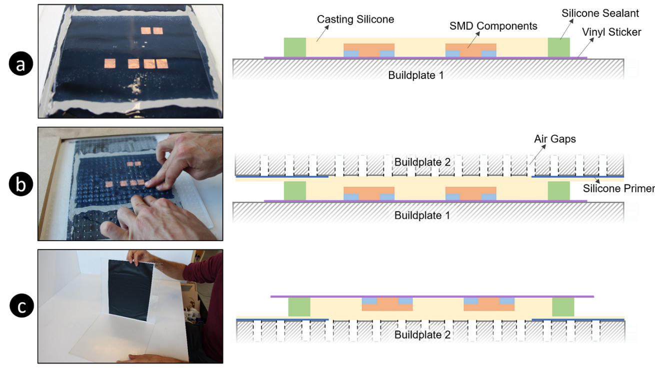

Figure 5. Transferring the component layer to the second buildplate: (a) coating the component layer with an extra film of PDMS, (b) aligning the second buildplate and apply pressure to let all air escape, (c) after curing, release first buildplate.

While the silicones cure for approximately 15 minutes, the second buildplate is prepared to transfer the component layer onto, upside down (Figure 5a-b). This makes the connection pins of the ICs accessible for the circuit layers that will be built on top, after removing the first buildplate (Figure 5c). To ensure that the second buidplate sticks to the component layer during the remaining fabrication steps, all areas of the buidplate, outside the Silicone Device, are coated with silicone primer. This is done precisely by covering the buidplate with a vinyl sticker and removing the excess vinyl after cutting the outline of the Silicone Device with the laser cutter. Using this mask, only regions within the Silicone Device are not coated and will therefore be easy to remove from the buildplate at the end of the workflow. A grid of small holes (1mm) is cut in the second buildplate, at intervals of approximately 1cm, to allow air to escape when pressing the buildplates on top of each other (Figure 5b). Finally, the second buildplate is covered with a thin film of casting silicone, to facilitate binding with the cured component layer. The second buildplate is now positioned precisely on top of the first one and pressure is applied to ensure all air escapes through the holes (Figure 5d). Also excess casting silicone, from the thin binding layer, will escape through the holes and can be removed later. Positioning the buildplates in a straight corner facilitates the precise alignment of the two plates. Within 15 minutes, the second buildplate is cured on the component layer and the first buildplate is released by loosening the scotch tape from the initial vinyl sticker (Figure 5c). This vinyl sticker, however, remains attached to the component layer and will be used for producing the first circuit layer.

Circuit Layers

The production of a new circuit layer starts with covering the previously cured silicone layer with a vinyl sticker. When producing the first circuit layer, the vinyl sticker already attached to the component layer can be reused. The buildplate, containing the previous layers, is precisely positioned in the top corner of the laser cutter to ensure precise alignment. The circuit traces for the corresponding layer are patterned in the vinyl sticker and removed with tweezers (Figure 6b). We recommend all traces to be at least 0.5mm wide. Precisely

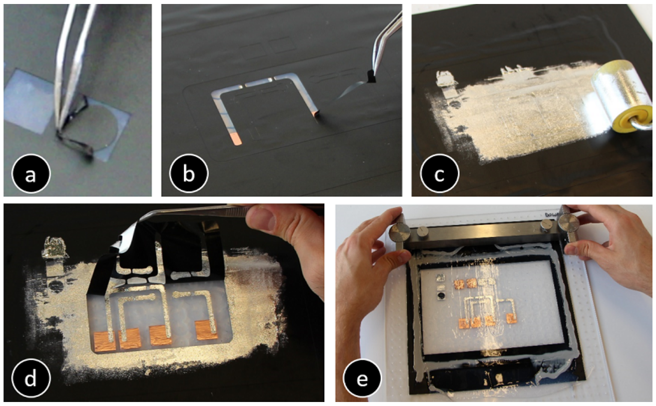

Figure 6. **Producing a circuit layer: (a) calibrating the laser cutter for cutting vinyl mask, (b) engraving and removing all circuit traces, (c) coat mask with Galinstan, (d) remove circuit mask, (e) blade coating of PDMS.**

