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Archimedean spiral design for extremely stretchable interconnects

Cheng Lv [a], Hongyu Yu [b,c], Hanqing Jiang [a,*]

[a] School for Engineering of Matter, Transport and Energy, Arizona State University, Tempe, AZ 85287, USA

[b] School of Electrical, Computer and Energy Engineering, Arizona State University, Tempe, AZ 85287, USA

[c] School of Earth and Space Exploration, Arizona State University, Tempe, AZ 85287, USA

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ABSTRACT

The island-interconnect structures have been widely used in stretchable electronics. This Letter compares the stretchability of two serpentine-based and one spiral-based interconnects, under the limitations of the same in-plane area and contour length rooted from the same areal coverage and electrical resistance. Finite element analysis was conducted and the results showed that the spiral-based interconnects are more stretchable (up to 250% under elastic deformation) than serpentine-based structure. It is believed that a uniform and small curvature contributes to a greater stretchability. The Archimedean spiral pattern as the stretchable interconnection only presents one successful example of the new design concept.

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1. Introduction

Recent years have witnessed the rapid development of stretchable devices [1–3]. Many approaches have been utilized and there are generally two categories. The first approach is to use organic materials that are intrinsically stretchable; however, they suffer with low electrical mobility for high-performance electronics [4–6]. The second one involves so-called island-interconnect structure where the inorganic devices are placed on the rigid island while the interconnects are stretchable to make the entire system stretchable [7–11]. The island-interconnect structures are usually supported by elastomeric substrate and the recent development on foldable electronics has extended this structure to foldable substrate using the concept of paper folding (i.e., origami) [12–14]. The rational on the design of stretchable interconnects is to improve the stretchability. The interconnects are usually patterned to serpentine shape [8,15,16] and recently to semi-similar serpentine shapes [17–19]. The serpentine-based design in general utilizes the concept of kirigami (i.e., paper-cutting) to make non-straight lines from a two-dimensional plane such that the in-plane stretching is compensated by out-of-plane deformation [20]. This Letter studies spiral based interconnects and compares the stretchability between the serpentine-based and spiral-based interconnects under the constraint of the same in-plane area and contour length. The results show that the spiral-based interconnects are much more stretchable than serpentine-based interconnects and can be stretchable up to 250% under elastic deformation and 325% without failure.

2. Design criteria and constraints

To fairly compare different interconnects for their stretchability, a uniform criterion should be used. For a typical island-interconnect structure, at the unstrained state, the islands should occupy the majority of the in-plane area to increase the areal coverage. Without losing generality, a 2 mm × 2 mm island and a 1 mm gap between islands are considered in this Letter, where a 2 mm × 2 mm island size is consistent with the size of some small chips and the areal coverage can achieve over 45%. Thus the area

* Corresponding author.
E-mail address: hanqing.jiang@asu.edu (H. Jiang).

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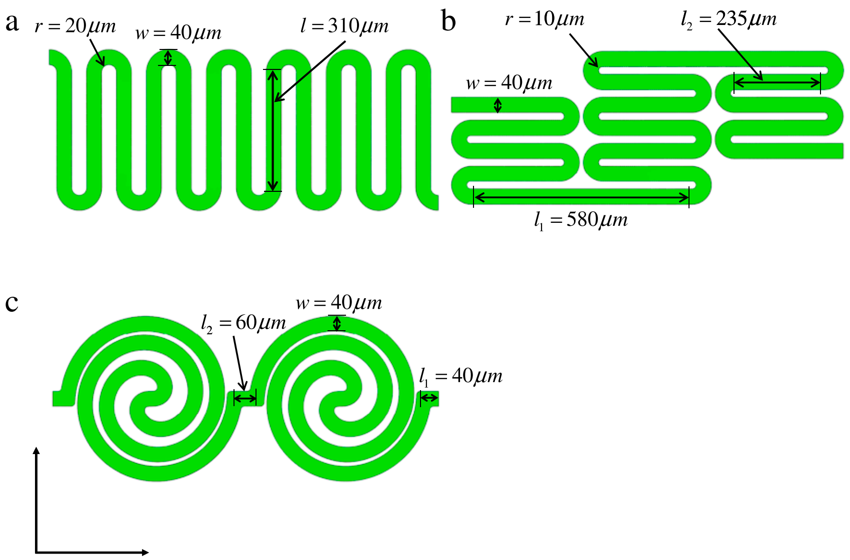

