Characterization of Stretchable Interconnects Fabricated Using a Low Cost Metallization Transfer Process onto PDMS

D. Hilbich, a G. Yu, a B. L. Gray, a and L. Shannon b

*Microinstrumentation Laboratory, Engineering Science, Simon Fraser University, Burnaby V5A1S6, Canada
bReconfigurable Computing Laboratory, Engineering Science, Simon Fraser University, Burnaby V5A1S6, Canada

The growing number of applications requiring conformal electronic devices incorporated into unconventional and dynamic surfaces has led to an increase in the development of stretchable electronics. Together with novel materials and fabrication processes, innovative conductive patterns are being developed in order to meet the needs of modern applications. Here, we present the design, fabrication, and characterization of first-order curved Peano structures fabricated using a newly developed thick film copper metallization transfer process onto PDMS. In order to maximize the stretchability of these structures, we present a characterization and analysis of the relationship between relative resistance and tensile strain in fabricated devices while systematically varying the geometric parameters of various curve designs. The response of the structures to cyclic failure and recovery is also characterized. These results demonstrate that the newly developed transfer process can be used to fabricate stretchable Peano curves and provide insight into the geometric optimization of these curves in stretchable electronics applications.

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Stretachable electronics is an emerging technology enabling new devices that cannot be fabricated using traditionally rigid substrates. The particular advantages of stretchable devices over their rigid counterparts are the ability to conform to a curved surface (for example, the human body), the ability to be folded within a constrained volume, and the ability to otherwise be physically flexed or stretched without failing. Existing applications are particularly prevalent in biomedicine and include wearable monitoring devices, implantable neural or muscular stimulators, implantable drug delivery systems, and fluid control systems; flexible sensors and actuators, and flexible integrated circuit technology. In an effort to further the development of these devices, there are two primary areas of improvement; the first area is in fabrication process technologies, and the second is in investigating new geometries that enable more effective stretchable structures.

With respect to fabrication technologies, there are several existing processes suitable for the development of stretchable electronics, including the direct metallization of polymers, nanocomposite polymer (NCP) fabrication, fabrication using conductive polymers, and inkjet printing of conductive inks. While many of these methods can produce impressive flexible features, the conductivity of non-metallic structures is generally poorer than deposited pure metals. Therefore, the metallization of polymers is commonly used due to high electrical performance and relatively low cost. In previous work, we have shown a new process for low-cost, large-scale, thick-film metallization of PDMS; in this work, we demonstrate the application of this process to stretchable electronics.

Using a given process, stretchable metal patterns on polymers can generally be achieved with pre-stressed, thin-film, metal conductors that form stretchable metallic surface waves or in-plane metal conductors that are able to stretch via the bending of curves in a Peano curve having rounded corners in Figure 1b. In an effort to further the development of these devices, we present the design, fabrication, and characterization of first-order curved Peano structures fabricated using a newly developed thick film copper metallization transfer process onto PDMS. In order to maximize the stretchability of these structures, we present a characterization and analysis of the relationship between relative resistance and tensile strain in fabricated devices while systematically varying the geometric parameters of various curve designs. The response of the structures to cyclic failure and recovery is also characterized. These results demonstrate that the newly developed transfer process can be used to fabricate stretchable Peano curves and provide insight into the geometric optimization of these curves in stretchable electronics applications.

The first characterization that we perform with physical models in order to maximize the stretchability of these structures, we present a characterization and analysis of the relationship between relative resistance and tensile strain in fabricated devices while systematically varying the geometric parameters of various curve designs. The response of the structures to cyclic failure and recovery is also characterized. These results demonstrate that the newly developed transfer process can be used to fabricate stretchable Peano curves and provide insight into the geometric optimization of these curves in stretchable electronics applications.

