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Ultra-Stretchable Archimedean Interconnects For Stretchable Electronics

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ABSTRACT

Stretchable inorganic electronic systems are promising research area for many applications, such as wearable electronics. The island-interconnects design represents one of the categories, which is widely used in stretchable electronics. Here we show, Archimedean-inspired design for interconnect that can achieve more than 1020 % of stretchability. Mathematical modeling followed by experimental validation is done to study the relationship between the stretchability and various geometrical parameters. Further, a numerical study is conducted comparing the stretchability of the Archimedean structure to that of the spiral and serpentine structures. We show that the Archimedean interconnects attain the lowest stress and thus the highest stretchability.

1. Introduction

In the recent years, scientific community has expressed increased interest to develop stretchable high-performance electronic devices with high-elastic mechanical responses for many applications, such as stretchable sensors [1-2], wearable electronics [3-5], and health monitoring systems [6-7]. A core challenge in each of these systems is to realize high level of stretchability while the electronic performance parameters remain unaffected by the deformation. Such an approach to extreme stretchability is based on using organic semiconductors materials, due to their natural ability to conform to mechanical deformation [8-9]. Nonetheless, a key challenge comes from limitations in its electrical conductivity and transport properties, which are inferior to those of inorganics [10-11]. Therefore, stretchable high-performance electronics need to use inorganic semiconductors materials, such as mono/poly-crystalline silicon (c-Si), amorphous silicon (a-Si) or nitrides, which are brittle and stiff, and thus their elastic stretchabilities are very low around 1-1.65 % [12-14]. Therefore, through optimization of mechanics and structural designs, brittle silicon can now be made stretchable, which leads to a mechanically compliant system that offers low modulus response to large strain [15].

Several structural designs have been developed to make stretchable devices, such as wavy and wrinkled designs [16-17], and serpentine design [18]. The first structural designs proposed in stretchable inorganic electronics, are the wavy and wrinkled designs. This is mainly because these designs show good conductivity and stretchability with soft compliant substrate. Single-crystal silicon nanoribbons are bonded with pre-strain polydimethylsiloxane (PDMS) substrate, and thus releasing the initial strain leads to the construction of periodic wavy structures [19].

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The island-interconnects structure presents another structure design, which is widely used in stretchable electronics. Islands are integrated with substrates, and combined with stretchable interconnects designs. Under stretching, the islands, which carry all the functional components are kept nearly un-deformed, while the thin interconnects deform to provide high stretchability. For many applications, the islands-interconnects design must be capable to achieve high-surface coverage of the functional components and high stretchability of the electronic interconnects. Representative interconnects design include straight [20], fractal-inspired [21], and serpentine [22]. Recently, a variety of fractal-inspired representative designs including lines (Koch, Hilbert, Peano), loops (Moore, Vicsek), branch-like meshes (Greek cross), and horseshoe have been demonstrated to be useful for various applications which required high surface filling ratio of active devices [23-25]. Compared with periodic serpentine, the fractal designed based on a selected dimension, allowed biaxial, radial and other deformation modes. However, this technology gives levels of stretchability less than 100 % [25].

Interconnects with a serpentine configuration are more flexible and more stretchable compared to the straight interconnects. Yan et al. proposed a 3D serpentine-like antenna, which exhibits mechanical and electrical robustness when the stretchability of the antenna is as high as 200 % [26]. Xu et al. introduced a set of interconnect design that exploits self-similar serpentine geometries with a biaxial stretchability of up to 300 % [27]. Hussain et al. demonstrated stretchability up to 800 % based on copper serpentine interconnects [28]. Rojas et al. showed high stretchability of monolithic single-crystal silicon spiral interconnects up to 1000 % [29]. Although serpentines-interconnects have been widely used as stretchable structures, Lv et al. have demonstrated that the archimedean-based interconnects can offer higher stretchability compared to serpentine-based interconnects [30]. The results show up to 250 % of applied elastic strain and 325 % without failure for archimedean interconnects design. Inspired by this work, we have modified the Archimedean design to increase the in-plane stretchability.