Fig. 1. In-plane shapes and dimensions of the geometries of three interconnect structures. (a) A serpentine structure. (b) A self-similar structure. (c) An Archimedean spiral structure.

can be filled in by interconnects is 2 mm $\times$1 mm. In this area, one interconnect or multiply interconnects can be placed. From the consideration of electrical conductivity, multiply interconnects have the merit since the breaking of one interconnect does not cause the electrical failure of the entire structure. Thus we consider placing four identical interconnects in the gap and each interconnect occupies no more than 0.5 mm (height) $\times$ 1 mm (width). Another constraint to fairly compare the stretchability among different interconnects is that the same cross-sectional area and in-plane contour length should be used and thus the electrical resistance among different interconnects are the same. With these constraints in placed, three different interconnects are studied in this Letter.

3. Geometries and materials

The in-plane shapes and the dimensions of the three interconnects patterns are shown in Fig. 1(a), (b), and (c), with names of regular serpentine, self-similar serpentine and Archimedean spiral, respectively. The regular serpentine has been extensively used as interconnects and the self-similar serpentine was studied very recently and found to be more stretchable under different constraints [19]. Here we propose this new pattern, Archimedean spiral. The patterns have the same thickness of 1 μm and the same strip width of 40 μm. The radius used in the regular and semi-similar serpentines are 20 μm and 10 μm, respectively. Other geometrical parameters are designed to satisfy the constraints as discussed in the previous section. In addition to the parameter shown in Fig. 1(a) and (b), the Archimedean spiral is prescribed by an analytical function in the polar coordinate as $r = \pm 60\theta^{1/1.7}$, $\theta = [0, 3\pi]$, and thus all three patterns have approximately the same span of 1000 μm in x-direction, the same height of 400 μm in y-direction and the approximately same contour length of 5650 μm. We model the interconnects as copper. The Young's modulus E is 119 GPa and the Poisson's ratio ν is 0.34 [19]. Plasticity is considered and described by $\sigma = E\varepsilon_Y + E_p\varepsilon_p^n$ with $\varepsilon_Y = 0.3\%$ as the yield strain [19], $E_p = 530$ MPa, and $n = 0.44$ [21].

4. Finite element analysis

Finite element package ABAQUS is used to conduct the analysis. Buckling analysis is carried out to obtain the first 10 buckling modes followed by importing these 10 buckling modes with random weight factors as imperfections. Then the prescribed displacement is applied at the rightmost end to stretch the interconnects while the leftmost end is fixed. At certain loading step, the prescribed displacement is removed to study if the deformation is recoverable. 20-node quadratic elements with reduced integration (C3D20R) are used in the analysis and the mesh convergence is ensured.

5. Results

Fig. 2 shows elastic stretchability of the three patterns (Fig. 1) under the constraints of the same in-plane span and contour length. Here the elastic stretchability is defined as at this critical strain the interconnect enters the plastic zone, i.e., the maximum equivalent strain exceeds the yield strain. We also studied the capability of restoration when the stretch is removed. Thus both the deformed state at the critical strain and the released state when the stretch is removed are shown for the three patterns, with the color map showing the equivalent plastic strain. To compare, the two states (deformed and released) at the half way of the critical strain are also given, which is still at the elastic range and thus the deformation is fully recoverable.

