Fabrication of stretchable interconnects embedded in Biocompatible Elastomers

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Abstract— **All commercial components of electronic/optoelectronic technologies use rigid substrates. High degree of conformability and fitting on curvilinear surfaces is highly favorable in devices having interaction with human body. The recent advanced of electronics in biomedical applications has led to the emergence of the need for stretchable electronics, which significantly increases the patient's comfort. The emergence of conformable electronic devices creates new opportunities in various fields including the biosensors and point of care testing (POCT) devices. Fabrication of stretchable conducting interconnects is of paramount importance for the feasibility of flexible and stretchable electronics. Metal interconnects embedded in elastomer (e.g., polydimethylsiloxane) is one of the major approaches in the state-of-the-art literature. In this paper, we have developed a relatively simple straightforward process for the fabrication of 250 µm wide stretchable copper tracks. Our fabrication process is based on commercially available double-sided flex (Cu–PI–Cu) substrates. In addition to fabricating reliable stretchable interconnects, this fabrication process provides some level of biocompatibility as well. This is due to the reason that everything is embedded in PDMS polymer for which the biocompatible grades are available.**

Keywords-elastomers; interconnects; flexible electronics; stretchable electronics

I. INTRODUCTION

Stretchable electronic systems need higher mechanical deformability and conformability than their conventional counterparts with solid and even flexible substrates. This field of research has been successfully used in a number of applications including biomedical devices [1], electronic skin [2], electronic textile [3] and even permanently deformable electronics [4]. The progress in this field has been reviewed in recent literature [5-8]. Stretchable electronics can also be considered an extended version of flexible electronics where much higher constrains of strains should be tolerated. Flexible electronics is a technology in which devices can be mechanically deformed and allows the integration of electronic components onto curvilinear surfaces. The compressive and tensile strains experienced in the bending process can lead to various failure mechanisms such as fracturing and buckling. Flexible electronics comes to a limit when conforming on extremely curvilinear or irregular surfaces as typically found in biological applications.

Stretchable electronics field of activity is developed in order to comply with higher degrees of conformability (twisting, stretching and compressing). Favorably the devices should be able to conform without compromising the electrical characteristics, e.g., conductivity. Various kinds of stretching can be considered for example biaxial, uniaxial or radial. Often fatigue tests need to be done in order to assess the performance of the devices under the predetermined test cases [9]. Although for certain applications even one-time deformation is sufficient [4]. Research on mechanically unconventional forms of electronics formally started about 20 years ago, with thin film transistors fabricated on flexible plastic sheets [10]. Advances in printing and related patterning techniques as well as processing on organic semiconductors were a major part of the initial progress in this field.

One of the mostly used materials for stretchable substrates is PDMS. PDMS is an elastomeric and transparent material which can be irreversibly bonded to other biocompatible materials, such as glass, silicon and PDMS itself. Au is the most frequently used material in metal interconnects because of its excellent biocompatibility and high conductivity. Cu is used as the main material for the interconnects in this work given its relatively high conductivity and its lower cost compared to Au. In this work, we have introduced a relatively economical way for the fabrication of reliable stretchable interconnects embedded in biocompatible elastomers. The presented technology in this work can be used in large area applications as well due to the relatively low costs of scaling. The performance of this fabrication method is demonstrated with some basic electrical circuits. We have shown that using this technology stretchable interconnects with relatively very high conductivity can be fabricated.

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II. Design

In stretchable interconnects, a variety of shapes can be designed: triangle, square, or rounded. Each one of them can withstand certain amount of elongations depending on their design. Normally the interconnects need to be supported by a polymeric support in order to increase the fatigue reliability [11]. The stretchable tracks are embedded in an elastomer as well to be confined spatially and fit on the curvilinear surface as much as possible. Normally in stretchable interconnects, the maximum strain occurs at sharp angles. If the edges are rounded, the strain will have a more uniform distribution along the meanders.

In this work, we used a round design for the stretchable interconnects. Fig. 1 shows a camera image of the fabricated stretchable interconnects. Our stretchable interconnects can be designed as single tracks as well as multiple parallel tracks as shown in the figure. In general, the applied strain on the tracks increases by increasing the width (w) of the tracks. The strain decreases by increasing the radius of the bends (r) with respect to width of the tracks (r/w ratio). On the other hand, decreasing w causes lower conductivity. Therefore, there is a tradeoff between the applied strain on the tracks and the conductivity. For this reason, in this work we decided to fabricate narrow parallel multi track meanders to decrease the strain at the same time keeping the conductivity relatively high.