In this paper, we study theoretically and experimentally the in-plane stretchability of Archimedean inspired design. It contains three serpentine designs with different radius linked together in small area to increase the stretchability and to reduce the gap space. The results show that, this structure can demonstrate in-plane high stretchability more than 1020 %. Mathematical modeling followed by experimental validation is done to study the relationship between the stretchability and various geometrical parameters. Our results can be useful in optimizing the Archimedean structure to enhance more stretchability. Further, a numerical study is conducted comparing the stretchability of the Archimedean structure to that of the spiral and serpentine structures. We show that the Archimedean interconnects attain the lowest stress and thus highest stretchability.

2. Background design and device principle

We showed in the Fig. 1 an example of the application of Archimedean interconnects in island-bridge structure. The islands represent in square shapes. The Archimedean structure is composed of three half circles and straight lines. The design contains three serpentine designs with different arc radius (R_1 , R_2 , and R_3) linked together in a small area to increase the stretchability and to reduce the gap space. Archimedean with this geometry can be extended in X (blue) and Y (red) directions, and thus, we can achieve a bi-axial stretchability.

Fig.1: Schematic of a 3 x 3 array of island-Archimedean structure, and illustration on the geometric parameters (with dimensions: 117 μm length (l), height (H), and width (t) = 5 μm).

To demonstrate the practical feasibility of the design, we carried out the fabrication of the same structures using bulk monocrystalline Si substrate. To make the devices with high in-plane stretchability, the width to thickness ratio of arms of Archimedean structures fabricated with silicon needs to be small (lower than 1 to avoid the out-of-plane buckling). For achieving this, we deposited 10 μm amorphous silicon (a-Si) on top of 300 nm thermally grown oxide on a 4-inch silicon wafer. Deposition of a-Si gives “virtual silicon-on-insulator (SOI)”, which is helpful in releasing the extremely flexible structure after processing, allowing reusability of the substrate. First, the stretchable design proposed here is patterned on the deposited a-Si using standard lithography process. To release the structures from the carrier Si/SiO₂ wafer, we designed 20 μm diameter holes in the Si island with equal spacing to assist in the etching of SiO₂ underlying the a-Si layer using vapor HF (VHF) [31]. To etch holes in the a-Si with high directionality, we performed deep reactive ion etching (DRIE) using combination of Carbon Tetrafluoride (CF₄) and Sulfur Hexafluoride (SF₆) gases in alternating steps of deposition and etching to achieve vertical profile. We used Aluminum (Al) as hard mask while performing DRIE. We patterned the Al hard-mask with ECI 3027 positive photoresist followed by Al wet etching to remove the Al from holes. Wet etching is preferred here because it is faster and selective, though it gives undercuts due to isotropic etching. The thickness of 100 nm Al is very less in comparison with the thickness of the a-Si to have any significant undercut effects. After DRIE and photoresist

removal, we release the structure by etching underlying oxide layer with VHF at 40 °C. The structure has 117 μm in length (l), and 10 μm in thickness. For our fabrication, we have kept the width (t) of the Archimedean arms as 5 μm equidistant which can further be decreased to give improved performance. The height (H) is varying from 150 μm to 400 μm . Let β denotes the height/width ratio (H/t), scanning electron microscopic (SEM) images of the fabricated devices for $\beta = 30$ are represented in Fig. 2.

Fig.2: Scanning electron microscopy (SEM) images of the structures after release. (a) Island-Archimedean structure for $\beta = 30$. (b) and (d) Enlargement of part of the Archimedean interconnects showing the width (t) and the gap (d) are almost 5 μm and 6.8 μm , respectively. (c) Release of islands with holes of 20 μm diameter.