The results clearly show that the Archimedean spiral has the largest elastic stretchability, up to 200%, while the regular serpentine and the semi-similar serpentine

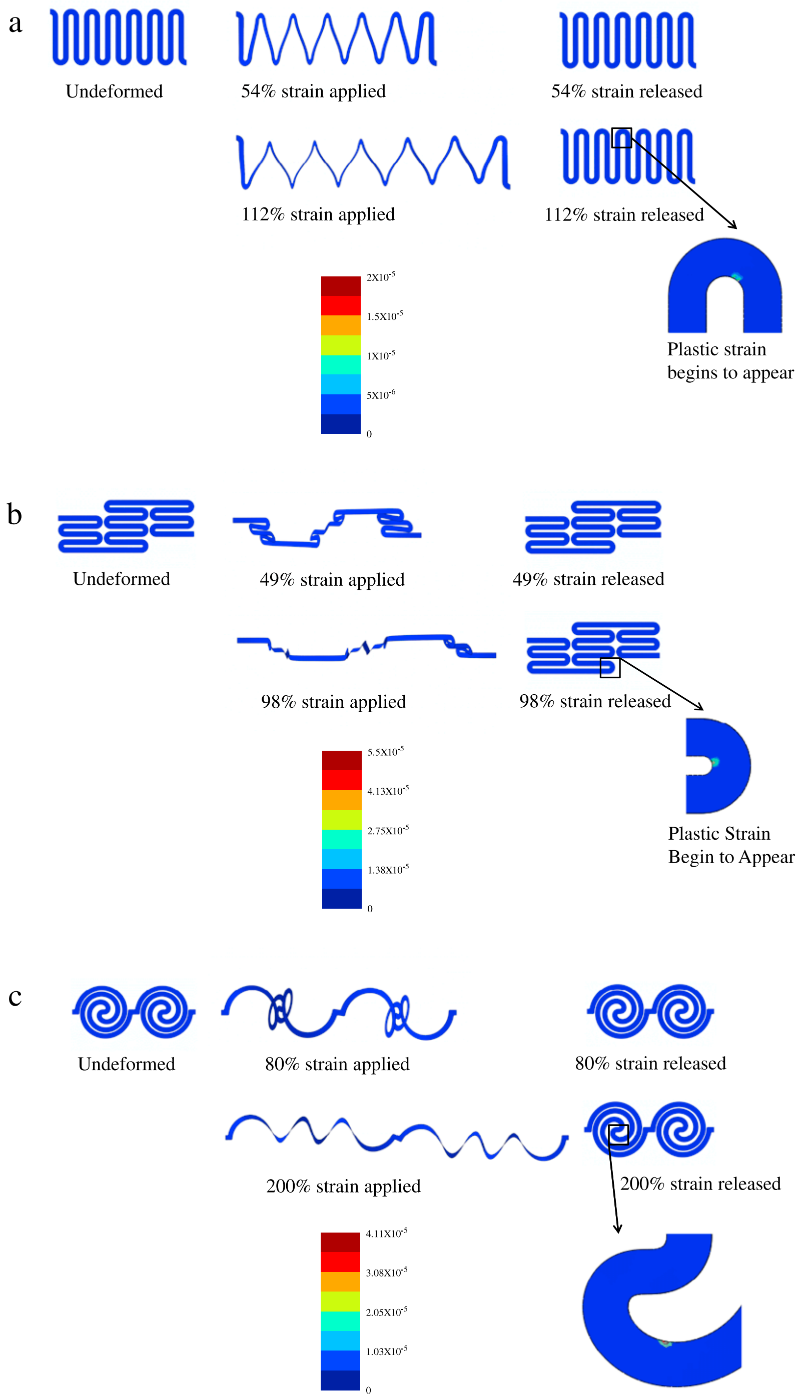

Fig. 2. Deformed and undeformed shapes of the three interconnect structures. (a) 54% and 112% strain are applied on the serpentine structure (Fig. 1(a)) and followed by strain relaxation. For 112% applied strain, plasticity begins to happen. The zoom-in view for one of the strain concentration location is shown. (b) 49% and 98% strain are applied on the semi-similar serpentine structure (Fig. 1(b)) and followed by strain relaxation. For 98% applied strain, plasticity begins to happen. The zoom-in view for one of the strain concentration location is shown. (c) 80% and 200% strain are applied on the Archimedean spiral structure (Fig. 1(c)) and followed by strain relaxation. For 200% applied strain, plasticity begins to happen. The zoom-in view for one of the strain concentration location is shown. The color maps indicate the magnitude of the equivalent plastic strain.