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Using a given process, stretchable metal patterns on polymers can generally be achieved with pre-stressed, thin-film, metal conductors that form stretchable metallic surface waves or in-plane metal conductors that are able to stretch via the bending of curves in a Peano curve having rounded corners in Figure 1b. In the work of Rogers et al., a fractal-inspired space-filling curve, or Peano curve, is investigated in order to support biaxial and radial strains while allowing for a range of conductor topologies that can be tailored to a given application. The traditional unit Peano curve is shown in Figure 1a, along with the modified unit Peano curve having rounded corners in Figure 1b. We expand on the investigation of Peano curves and similar patterns for use in stretchable electronics by fabricating a large set of repeated first-order Peano curve structures and systematically testing the effect of geometric parameter variation on stretchability, which is defined here as the ability to maintain conductivity under an applied strain. Until now, such geometric parameter variation has only been simulated, or physically tested to a lesser extent. In addition, we provide results for the evolving strain measured at conductive failure for these devices under cyclic stretching and relaxation conditions.

**Design and Fabrication**

**Metallization process.**—The devices used in this study are fabricated using a new low-cost, large-scale, transfer process recently developed by our group. Similar to other in-plane metallization methods, the deposition of metal is achieved via electroplating due to its relatively low cost and process complexity. The distinguishing feature of this process is the metal transfer step, which includes a heating method to facilitate the transfer of copper structures embedded into PDMS. This heating method eliminates the need for chemical processing during transfer and enables the direct transfer of metal patterns onto a wide range of substrates, potentially including fabric and human skin.

**Stretchable geometry.**—Serpentine patterns are commonly used when fabricating stretchable structures in planar metallization processes. These structures are formed by periodically repeating a horseshoe pattern defined by the trace width w, arc angle α, and radius r, as shown in Figure 1b. A scale factor equal to r/w is also defined, which is independent of arc angle. This horseshoe pattern is a modified version of the traditional unit Peano curve shown in Figure 1a. In this study, a horseshoe pattern repeated in one direction describes a first-order Peano curve, to which uniaxial strains can be applied while conductivity is maintained (Figure 1c). Higher-order Peano curves can be formed by repeating the unit horseshoe geometry in fractal-based patterns, and can support biaxial and radial strains. Although several groups have simulated and characterized a small set of these first-order curves, the systematic characterization of fabricated curves through parameter variation has not been shown.

The first characterization that we perform with physical models investigates the relationship between the strain measured at conductive failure and the scale factor. One set of simulations using first-order curves has shown that increasing the scale factor leads to a decrease in strain within the conductor during stretching, which can be interpreted as an increase in stretchability. Another set of simulations using
Characterization and Results

Test apparatus.— Samples are tested one at a time with one end fixed in position and the other end connected to a movable load cell (FUTEK LRF400, 5lb). The load cell is positioned with a linear stage (Zaber Technologies T-LS28-SMV). The positioning of the linear stage is controlled with LabVIEW (National Instruments) using a custom script. Tests are performed by commanding the linear stage to move the load cell, which pulls one end of the sample in tension while force and position measurements are recorded by the load cell and linear stage, respectively. Resistances are calculated using voltage measurements recorded during stretching using a 12-bit National Instruments PCI data acquisition card (NI PCI-6071E). Resistance and position values are both sampled at 20Hz, while the stage position is moved at 10 μm/s. To provide electrical connections to the samples, 3 M copper tape is attached to each end; a silver-based ink is added at these sites to ensure stable connectivity to the testing apparatus. Figure 2 shows an individual sample both with magnification (a) and without magnification (b), as well as the testing platform (c).

Uniaxial tension testing until failure.— The first set of experiments measures the relationship between strain and relative resistance as the samples are stretched uniaxially from a resting position to the point of failure using the testing apparatus shown in Figure 2c. Before stretching, initial values of resistance and stage position are recorded. Strain, also known as percent elongation or written \( \Delta l/l \), and relative resistance values are calculated from these measurements. As mentioned, three tests are performed for each of the twelve structures resulting in a total of thirty-six individually tested samples.

First, to determine the effect of arc angle, we compare structures with a constant scale factor while varying the arc angle. Groups of three samples with constant width and radius are tested. Each group have been unable to find results that demonstrate cyclic failure beyond conductive failure and recovery.