3. Results and discussions

3D Finite element models (FEM) of the device were developed with the software COMSOL to design, simulate, and investigate its mechanical behavior and to attain an optimum performance of the structure. We utilized the Solid Mechanics module to study the Archimedean deformation due to different axial strain values. To avoid the inference, in the model definition section, contact pairs were defined at the straight lines of the structure and then, they were exploited in the boundary conditions section of the Solid Mechanics section. To simulate the stretchability of the Archimedean with two islands, an in-plane displacement is applied on one of the islands while the second one was declared as fixed, Fig. 3(a). The stretchability is defined as the critical applied strain which the amorphous silicon (a-Si) of the Archimedean structure will fracture. Since the structures show high stretchability and thus large deformation, non-linear geometry was used. For the material of the structure, the amorphous silicon was used with 80 GPa for Young's modulus. Tetrahedral elements were selected as the element type to mesh the structure. For the convergence of the FEM simulation, finer element mesh was determined to be the optimal for meshing, hence, used for all the simulation results presented in this work. To run the simulation, the predefined parameter was used in the stationary study and solved for a range of values from 0 μm of displacement to X μm . For $\beta = 80$ ($H = 400$ μm) and

a thickness (w) of 10 μm , the result shows that the maximum strain and stress appear at the base of the structure and at the half-circle as shown in Fig. 3(b). This result shows that interconnects with high radius must be considered to reduce the strain (stress) at the half circle. In the future work, to minimize the stress localization appears at the bases of interconnects, it required to replace the straight arms with serpentine [29]. Hence, a systematic study of the relationship between the stretchability and geometrical parameters (β) is performed. As in Fig. 3 (c), it is observed that for $\beta=40$ the maximum X-displacement (mentioned to the maximum displacement before fracture) is 622 μm (530 % of stretchability) which it defined at $\epsilon_{\max}=1.6$ % (yield fracture).

Fig.3: (a) Boundary conditions for Archimedean structure connected with two islands. (b) 3D stress distribution under applied displacement of 400 μm for $\beta = 80$. The enlarged view shows a maximum stress at the half circle and the base of the interconnections.(c) FEM results of deformed configurations under uniaxial tensile strain until fracture ($\epsilon_{\text{max}}=1.6\%$) for $\beta=40$.

Mechanical characterization was carried out on a semiconductor probe station, on which we applied uniaxial strain (stretching) using the probes and respective deformations are captured using digital microscope, see Fig. 4. An axial displacement is applied manually by using one of the probe needles on one of the islands while the second one was fixed. The stretchability of the structures was investigated by keeping the screw rotated which in its turn created an axial displacement on the islands until seeing structure failure. The measurements of the axial deformation are captured using digital microscope .

Fig.4: Experimental setup.

Fig. 5 (a) shows the experimental results and finite element simulations of the Archimedean structure for $\beta=30$ under different axial strain values. The results demonstrate stretchability up to 170 % before fracture ($\epsilon_{\text{max}}=1.6\%$ which represents the yield fracture). According to existing studies, the stretchability of the serpentine design depends on the ratio of width/radius [29]. Hence, due to the similarity of the Archimedean with the serpentine, the same conclusion can be drawn on the effect of the aspect ratio on the Archimedean stretchability [32]. In case of $\beta=30$, the t/R_3 ratio is 0.15, hence the maximum stretchability expected is near of 180 %. The structure shows a failure near the interconnects base due to the fact that the bending moment generated from the internal restoring forces is maximum at that point (base), hence, the corresponding von Mises stress. The experimental results of the stretchability for $\beta = 80$ (see Fig. 5(b)) show different mechanical deformations, in which the maximum stress appears at the half circle due the large bending moment at this point. In this case, the resulting stretchability for

overall applied strain is increased to 1020 %, while the maximum stretchability expected is near of 700 %. The mismatching between the experimental and numerical values is suspected, since the numerical values of the stretchability are calculated based on one radius value (R_3), while the Archimedean structure has three different values of the radius (R_1 , R_2 , and R_3). Hence, a more accurate formula taking into accounts of different radius values should be utilized.