have 112% and 98% elastic stretchability, respectively. The deformed states show that the in-plane stretching is companied by out-of-plane deformation (mainly twisting and bending) or in other words, the out-of-plane

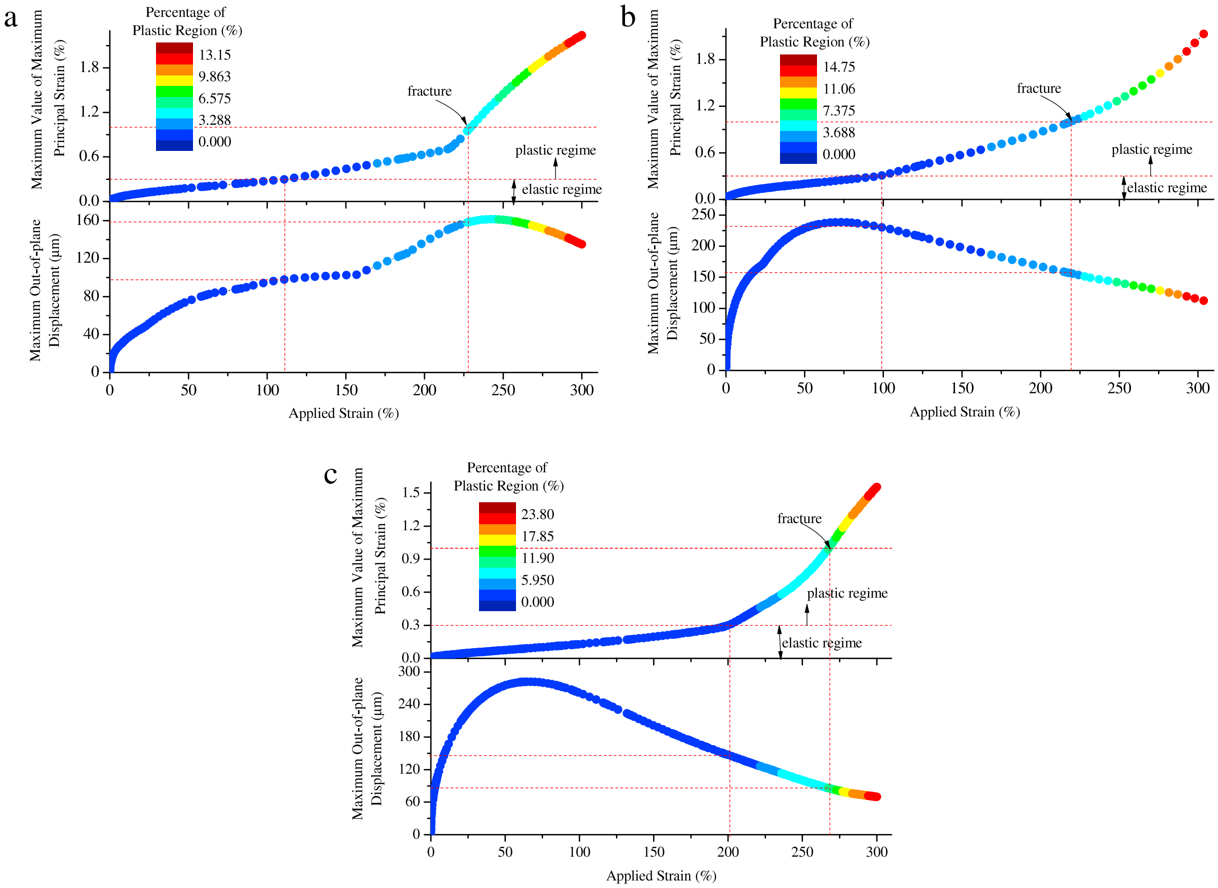

Fig. 3. The relationship between the maximum value of the maximum principal strain, maximum out-of-plane displacement and the applied strain with a color map indicating percentage of plastic zone, for (a) the serpentine structure, (b) the self-similar structure, and (c) the Archimedean spiral structure.