The strain measured at the point of conductive failure, defined here as failure, is used to determine the stretchability of a given structure in this study. A comparison of the stretchability between all structures is then used to determine the effects of geometric parameter variation. In the cyclic failure tests, the strain is measured both at the point of failure during stretching and at the point of conductive recovery, defined here as recovery, during relaxation in order to quantify the ability of these structures to recover after iterative failures. Twelve different structures are evaluated with geometric parameters given in Table I. In order to provide statistical support to the results, three samples of each structure are fabricated, resulting in a total of thirty-six individually tested samples.

Characterization and Results

Table I. Geometric parameters for the twelve different structures tested in this study. The dimensionless scale factors (equal to \( r/w \)), \( \alpha \) and \( \beta \), are 4.57 and 8.85, respectively.

| Structure Number | Arc Angle (°) | Copper Width (μm) | Scale Factor |
|------------------|---------------|-------------------|--------------|
| 1                | 180           | 100               | β            |
| 2                | 180           | 200               | β            |
| 3                | 180           | 300               | β            |
| 4                | 270           | 100               | α            |
| 5                | 270           | 100               | α            |
| 6                | 270           | 200               | β            |
| 7                | 270           | 200               | α            |
| 8                | 270           | 300               | β            |
| 9                | 270           | 300               | α            |
| 10               | 285           | 100               | β            |
| 11               | 285           | 200               | β            |
| 12               | 285           | 300               | β            |

Figure 1. (a) Traditional unit Peano curve (b) Modified unit Peano curve, or horseshoe pattern, defined by trace width \( w \), radius \( r \), and arc angle \( \alpha \), (c) First-order Peano curve as a unit horseshoe pattern repeated in one direction.

second-order curves has shown that, at a certain point, increasing the scale factor can decrease the strain measured at the onset of plastic deformation within the conductor, which can be interpreted as a decrease in stretchability [Ref. 16, supplemental]. The scale factor that results in the largest strain before the onset of plastic deformation can be identified as the optimal scale factor. In order to reconcile these results, we test geometries using the optimal scale factor found in simulation, defined here as \( \alpha \) and approximately equal to 4.57, and the beyond-optimal scale factor used in fabrication, defined here as \( \beta \) and approximately equal to 8.85.

The second result that we propose to verify with physical models is that stretchability is proportional to a curve’s arc angle. Previous simulations have shown that the strain measured at the onset of plastic deformation within the conductor increases proportionally to the arc angle, from 180° to 270°. In order to verify these simulations and expand the current understanding beyond the 270° limit, we perform characterization experiments on geometries having 180°, 270°, and 285° arc angles. Arc angles greater than 285° are not tested as the resulting curves exhibit prohibitively small separation distances or overruns between neighboring traces.

Finally, the ability of these structures to recover after being stretched beyond conductive failure and relaxed is also shown. Previous studies have performed cyclic testing of similar structures at relatively lower strains to measure the response to fatigue, but we
The decrease in strain at failure for arc angles of 285° compared to 270° is consistent among the sample groups and is intriguing because it breaks the trend of increasing strain with increasing arc angle. However, we found no studies in literature that confirm the consistency of these results, which warrants further investigation of arc angles beyond 270°. One possible explanation for this behavior is that larger arc angles could result in areas of increased strain within the conductor, particularly where the angle of the conductor path is opposed to the direction of tension.