The other important issue in the design of stretchable interconnects is fatigue cycling reliability of the sample in different elongations. For example, in horseshoe design as discussed in [11], more condensed meanders perform better in cycling tests. Using the metal layer as conductive tracks without the presence of the support layer leads to the failure of the meanders in the much lower strains (ε) due to the relatively high stiffness of the metal layer. The polyimide (PI) layer as an intermediate layer, due to its high fatigue resistance, can increase the strength of the meanders. PI has a lower Young modulus (E) of elasticity than Cu while having a much higher modulus than PDMS. As it is only flexible and not stretchable it serves as a good intermediate layer between Cu and PDMS and prevents direct contact between them (E_{PDMS}=1.5 MPa, E_{PI} =5GPa, E_{Cu}= 120 GPa). PI as a flexible material reduces crack propagation in higher elongations as well [11].

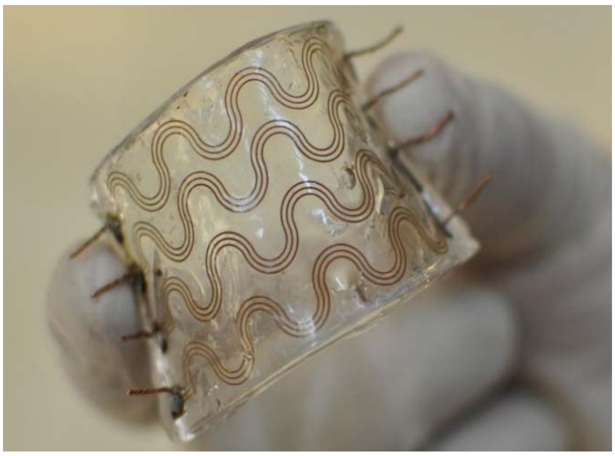


Figure 1. camera image of fabricated stretchable interconnects. 3 parallel tracks are embedded in PDMS.

In this work the PI is patterned with exactly the same width of the metal. The width of the PI layer can be designed more than Cu in order to increase the cycling reliability by introducing an extra mask in the fabrication process. Although it is believed that due to the extremely high stretchability of these tracks it is not generally needed.

III. Fabrication

A schematic diagram of the fabrication process is illustrated in Fig. 2. Fabrication starts on a double-sided flex substrate (Pyralux AP 9111R). It consists of a Cu/PI/Cu, where the thickness of Cu and PI are 35µm and 25µm, respectively (Fig. 2a). The first step of the fabrication is patterning one of the Cu layers to form the meander shape tracks and pads using standard photolithography.

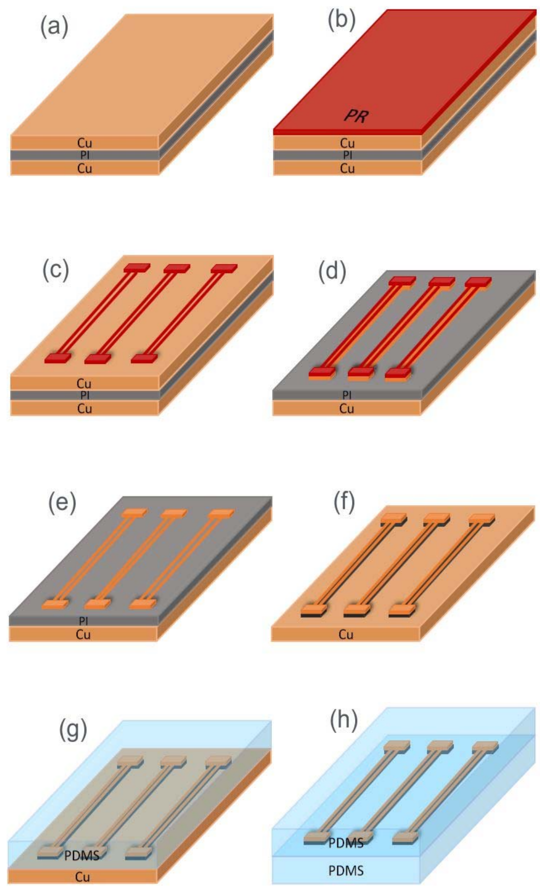
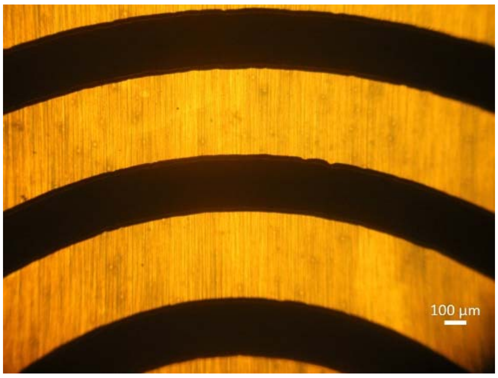