deformation compensates the in-plane deformation. Particularly for the Archimedean spiral structure, the unfolding-like deformation occurs to compensate the in-plane stretching. When the critical strain is released, the interconnects almost recover to the undeformed shapes, even when the plastic deformation has occurred, which is because at the critical point or little over the critical point, the regions that enter the plastic zone are very limited and the majority of the interconnects are still within the elastic domain. Not surprisingly, the plastic deformation are localized at the regions with large curvature. The reason that the comparison on elastic stretchability between the regular serpentine and the semi-similar serpentine is different from the previous study [19] is due to the different constraints.

Fig. 3 further compares the stretchability of the three patterns. Here the stretchability is defined as the critical strain at which the maximum of the maximum principal strain exceeds the fracture strain, 1%. Fig. 3 also compares the out-of-plane deformation among these three patterns. The color map indicates the percentage of the materials with plastic deformation. The results conclude that the Archimedean spiral still has the largest stretchability, up to 270%, while the other two serpentine structures are very similar, with about 220% stretchability. The Archimedean spiral structure also has the greatest out-of-plane deformation when the outer ring of the spiral rotates to compensate the in-plane stretching. From the application perspective, smaller out-of-plane deformation is desired in order to have denser stacking in the thickness direction. However the maximum out-of-plane deformation, 300 μm, is within the range of the thickness of a island or device, which will not affect the stacking density in the vertical direction. As the color map shows that the percentage of entering plastic deformation is rather small, on the order of 1%, which indicates that the structure has fairly good capability of restoring to the undeformed state even entering the plastic zone.

The comparisons shown in Figs. 2 and 3 seem to suggest that an uniform and small curvature may contribute to a greater stretchability under the constraints of same in-plane span and contour length. The regular and semi-similar serpentines have zero curvatures over the straight lines but also large curvatures at the junctions between straight lines. Because of the design limitations for the serpentine based structures, large curvatures are needed to have a large areal filling ratio. Thus the curvature for the serpentine based structure has to change from zero to a large curvature. To obtain a smooth and small curvature along the contour length, we can seek lessons from nature, which in fact motivated this work to study the spiral structures. One particular pattern is the golden

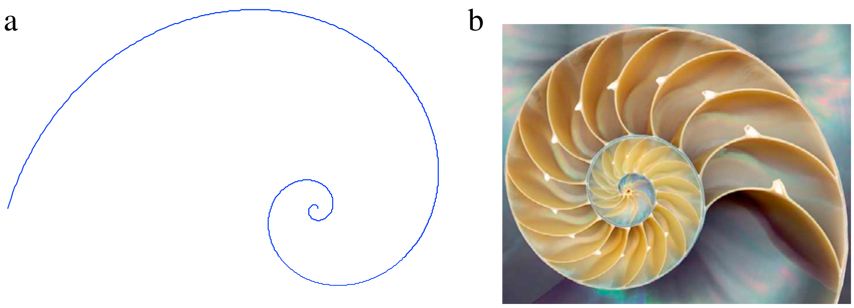

Fig. 4. Spirals in nature. (a) A golden spiral with the polar angle varying from 0 to 3π. (b) A nautilus shell as one of the most famous examples of approximate golden spiral structure appears in nature [22].