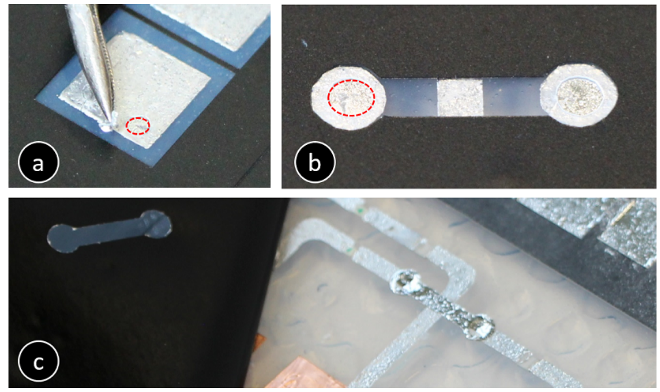

Figure 7. Fabricating two stretchable VIAs: (a) calibrating laser cutter, (b) cutting precisely through one layer of PDMS, (c) filling VIAs with Galinstan.

cutting through the vinyl sticker without damaging the underlying silicone layer requires fine-tuning the power of the CO2 laser cutter. To facilitate this process, a calibration pattern is added on an empty spot in the design. As shown in Figure 6a, this calibration process consists of patterning a circle enclosed in a slightly larger square. The first pattern is cut at a very low power and the power is incrementally increased and tested until the square can be peeled off while the inner circle remains attached. This is the final power setting for cutting precisely through only the layer of vinyl. Once the vinyl circuit mask is ready, it is coated with Galinstan using a paintbrush or paint roller (Figure 6c). Next, the vinyl sticker mask is peeled off, leaving only the Galinstan circuit traces on the previous silicone layer (Figure 6d). The entire layer is spray coated with primer to realize a strong binding with the next silicone layer. This is especially important for the first circuit layer and will ensure a strong binding between the bottom of the ICs and the circuit layer on top.

The Galinstan traces are sealed by covering the circuit with PDMS (Figure 6e). Again, this step starts with prototyping a rough outline of a mold using silicone sealant. While the silicone sealant is still malleable, PDMS is casted and both silicones are blade coated at the thickness of the previous layers plus the new layer. We recommend at least 300μm for circuit layers. Casting silicone will neither mix with nor move Galinstan particles as the forces caused by the floating silicone do not exceed the surface stress to break the oxide skin of Galinstan. After 15 minutes, the silicone is cured and the process is repeated for the next circuit layer. When the last circuit layer is finished, the outline of the Silicone Device is patterned through all layers using a laser cutter. The Silicone Device is now easy to remove from the buildplate as no silicone primer was used in the region below the outline of the Silicone Device (Figure 5b).

Vertical Interconnect Accesses

Compatible with our existing workflow, we devised a technique for realizing stretchable buried VIAs, that interconnect circuit layers and therefore allow for non-planar circuit designs. To make a VIA between two circuit layers, we integrate a circular conductive Galinstan pad of 5mm, at the same location, on both layers. These two connection pads are interconnected by cutting a circular interconnect of 4mm through the silicone that isolates the two layers (Figure 7b). The slightly larger pads maximize the contact region between the two contact pads. When making a VIA between, for example, circuit layer 1 and 2 (Figure 3), the circular interconnect is cut when the vinyl circuit mask of layer 2 is finished. Applying the layer of Galinstan on the circuit mask of layer 2 fills the VIA and interconnects the two layers (Figure 7c).

Similar to fine-tuning the laser cutter for patterning vinyl sheets, precisely cutting through a layer of silicone for realizing the circular interconnect requires fine-tuning. The calibration pattern shown in Figure 7a facilitates this process by adding a series of VIAs at an empty region on the buildplate. The first circular interconnect is cut at a very low power, and the power is incrementally increased until the laser just cuts through the layer of silicone and exposes the Galinstan below. Damaging the silicon layers below is also mitigated as the CO2 laser cutters traditionally do not cut through metal alloys, such as Galinstan.

With our technique, VIAs can interconnect circuit traces between all adjacent layers. This is a unique property, often referred to as buried VIAs, as the VIAs do not necessarily have to pass through all layers. Especially for DIY PCB fabrication techniques, buried VIAs are a very unique property not supported by other techniques, such as photo etching and PCB milling.

