A SEWING-ENABLED STITCH-AND-TRANSFER METHOD FOR ROBUST, ULTRA-STRETCHABLE, CONDUCTIVE INTERCONNECTS

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ABSTRACT

Fabricating highly stretchable and robust electrical interconnects at low-cost remains an unmet challenge in stretchable electronics. Previously reported stretchable interconnects require complicated fabrication processes that result in devices with limited stretchability, poor reliability, and large gauge factors. Here, we demonstrate a novel sew-and-transfer method for rapid fabrication of low-cost, highly-stretchable interconnects. A zigzag pattern of thin metal wires is sewn into a polymeric film using a commercial sewing machine and a double-thread stitch, where one of the threads is water-soluble polyvinyl alcohol (PVA). The pattern is subsequently transferred onto a stretchable elastomeric substrate by dissolving the PVA in warm water. The resulting structures exhibit extreme stretchability exceeding 500 % strain for a zigzag angle of 18° . They are also highly robust, capable of withstanding thousands of repeated stretch-and-release cycles (18,000 at 110 % strain, 50,000 at 55 % strain, and $>120,000$ at 30 % strain) without any noticeable change in resistance even at maximum strain levels. Using this technique, we demonstrate a stretchable inductive strain sensor for monitoring balloon expansion in a Foley urinary catheter. The sensor is capable of detecting changes in balloon diameter from 9 mm to 38 mm, with an average sensitivity of 4 nH/mm.

INTRODUCTION

The concept of stretchable electronics has garnered significant interest over the past decade with its promise of providing an adaptable platform for wearable electronics, implantable microsystems, and soft robotics [1–5]. Stretchable interconnects are a key component in such systems, with recent publications reporting various approaches using patterned meander/wavy metallic thin films [6–9] or liquid metal-filled microchannels integrated onto elastomeric substrates [10,11]. Designs such as these offer acceptable operation under limited strain values. Their fabrication, however, requires cleanroom facilities (deposition and lithography) and the resulting interconnects suffer from various functional limitations including structural weakness, limited stretchability, liquid metal leakage, and a large impedance change with applied tensile strain (although of limited value for electrical interconnects, this effect has been used to fabricate strain sensors, [12–15]).

As an alternative to expensive cleanroom fabrication techniques, we present a sewing machine-enabled stitch-and-transfer method for the fabrication of extremely-robust and highly-stretchable electrical interconnects embedded in elastomeric substrates. Sewing machines provide extraordinary and sophisticated capabilities for precise manipulation of threads to form complex patterns on fabric and polymeric substrates. Although they are currently limited to the textile industry, the economical nature of sewing machines may soon place them among a growing toolset of rapid-prototyping technologies that have been featured in recent publications, including cutter plotters, [16] laser engravers, [17,18] inkjet printers, [19,20] and 3D printers [21–25]. Using this technology, we were able to create intricate arrays of metallic wires sewn onto a poly(ethylene terephthalate) (PET) sheet, transfer them to a stretchable substrate

(Ecoflex®), and release them from the PET by dissolving one of the threads in water (due to its stretchability and stickiness, direct sewing onto elastomers is not feasible/practical). By adjusting the tension, geometry, and length of the patterns, a variety of interconnects were fabricated showing stretchabilities of up to 500 %. In addition, since solid wires were used in their construction, the resistance remained constant throughout the strain cycle, an important criterion for proper function of electronic circuits. This technique extends the applicability of sewing machines from commercial textiles to the fabrication of smart electro-opto-fluidic microsystems on stretchable substrates.

Figure 1: (a) A schematic of the primary sewing machine components illustrates the process of creating zigzag wires using a metallic wire and a water-soluble PVA thread. (b) An overview of the stitch-and-transfer process for fabricating stretchable interconnections. (c) A sketch of a sewn zigzag pattern, identifying the design parameters of the pattern (W_0 is the un-stretched width and γ_0 is the pitch angle).

FABRICATION PROCESS

Figure 1a illustrates the main operational components of a sewing machine, comprising a needle threaded with the primary thread, a substrate for processing, and a second thread source (bobbin). During operation, the threaded needle penetrates the substrate, and its thread is interlaced with that of the bobbin to create a secure sewn pattern with a different thread on each side of the substrate. Most modern sewing machines can additionally control the lateral motion of the needle during sewing, allowing for the creation of various sewing patterns (e.g., zigzags). The patterns are selected by the operator by using dedicated knobs or levers on the machine, and they can be fine-tuned by adjusting the tension of the primary thread. This capability of generating various patterns, along with the ability to accommodate two types of threads (e.g., a

dissolvable polymer as the primary thread and a thin wire as the secondary one) are key features for fabricating robust stretchable interconnects.