Next, we study the relationship between the stretchability and geometrical parameters ($\beta = H/t$). Fig. 3(c) shows that the stretchability of the interconnect increases when β increases, it increases as the height H of the straight lines increases or the width t decreases. A reasonable interpretation is that, increasing β for low to high, the total end-to-end length increases, which this significantly reduces the overall structure stiffness. Hence, under the same in-plane applied strain, we report high stretchability for high β . For $\beta > 40$, the relationship between stretchability and β is linear; this will lead to significant enhancement of the stretchability for high values β . The improved high stretchability for $\beta = 80$ encourages the efforts toward optimized designs to efficiently increase β for ultra-stretchable applications.

(a) Height/width ratio (β) = 30

(b) Height/width ratio (β) = 80

(c)

Fig. 5: (a) Full extension test under several stages of applied tensile strain until fracture and corresponding FEM results for $\beta = 30$. (b) Full extension test under several stages of applied tensile strain until fracture for $\beta = 80$. (c) Experimental and FEM results of the maximum stretchability ($\epsilon_{stretchability}$) versus the height/width ratio (β).

Next, a numerical study using FEM is performed on the Archimedean structures for $\beta = 40$ to investigate the influence of number of half circles (N) on the stretchability. It is observed that when N decreases from 3 to 2, the stretchability decreases from 540 % to 134 %. Our results show that maximum von Mises stresses of Archimdean interconnect increases from 809 MPa to 1290 MPa subjected to the displacement of 130 μm , Fig. 6.

Fig. 6: 3D stress distribution under the same applied displacement of 130 μm for (a) $N=2$ and (b) $N=3$. The results show that stretchability decreases up to 396% from $N=3$ to 2.

Then, we compare the stretchability of the Archimedean structure to that of spiral and serpentine based interconnects, Fig. 7. As shown in Figs. 7(a-c), for a proper comparison between different interconnects, various geometrical parameters ($t = 5 \mu\text{m}$, $H = 400 \mu\text{m}$, $w = 10 \mu\text{m}$ and $l = 117 \mu\text{m}$) are considered constant, only for spiral structure the height and the length are taken 500 μm and 900 μm , respectively. Figs. 7(d-f) show the 3D simulation results of the stress distribution for 100 % stretchability. The lowest value of the maximum von Mises stress is found at the Archimedean structure with $\sigma_{\max} = 273 \text{ MPa}$ compared to the spiral and the serpentine structures, which have $\sigma_{\max} = 454 \text{ MPa}$ and $\sigma_{\max} = 518 \text{ MPa}$, respectively. Figs. 7(g) and 7(h) compare the evolution of strain and stress for the three structures. The results show that the Archimedean design has the lowest strain (%), which is equal to 0.2 % for 100 % stretchability. The in-plane deformation mechanics of these three structures are related to the width (t), height (H), and the radius (R). The maximum strain of the spiral design is proportional to the width and inversely proportional to the radius of the half circle [29]. Similarly a serpentine structure with narrower width, higher radius, longer arm length and low unit cell numbers leads to a low stiffness and low intrinsic strain [32-33]. Compared to the one cell serpentine design, Archimedean design contains one cell serpentine with arc radius R_3 higher than the radius R from one cell serpentine design and two cells serpentine design with arc radius (R_1 and R_2) at low length scale, and thus, it shows low stiffness and high stretchability. Hence, the use of Archimedean as interconnects allows to high stretchability compared to the two other designs.

Fig. 7: Schematic diagrams for (a) Archimedean, (b) Spiral and (c) Serpentine. (d)– (f) Maximum von Mises stress of FEM results of the three structures under 100 % of stretchability. (g) and (h) Maximum strain and von Mises stress distribution of FEM results of the three structures until 100 % of stretchability .

4. Conclusions

This paper presented a high stretchable structure based on Archimedean design. The numerical study followed by experimental validation shows more than 1020 % of stretchability for high height/width ratio. It is found that increasing the width/width ratio is a very effective way to increase the stretchability of the Archimedean structure. A comparison study of the maximum stress is performed for 100 % stretchability of Archimedean, spiral and serpentine interconnects. Our results show that the Archimedean interconnects attain the lowest stress and thus high stretchability. These results are valuable for future miniature devices, which need extremely stretchable interconnects in microscale.

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