SENSOR TOOLKIT

Silicone Devices are self-contained and embed various types of components for input and output, processing, and power. To help makers and interaction designers with fabricating a wide variety of Silicone Devices, this section shows how to fabricate and combine various basic input sensors, such as push, sliding, pressure, proximity, and strain sensors. Additionally, we demonstrate how to seamlessly embed a wide variety of off-the-shelf components to make visually aesthetic Silicone Devices.

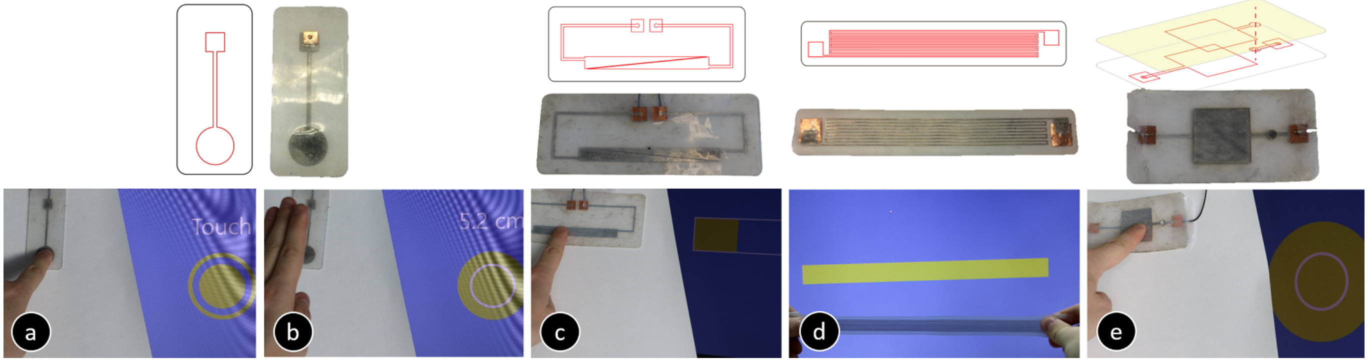

Figure 8. Stretchable input sensors compatible with our workflow: (a) a touch sensor, (b) a proximity sensor, (c) a slider, (d) a strain sensor, (e) a capacitive pressure sensor

Stretchable Input Sensors

Figure 8a shows our five stretchable input sensors. Although these sensors are demonstrated individually, they integrate in any circuit and thus fit in the layup of any Silicone Device. The touch and proximity sensor (a-b) use capacitive sensing and consist of a circuit layer, integrating a conductive pad, and a (empty) component layer which conceals the circuit layer (Figure 3). The proximity sensor differs from a traditional capacitive touch sensor in that it connects to a larger resistor which increases the sensitivity of the pad at the expense of noise. Our implementation has a sensing resolution of 0-7cm from the sensor pad using a resistor of 10 MΩ. The continuous slider (c) has a similar layup but interpolates the position of a touch point using two capacitive electrodes.

In contrast to the previous sensors, the strain sensor (Figure 8d) uses resistive sensing and consists of a meander pattern of traces to increase the length and thus the resolution of the sensor. Stretching the sensor narrows the microfluidic channels and results in a higher resistance. Upon release, the microfluidic channels restore, the Galinstan self-heals, and the resistance returns to the original value. While strain sensors using liquid conductors have been explored [21], previous DIY fabrication techniques for stretchable circuits, such as stretchis [38] and iSkin [36], do not support strain sensors as the resistance of PEDOT:PSS ink or carbon black particles, used in these approaches increases non-reversibly after the first stretch and continues to increase with every stretch. Our strain sensor has 9 interconnected tracks of 14cm each and a sensing resolution between 190 Ω to 650 Ω when stretched 0-150%.

Although the strain sensor could measure pressure, as pressure also narrows the microfluidic channels, we advise using a capacitive sensing technique (Figure 8e). In contrast to the previous sensors, the capacitive pressure sensor consists of two circuit layers with a conductive pad on each layer. When pressure is applied, the silicone between the two conductive pads compresses which increases the capacitance. One can increase the distance between the two pads by thickening the first circuit layer with more silicone in order to increase the resolution of the pressure sensor. The force required to operate the pressure sensor can be controlled by using softer or harder PDMS. Shore A 40 silicone[4], for example, is a harder silicone compared to Shore A 15 silicone used in our prototypes. These fine-tuning strategies make our capacitive pressure sensor more versatile compared to measuring pressure using the strain sensor.