The complete fabrication process is illustrated in Figure 1b. The zigzag patterns are fabricated using a conventional sewing machine (Singer® 2277 Tradition). First, a dissolvable PVA thread (80 μm -diameter, purchased from Superior Threads) is positioned on the spooling pin, and a thin (90 μm) magnet wire (TEMCo® Industrial Power Supply, Fremont, CA) is loaded into the bobbin of the machine. The PVA is threaded through the needle, and its tension is adjusted such that the conductive wire remains on one side of the substrate throughout the sewing process. Next, an appropriate stitch setting is selected (i.e. zigzag with desired track width and angle). The trace pattern is then transferred onto a 100 μm -thick PET sheet (3M® PP2500) by a standard sewing technique (Figure 1b-i,ii). Subsequently, the wire side of the PET sheet is covered with an elastomer pre-polymer (Ecoflex®, Smooth-on, Inc.); an acrylic frame is used as a spacer to control the thickness of the elastomer. The Ecoflex® is allowed to crosslink at room temperature for 5 hours. This step transfers the sewn metallic pattern onto an elastic substrate. Finally, the stretchable embedded wires in Ecoflex® are released from the PET by soaking the structure in water at 40 °C for 15 min. By submerging the structure in warm water the PVA thread dissolves, allowing the stretchable connections to be easily peeled off the PET sheet, (Figure 1b-iii,iv). Finally, the PET substrate is peeled off releasing the stretchable substrate with the embedded patterned wire (Figure 1b-v,vi).

Figure 2. (a) Photograph of stretchable interconnects with different un-strained pitch angles (γ_0); the right-most pattern features a wire/conductive thread hybrid implementation. (b) Fabricated stretchable interconnect wound around a toothpick. All scale bars: 3 mm.

Figure 1c illustrates a typical pattern. The stitching parameters can be easily adjusted to create various zigzag patterns with controllable un-strained width (W_0) and pitch angle (γ_0). For a zigzag pattern, stretchability is primarily determined by the pitch angle, which is inversely proportional to the maximum elongation of the structure. Theoretically, the angle can be made arbitrarily small; in practice, however, γ_0 has a lower limit, below which the concentrated stress at the sharp concave trace corners results in plastic deformation and eventual failure of the wire. In addition, a very small pitch angle limits the amount of elastomeric material between adjacent legs, resulting in a weaker bond between the wire and the elastomer. To avoid these issues, our devices were fabricated with a minimum un-strained pitch angle of 18°, which was experimentally determined to be the best for the wire diameters. Various zigzag patterns were fabricated using the method just described; Figure 2a shows several implemented patterns embedded in Ecoflex®. Upon qualitative inspection, the structures were found to be highly elastic, soft, and partially

adhesive, all qualities that enable uniform contact between the wires and any adjacent surface even at high curvatures ($> 0.52 \text{ mm}^{-1}$), Figure 2b.

MECHANICAL AND ELECTRICAL CHARACTERIZATIONS

The stretchable interconnects were quantitatively evaluated in terms of their impedance stability in response to strain and their robustness under repeated stretch/release cycles. As mentioned above, stretchable conductive patterns that are fabricated via thin metal layer deposition on elastomeric substrates or rely on liquid-alloy-filled microchannels show a significant increase in their impedance as the structures are subjected to strain. In contrast, our structures use zigzag solid microwires, which exhibit very low impedance change even at strain levels as high as 500 %. The resistance of interconnects with different un-strained pitch angles γ_0 was measured under variable tensile strain. Each interconnect sample was clamped by its two ends and connected to a multimeter to continuously record the resistance change in the tracks. The tensile strain was continuously increased until the wires were completely straightened ($\gamma = 180^\circ$).

Figure 3. (a) Normalized resistance change for stretchable interconnects under various strains for 50°, 31° and 18° un-strained pitch angles. (b) Maximum stretchability of zigzag interconnections as a function of un-strained pitch angle γ_0 .