Next, to determine the effect of the scale factor, we compare structures with a constant arc angle while varying the scale factor. Simulations in Ref. 16 suggest that structures with a beyond-optimal (larger) scale factor will result in a lower value for the strain measured at failure compared to the structures with the simulated optimal scale factor. However, this is contrary to the observations in Ref. 19, which indicate that increasing the scale factor increases the strain measured at failure. For structures having 300 μm and 200 μm trace widths, we observed an increase in the average strain at failure for the optimal scale factor compared to the larger scale factor determined from Ref. 16. However, for structures having 100 μm trace widths, this relationship is reversed. Therefore, a conclusive statement regarding the relationship between scale factor and strain at failure cannot be made for the geometries that were tested. This result provides support for the inconsistency between the two studies that were compared, and could indicate that maximizing the scale factor may yield inconsistent results, and could also be process dependent. Furthermore, a more detailed analysis of the simulations in Ref. 19 shows that while increasing the scale factor consistently improves stretchability according to a predictable relationship, this relationship appears to break down and become less predictable at scale factors lower than approximately 7.5. Therefore, while a scale factor of approximately 4.57 was predicted to be optimal in Ref. 16, this falls in the region of decreased predictability shown in Ref. 19, further justifying the discrepancy between these two studies. This is of particular importance considering that smaller scale factors correspond to more compact designs. That is, for a given trace width, a smaller radius reduces both the footprint and the scale factor. The drive to design for smaller footprints must then be balanced by the observation that miniaturization may have an unpredictable impact on stretchability. Therefore, detailed simulations may be required for new designs in order to achieve the desired balance between decreasing the device footprint and the resulting unpredictability of a decreased scale factor.

Cyclic tension testing.— After collecting strain and relative resistance measurements for all thirty-six samples, a subset was chosen to conduct further cyclic failure experiments. Six Samples, comprising one sample from structures 2, 5, 6, 7, 9, and 12 (see Table I), are chosen for these tests, as these structures represent the population of geometric parameters used in this study. The experiment is performed by once again stretching the sample until failure and recording the strain and relative resistance. Then, the sample is relaxed and the strain and relative resistance are recorded once conductivity is recovered. The cycle of failure and recovery is carried out for ten iterations. Figure 4 shows a single representative sample of the strain measured at the conductivity limit during ten cycles of failure and recovery. Structure number 6 from Table I was used for the test shown in Figure 4. The strain value for the initial failure is constant and is shown for reference against the strain value for failure and recovery in each cycle. It can be seen that the strain at failure and recovery are both relatively stable. Also, the strains at failure and recovery are both lower at each iteration than the strain at the initial failure, which is reasonable since the structure would not initially contain any of the breaks, cracks, or other discontinuities that presumably occur during the first failure. It can also be seen that the strain at failure is larger than the strain at recovery, which indicates that the structures are more effective at retaining conductivity while being stretched than they are at recovering conductivity after being relaxed. Although the failure and recovery occur at a relatively consistent strain, the relative resistance values measured at this point are less consistent. This may be
attributable to the fact that the failure and recovery occur at a location in the conductor that has an unstable connection. Thus, it may be expected to display a larger degree of variation. At successive iterations, the relative resistance at recovery tends to follow the relative resistance at failure, although it is smaller. This trend is consistent in all structures undergoing this test. Considering that the recovery happens at lower strains compared to failure, it is not surprising that the relative resistance should also be lower, as relative resistance tends to be proportional to strain.

Having collected cyclic failure and recovery data for the six different samples, the average strain at failure and recovery across all iterations for each sample are calculated and plotted together in Figure 5. Figure 5 shows once again that the strain at the initial failure is the largest for all samples, followed by the average strain at failure and the average strain at recovery. Unsurprisingly, it can also be seen that samples with a larger strain at the initial failure generally have a larger average strain at failure and recovery across all iterations. The relative resistance values measured during failure and recovery are found to be generally less consistent compared to the strain. However, for all samples, the average relative resistance at failure is higher than the average resistance at recovery.

Conclusions

We have performed the characterization and parametric analysis of first order curved Peano structures fabricated using a newly developed thick film copper metallization transfer process onto PDMS. The relationship between relative resistance and tensile strain is investigated by systematically varying the geometric parameters of various curve designs while undergoing uniaxial tension tests. These tests include stretching until failure and cyclic testing of failure and recovery. The geometries resulting in maximum strain before failure are found to match simulated predictions in literature with two caveats. First, maximum strains are found to be lower in 285° geometries compared to 270° geometries, demonstrating that the gains typically associated with increasing arc length are limited. Second, the gains typically associated with maximizing the ratio of radius of curvature to wire width are shown to be limited in the context of miniaturized devices. In addition, cyclic failure and recovery tests show that these devices consistently fail and recover conductivity at strains that are stable over ten iterations, while the relative resistances during cyclic testing are less consistent.

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