Off-The-Shelf Components

Silicone Devices are self-contained and thus embed components for power, processing, as well as input sensing and output. While the previous section shows that some stretchable input sensors can be produced using only conductive pads and traces, other components, such as batteries, micro-controllers, and LEDs are more complex and require integrating a rigid package. Our fabrication workflow requires using SMD (Surface-mounted Device) packages as connection pins have to be flat to ensure they are not covered with silicone during the production of the component layer (see Section "Fabrication Workflow"). Our workflow supports SSOP (Small Outline Integrated Circuits), QFP (Quad Flat Package), and similar packages with a pin spacing of at least 0.8mm, as our fabrication workflow requires traces to be at least 0.5mm wide. Other types of IC packages, such as through-hole technology, can be integrated using sockets that expose SMD connectors (Figure 9a-b). Sockets are also desired when components have to be replaced often (e.g. batteries) or when the components have to be removed for fine-tuning (e.g. parameters on a microcontroller). We successfully integrated various components, including LEDs, pushbuttons, switches, segment displays, pin headers, coin cell batteries using a holder, and microcontrollers, such as the ATtiny85-20SU, Atmega328-AU and the ATtiny85 and Atmega328P using DIP sockets (Figure 9).

According to our standard fabrication workflow, components are entirely covered in silicone and thinner packages are therefore preferred. However, when integrating thicker or removable components, it is often desired to cast such components only partially in silicone. In this alternative workflow, the component layer cannot be blade coated as components protrude from the surface. Instead the component layer has to be measured after curing to allow for blade coating circuit layers on top at the desired height. Additionally, in order for the second

[4]https://polyestershoppen.nl/siliconenrubber/siliconenrubber-shore-40-426.html

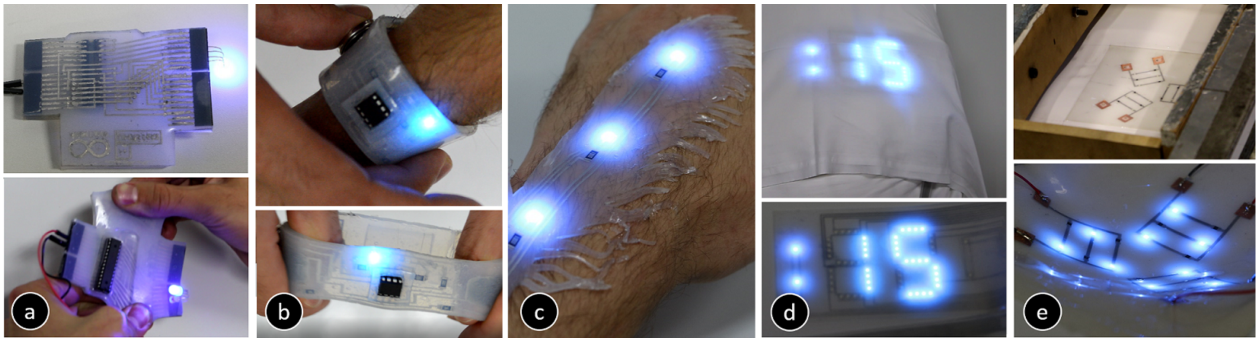

Figure 9. Example Designs and Use Cases: (a) a stretchable Arduino Uno Platform, (b) an interval timer for running, (c) an interactive aesthetic tattoo, (d) a stretchable clock embedded in textile, (e) a thermoformed rigid object with a Silicone Device seamlessly embedded in its surface.

buildplate to attach to the component layer, holes are required in the second buildplate that align with the components that protrude from the component layer. When casting sockets in silicone, it is recommended to leave the through-hole component inserted to prevent silicone from filling the socket.

Although Silicone Devices are self-contained, pads can be integrated to allow external wires to be connected for testing or intercommunication. Directly exposing the ends of microfluidic channels is not feasible as the liquid conductor will leak out. Instead, zero ohm resistors, pin headers, or strips of copper tape can be integrated at the edges of the component layer or one of the circuit layers which can later serve as contact pads for the Silicone Device. One could also integrate a connector at other positions in the component layer or last circuit layer by locally removing the silicone on top of the contact pad after curing.