Figure 3a shows percentage resistance change ($\Delta R/R_0$) vs. strain for patterns with different un-strained pitch angles of 18°, 31°, and 50° (R_0 is the initial resistance, $< 1 \Omega$, and R is the strained resistance). The red X marks show the strain levels at which interconnect fails (open circuit). As can be seen, the impedance values are stable up to the breaking point, with 18° pitch angles being able to withstand 500 % strain. Furthermore, as long as the stretchable interconnects were not subjected to strains beyond elastic limit, no hysteresis was observed. We also investigated the maximum strain for stretchable interconnects having different values of un-strained design parameters (γ_0 and W_0), Figure 3b. As expected, the maximum attainable mechanical tensile strain of various samples shows an inverse relationship with the un-strained pitch angle γ_0 (no dependence with W_0 was observed).

Figure 4a shows the normalized resistance change of different stretchable interconnects with different un-strained pitch angle γ_0 in response to various degrees of bending. In order to evaluate the reliability of interconnects; the patterns were subjected to repeated stretch-and-release cycles at various strain levels (30–110 %). Each test sample was clamped at one end and attached to a magnetically-controlled diaphragm at the other end. The diaphragm displacement stretched the sample at a rate of 60 % per second for 120,000 cycles. The electrical resistance of the sample was measured continuously during the stretching and releasing

cycles. The test was repeated for five samples having different γ_0 values. Figure 4b shows the results in which the samples exhibited no failure or resistance increase for more than 15,000 cycles at both strain levels. For 30 % strain, satisfactory device performance was maintained for more than 120,000 cycles. For larger strains (110 %), however, the devices showed degraded performance and failure at a lower number of cycles. Interconnect failure was primarily due to wire breakage at the corners of the zigzag pattern caused by metal fatigue.

Figure 4. (a) Normalized resistance change for stretchable interconnections under various bending angles for 50°, 31° and 18° un-strained pitch angles γ_0 . (b) Normalized resistance change during 120,000 stretch/release cycles at 30 %, 55 % and 110 % strain levels.

STRETCHABLE INDUCTIVE STRAIN SENSOR

To demonstrate a practical application, we fabricated an inductive strain sensor that was subsequently mounted onto the balloon of Bardex® Foley urinary catheter for monitoring the inflation of the catheter balloon inside bladder. The device consisted of a stretchable single loop coil created on Ecoflex® via the sew-and-transfer method and bonded around the balloon region of a 20F Foley catheter using uncrosslinked Ecoflex®. The coil was made of a single loop of wire (100 μ m thick) patterned into a curved zigzag with 400 μ m spacing between each zigzag. Figure 5a shows a photograph of a Bardex® Foley catheter with the sensor attached. By inflating the balloon, the spacing between the zigzag angle and coil diameter increases significantly, Figure 5b. Since the inductance of a coil is directly proportional to its diameter ($L \sim d$), inflating the balloon leads to an increase in the coil inductance. The inductance was continuously monitored at 200 kHz with an LCR meter (GW Instek LCR-819), Figure 6a.

Figure 5. Stretchable inductive strain sensor attached to the balloon of a Foley urinary catheter (a) before inflating the balloon of the catheter and (b) after inflating it and stretching the coil. All scale bars: 3 mm.

The sensor was tested by gradually inflating the balloon with water and subsequently deflating it. The measured inductance vs. balloon diameter (between 9 mm and 38 mm) is plotted in Figure 6b, showing a positive trend between the inductance and the

diameter with an average sensitivity of 4 nH/mm and very little hysteresis (a maximum of 3.1%).

Figure 6. (a) Schematic of the experimental setup. (b) Sensor inductance change versus diameter of the coil.

CONCLUSIONS

We successfully developed a method of fabricating extremely robust and highly stretchable electrical interconnections via a sew-and-transfer technique. The stretchable pattern is formed using a combination of a water soluble thread and a thin metallic wire sewn onto a polymeric substrate and subsequently transferred to an elastomeric substrate. The structures can stretch up to 500 % without significant loss of conductivity. The devices tolerate repeated stretch-release cycles ($> 120,000$ for 30 % strain, up to 18,000 for 50 % strain) with failure at high strain levels mainly due to the metal fatigue at the sharp concave corners. As a proof of concept, we fabricated a stretchable inductive strain sensor that can be attached to a commercial Foley urinary catheter to measure inflation of the balloon tip in the bladder.

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