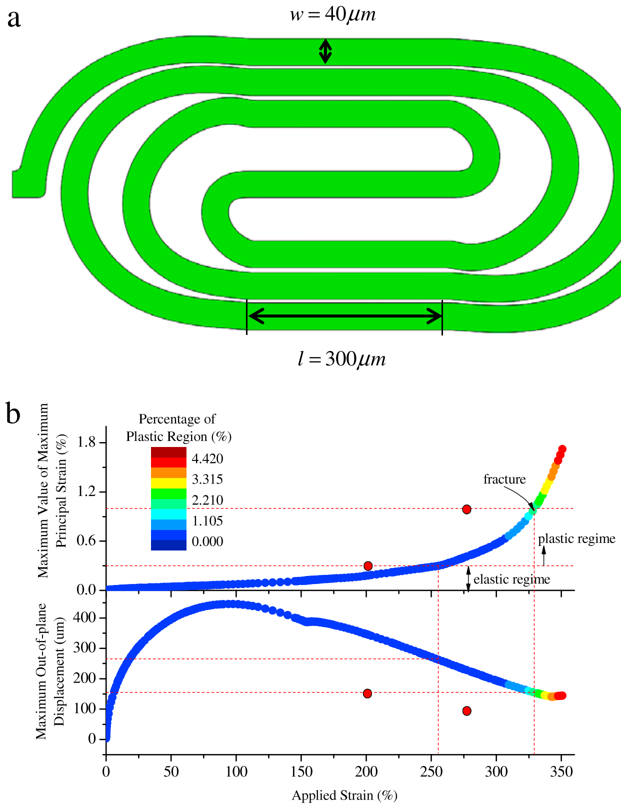

Fig. 5. Geometry and results for the modified Archimedean spiral design. (a) In-plane geometry and dimensions of the modified Archimedean spiral design. (b) The relationship between the maximum value of the maximum principal strain, maximum out-of-plane displacement and the applied strain with a color map indicating percentage of plastic zone for the modified Archimedean spiral design. The red dots show the corresponding results for the original spiral design (Fig. 1(c)).

spiral (Fig. 4(a)) that can be found in many species, such as a nautilus shell (Fig. 4(b)), where the curvature evolves smoothly along the contour length. However, the golden spiral (expressed in $r = ae^{b\theta}$ in a polar coordinate system) cannot be directly applied as a stretchable interconnect because the spiral lines aggregate at the center of the spiral, in other words, the spacing between the spiral lines decreases as the spiral curves to the center, which leads to large curvatures and does not benefit the stretchability of the interconnects. Therefore, the Archimedean spiral (in general $r = \pm a\theta^t$ $(t < 1)$ in a polar coordinate system) is used to have an uniform and small curvature along the contour length.

However, the Archimedean spiral also has one limitation, which is the horizontal span and vertical span are very close; such that to fill in a non-square area (e.g., 1 mm in width and 0.5 mm in height as in this Letter), two spirals have to be used. To make the spiral-based structure more versatile to fit in non-square area, a modified Archimedean spiral is used, as shown in Fig. 5(a). The spirit of this modification is to adjust the ratio between the horizontal and vertical dimensions to fit the non-square area. The approach used here is to modify the original Archimedean spiral by multiplying with a smooth approximation to a step function of θ in polar coordinate system and then inserting straight lines to fit the in-plane area.

The stretchability of the modified Archimedean spiral was then studied by applying a prescribed displacement at one end while the other end is fixed and the results are shown in Fig. 5(b). The same legend as that in Fig. 3 was used here and the results for the original spiral design were marked by the red dots. Clearly, Fig. 5(b) shows that the modified Archimedean spiral is more stretchable than the original spiral design, with over 250% elastic stretchability and 325% stretchability before fracture. The maximum out-of-plane displacement is about 450 μm and acceptable. The reason that the modified Archimedean spiral is more stretchable is because the newly added straight portions make the structure easier to generate out-of-plane deformation while at the same time does not introduce large curvatures.

6. Conclusions

This Letter studies the stretchability of serpentine-based and spiral-based interconnects, under the limitations of the same in-plane area and contour length rooted from the same areal coverage and electrical resistance. The results found that the spiral-based interconnects are more stretchable than serpentine-based structure. It is believed that a uniform and small curvature contributes to a greater stretchability. To experimentally realize this design, the entanglement within a spiral would be avoided by elevating it above the substrates. The Archimedean spiral pattern as the stretchable interconnection only presents one successful example of the new design concept. The idea behind it can be readily extended to the design of interconnection or other related fields that demand high stretchability. Instead of applying periodic pattern, non-periodic pattern may provide more degree of freedom during the design process, especially under certain extreme conditions.

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