Aesthetic Appearance

Before removing the Silicone Device from the buildplate, one can precisely pattern all layers with a laser cutter to cut the Silicone Device in the desired shape. The stretchable input sensors shown in Figure 8 also support custom designs. For example, a touch, proximity, or pressure sensor can be designed in the shape of a star or palm tree. Furthermore, circuit traces could be routed to render an aesthetic shape as demonstrated by Lo et al. [17]. One could also add conductive paths, text, or shapes to circuit layers which are not connected to the functional circuit traces which only improve the aesthetic or usability qualities of a Silicone Device (Figure 9). Such aesthetic details are convenient to produce by patterning these details on the vinyl sticker mask using the laser cutter before applying the conductive Galinstan coating.

To improve the aesthetics of a Silicone Device even further, one can also add color pigments to the casting silicone or apply inks locally on the component layer or the last circuit layer. This latter improvement is applied by coating a vinyl mask, patterned with a laser cutter, with ink before before removing all layers from the buildplate to ensure precise alignment.

EXAMPLE SILICONE DEVICES AND USE CASES

Using the workflow presented in this paper, we fabricated five Silicone Devices shown in Figure 9. Below we discuss a number of use cases that these devices illustrate.

Stretchable Circuits

Our workflow enables makers to prototype custom stretchable circuits, such as the Stretchable Arduino Uno development board shown in Figure 9a. This Arduino version embeds the Atmega328 microcontroller using a DIP socket, and consists of 25 VIAs to interconnect 3 circuit layers. Our Stretchable Arduino can be programmed via UART and integrates all programmable GPIO pins of the Arduino Uno.

Besides being stretchable, our workflow is a valuable alternative to existing DIY production techniques for rigid PCB as it allows for producing arbitrarily complex multi-layered circuits within several hours. In contrast, traditional DIY PCB prototyping techniques, such as photo etching or PCB milling, are often limited to 2 circuit layers, and do not support buried VIAs.

Stretchable Wearables

Silicone Devices allow for prototyping systems that have to be self-contained and do not allow for external power or processing, such as wearables. Figure 9b shows a wristband that serves as an interval timer while running. With the capacitive button, one of the three modes is selected: 3min running-1min walking, 5min running-5min walking, and 10min running-5min walking. The current mode is indicated by the 3 LEDs. The capacitive button is pressed for 2 seconds to start/stop the workout. During the workout, the LEDs blink to indicate the user should run. When the LEDs are dimmed, the user is supposed to walk. The wristband is powered by a replaceable coin cell battery and controlled using a ATtiny85-20SU microcontroller.

Silicone Devices are ideally suited for prototyping health monitoring wearables. As bands can be designed to stretch and fit tightly around the ankle, wrist, chest, or head, health sensors, including heart rate or blood pressure sensor are firmly in contact with the skin.

Interactive Tattoos

In addition to the skin sensors demonstrated by Weigel et al. [16, 36, 37], our fabrication technique allows for prototyping skin compatible devices that are self-contained. Instead of wrapping Silicone Devices around the body using stretchable bands, Figure 9c shows a circuit that is cured on the human body and therefore stretches and conforms with the human

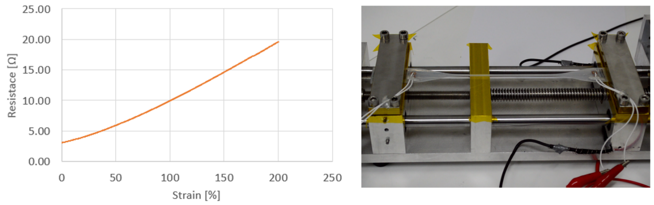

Figure 10. A strain test on an ISO37-2011 1A compatible sample using an extensometer to characterize the resistance during strain.

skin. This aesthetic interactive tattoo embeds our strain sensor to light up specific LEDs when flexing the wrist. The tattoo was first produced on a buildplate according to the workflow in this paper after which it was cured to skin by applying an extra film of skin compatible casting silicone.

Embedding Electronics in Textiles

As Silicone Devices are highly flexible and stretchable, they are compatible with textiles. Figure 9d shows a stretchable clock embedded in a pillow to reveal current hour while preserving its softness and malleability. The hour is displayed for 5 seconds after pulling a strain sensor integrated in the clock. The stretchable clock embeds two large seven-segment displays consisting of 60 LEDs in total, a coin cell battery, and an Atmega328-AU.