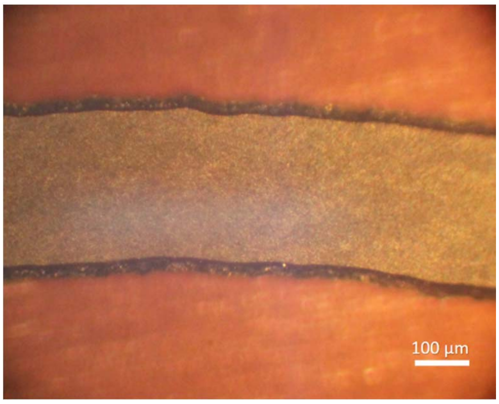
Figure 2. Complete fabrication steps. a) The starting substrate is commercially available double sided flex; 25 µm thick PI sheet sandwiched between 35 µm thick Cu layers (Pyralux AP 9111R). b) Positive photoresist spin coated on top Cu layer. c) photolithography of Cu layer to pattern meander shaped tracks and pads. d) etching Cu layer while photoresist protects the pads and tracks. e) Positive photoresist is stripped away. f) PI is dry etched using patterned Cu as the hard mask. g) After soldering the wires to the pads, top side of the sample was cast in PDMS h) Cu layer from the back side is wet etched and second side of the sample is cast with the same condition.

For this purpose, positive S1813™ photoresist from Microchem® was spin coated on Cu layer and prebaked for 10 minutes at 90^0C (Fig. 2b). After patterning the meanders on photoresist, the sample was developed in KOH. Post-bake was done for 12 minutes at 120^0C. Subsequently, Cu layer was etched in Edinburg etchant using 40% $FeCl_3$ (Fig. 2c). The Cu layer on the back side was protected during the etching process by an adhesive tape (Fig. 2d). Next the photoresist is stripped away in acetone (Fig. 2e). Then, PI layer is dry etched in a reactive ion etching (RIE) system for which Cu serves as the hard mask. The 25 μm thick PI layer was dry etched for about 90 minutes with 100 sccm of O_2 and 90 sccm of SF_6 at 300 W (Fig. 2f). At this stage, the external wires are soldered to the pads. Please note that since the Cu layer from the double-sided flex is thick enough, the wire bonding step can be done using normal soldering. Then the top side of the sample is covered with Sylgard™ 184 PDMS using a spinning step. PDMS was prepared by mixing the precursor with cross linker in a 10:1 weight ratio and was cured in an air convection oven at 80^0C for 2 h (Fig. 2g). Then, the Cu layer from the back side of the sample is etched away. The final step is putting PDMS on the back side of the sample similar to the process done for the top PDMS (Fig. 2h).

Fig. 3 shows the Optical microscope images of fabricated tracks before and after dry etching the PI layer.



(a)



(b)

Figure 3. Optical microscope images of 250 μm wide tracks both before (a) and after (b) the RIE dry etching step.

IV. Results

To see the performance of the presented technology the samples were electrically and mechanically tested. Please note that the resistance of the tracks was less than 1Ω due to the excellent conductivity of Cu. To demonstrate the electrical conductivity of the sample two LEDs were connected to the middle tracks and the sample went under different mechanical conditions including elongation, twisting and bending. Fig. 4 shows the 250 μm wide tracks with a spacing of 300 μm. The initial length of the sample was 6 cm and it is elongated to about 8 cm as clearly visible from the bottom side of the image. Please also note that the bending test illustrated in the same figure shows that the sample can be bent into extremely low radius of curvature.

As illustrated in Fig. 5, the sample can be elongated to more than 30 % at the same time conducting electricity. The LEDs were ON completely during the test and no change in the intensity of light was observed. After 30 % the LEDs were also ON but are placed out of the camera frame.

By increasing the elongation to more than 30 %, the PDMS layer ruptured. It is worth noting that the flexible interconnects came out almost intact from the ruptured PDMS. This experiment shows clearly that this technology can be very promising in relatively high strain applications. We believe that by replacing PDMS with a different grade capable of tolerating more strain or even silicone rubbers the tracks can be elongated to about 100 %. In [11] sputtered Au with much lower conductivity was used as the metal and the PI thickness was 12 μm (about half compared to this work). Therefore, considerably improved results can be anticipated.

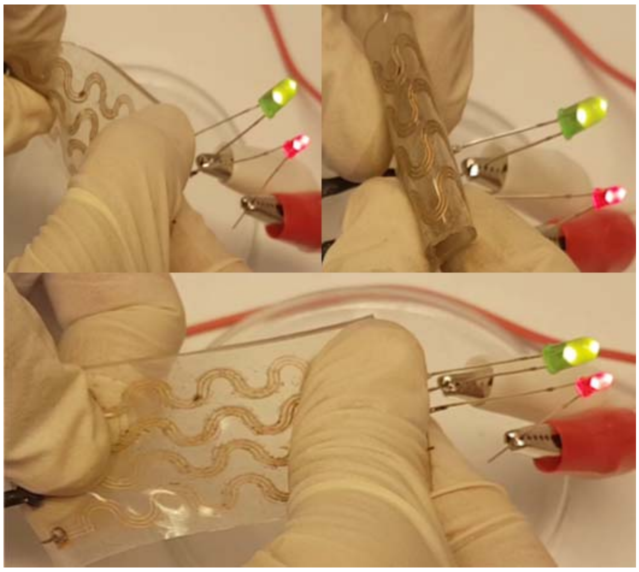


Figure 4. The performance of the fabricated multiple tracks when it is twisted, bent and stretched.

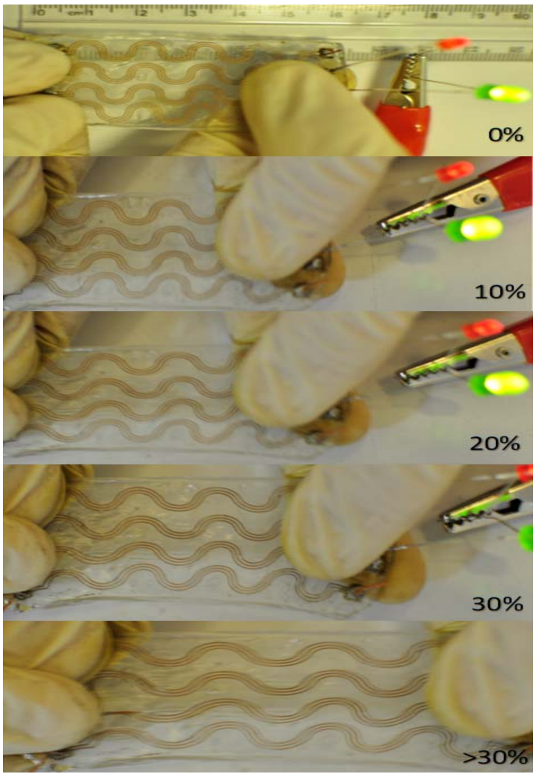


Figure 5. images of LEDs with multiple track interconnects with elongations ranging from zero to more than 30%. The LEDs were ON during the test.

V. CONCLUSION

In this work we have shown a stretchable technology based on the meander formed metal interconnects embedded in PDMS elastomer. This technology provides excellent results mechanically as well as electrically. Since the Cu tracks are supported with flexible PI layer it can undergo various bending, twisting and elongation conditions without compromising its favorable electrical properties. This work and similar technologies try to provide a flexible / stretchable platform for conformability of electronics on curvilinear surfaces such as human body / tissue / organs. Besides human body many objects are interacting with us on a daily basis which have irregular shapes such as automobile parts, tools, clothing, etc. The stretchable technology is an emerging field of research creating vast new opportunities. It also makes the engineers rethink the conventionally rigid shaped electrical boards and devices. In the past decade researchers have used this technology in several applications including sensing and actuation, human machine interface as well as biomedical.

The presented technology in this work fits well with the goals of stretchable electronics. It provides a relatively inexpensive platform for the fabrication of stretchable interconnects with extremely high conductivity, relatively high reliability and biocompatibility.

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