Washable Electronics

Silicone Devices entirely concealed in silicone are waterproof and heat-resistant. Both casting silicone and Galinstan withstand high temperatures as demonstrated in the next section. This makes interactive textiles, wearables, and tattoos with embedded electronics convenient to wash and maintain.

Thermoforming Rigid Interactive Objects

Instead of considering strain as a feature of the final circuit, it can also be leveraged in a post-fabrication step to stretch circuits over top of rigid objects by means of thermoforming. Figure 9e shows a thermoformed rigid object with a Silicone Device seamlessly embedded on top of its surface. After fabricating the Silicone Device according to our workflow, the circuit was cured onto a sheet of polypropyleen using an additional film of casting silicone and silicone primer. The sheet, including the Silicone Device, is then heated to a pliable forming temperature of 130°C and vacuum formed using an industrial thermoforming machine.

EVALUATION

Durability of Stretchable Circuit Traces

To evaluate the conductivity and self-healing properties of Silicone Devices, we conducted a stretch test using an extensometer (Figure 10) on a dumb-bell shaped standardized ISO strain sample (ISO37-2011 1A), fabricated using the workflow presented in this paper. The sample includes a single conductive trace with a length of 6cm, a width of 1mm, and contact pads for fine-grained four probe resistance measurement. We observed an initial, 0% strain, resistance of 2.83 Ω. We then applied a strain from 0% to 200% and back to 0%. We repeated this procedure 1000 times.

Figure 10 visualizes the slight increase in resistance during one stretch. During subsequent stretches, the resistance always immediately returned close to its original resistance of 2.83 Ω with an increase of 0.16 Ω (5.7%) after 1000 stretches. After all repetitions, the circuit self-healed further and returned to the exact original resistance within a few minutes. For comparison, Wessely et al. [38] applied 50% strain to their sample of PEDOT:PSS conductive ink and measured a non-reversible increase of 6455.5% after the first 10 stretches and an additional increase in resistance of 1.07% with every stretch for a total extra increase of 1059.3% after the remaining 990 stretches.

After this procedure, we stretched the same sample up to 400% and measured that the circuit still self-healed upon release. At 450% strain the PDMS tore, breaking the Galinstan circuit trace.

Preliminary User Feedback

To understand how our workflow is experienced by non-engineers, we conducted a small workshop with three participants. We recruited two participants (P1, P2) with extensive experience in prototyping rigid PCBs in DIY lab settings to get early insights on how our workflow compares to rigid PCB prototyping techniques. The last participant (P3) had only limited experience with breadboard prototyping using the Arduino platform. While P1 had a background in Media Design, P2 and P3 had backgrounds in Computer Science.

Participants were first introduced to our workflow during a 30 minute presentation which covered and visualized the basic workflow (see Section "Fabrication Workflow"). Then they were shown the prototype in Figure 1d, consisting of two LEDs, two resistors, two VIAs, and four copper contact pads, and were asked to individually prototype this sample. The design files for the laser cutter as well as the slide deck were distributed to all participants and could be accessed at any time during the workshop. All participants worked on their prototype in parallel and were allowed to discuss the steps with each other and ask questions to the authors of this paper. Participants reported on their experience through a questionnaire.

All participants were able to complete their Silicone Device in less than four hours, including a short coffee break. One of the VIAs of P1's prototype failed as there was not enough Galinstan in the VIA while casting silicone over. As some silicone could therefore touch the previous layer of silicone at the location of the VIA, the VIA was completely insulated and Galinstan could not run through. Although, it was the first time we experienced this, P1 was able to patch his prototype by locally removing some silicone, adding some more Galinstan, and casting some silicone over the VIA. Later P1 commented that errors are inherent to all DIY techniques and that fixes to circuits, produced with other DIY techniques, would be more intrusive.

Participants perceive the workflow as enjoyable and were satisfied with the end result. Although participants commented that the process involves some manual work, they understood the rationale behind all steps and noticed that every step is necessary for producing a robust Silicone Device. When asked to compare our technique to other PCB fabrication techniques, P1 and P2 would prefer milling a copper clad laminate for producing simple 2 layered rigid PCBs, as this process is less messy and less lengthy. However, all participants would like to use our technique in the future for producing stretchable circuits. P1 commented that, he as a maker and designer, would especially be interested in using this technique for prototyping self-contained stretchable wearables that conceal all components and are disposed once the battery runs out of power. All participants also noticed they would probably be much faster in producing Silicone Devices when using this process more often.

DISCUSSION AND FUTURE WORK

Silicone Devices support multi-layered circuits and embed all components. As such, they are thicker compared to stretchable prototypes that only integrate conductive pads [38, 36, 37]. The thickness of Silicone Devices could be optimized further by embedding thinner components or by casting components partially in silicone. With a conductivity between $0.01\,\Omega/\square$ to $0.02\,\Omega/\square$, Galinstan supports high frequency signals and is therefore ideally suited as conductor in advanced circuits. In contrast, PEDOT:PSS and carbon particles, used in some earlier approaches [38, 36], have conductive performances that are orders of magnitude lower compared to Galinstan and therefore deteriorate high frequency signals, such as serial communication, I2C, PWM, and audio signals. Given these superior conductive properties, the Galinstan circuit traces could be even smaller than 0.5mm, as recommended in this paper. However, we noticed peeling off the vinyl circuit mask, used in our fabrication technique, occasionally introduces interruptions in thinner circuit traces as the oxide skin of Galinstan binds particles in circuit traces to particles on top of the vinyl mask. Besides, dust particles could easily interrupt thin circuit traces as Silicone Devices are produced outside cleanrooms.

Although our fabrication approach is lengthy and requires a number of manual steps, all participants in our workshop could complete their Silicone Devices within four hours. We expect makers to become more skilled and thus faster when using our technique more often. The authors of this paper, for example, completed a similar Silicone Device within one hour. However, prototyping and populating rigid PCB, using photo etching or PCB milling techniques, is also a tedious and mostly manual process. Unlike these traditional PCB prototyping techniques, our approach also supports stretchable buried VIAs. Even in professional PCB manufacturing processes, buried VIAs come at supreme costs as they require multiple through-hole plating steps.

As confirmed by our participants, the most crucial step in our fabrication approach, requiring the most precision, is transferring the component layer from one buildplate to other. This step is required as our workflow is inverted, starting with the component layer and ending with the bottom circuit layer. Inverting this workflow ensures that all surface areas of off-the-shelf components are easy to spray coat with silicone primer which is essential to avoid components from moving and causing short circuits. We experimented with fabricating Silicone Devices starting with the bottom circuit layer. In this alternative workflow, however, every package has to be manually coated with silicone primer using a thin brush to avoid coating, and thus insulating, connection pads.

While our toolkit consists of five stretchable input sensors, of which the fabrication is compatible with our workflow, more sensors can be added in the future, such as a stretchable coil for realizing an electromagnet that provides tactile feedback or inductive charging. Our strain sensor could be extended with more advanced signal processing for measuring heart rate or blood pressure. As Galinstan does not come in translucent forms, this conductor cannot be used for producing stretchable EL-displays. However, stretchable displays consisting of translucent PEDOT:PSS ink [38] can be integrated in Silicone Devices, similar to off-the-shelf components. As PEDOT:PSS ink tolerates significantly less stretch compared to Galinstan, we recommend casting such EL displays in a harder silicone, to ensure the majority of stretch absorbed by the surrounding softer silicone. In contrast to these stretchable sensors, off-the-shelf components, such as microcontrollers and batteries are traditionally not stretchable. However, material scientists and engineers are already working towards stretchable variants of these components [22].

CONCLUSION

In this paper, we presented a scalable and accessible DIY fabrication approach for making Silicone Devices. These devices are highly stretchable, and seamlessly embed all components for sensing, processing, and powering the circuit. Our DIY approach scales to arbitrarly complex devices as it supports multi-layered circuits which are interconnected using stretchable buried VIAs. Circuit traces use Galinstan as conductors in tiny micro-fluidic channels. Galinstan has superior conductive properties and maintains it conductive performance while stretching. Hence, Silicone Devices always self heal after stretching. To enable makers and interaction designers to prototype a wide variety of Silicone Devices, we also demonstrated how to make basic stretchable input sensors, including a highly reliable strain sensor, using our approach. We demonstrated the versatility and novel opportunities of our technique by prototyping a diverse set of samples and exploring their use cases. Finally, strain tests report on the reliability of our circuits and preliminary user feedback reports on the user-experience of our workflow by non-engineers.

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