Simulation of a Tether Structure for Ultra-stretchable Monolithic Silicon Fabric

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Abstract: We have simulated silicon as the base material structure for a hexagonal island network, which are connected through spiral springs to form an ultra-stretchable arrangement . In this work, we simulated a spiral tether structure for stretchable and adaptable electronic systems. The Structural Mechanics and MEMS module were used to extract important information from the proposed designs.
Keywords: flexible silicon, MEMS, flexible electronics.

1. Introduction

The role of stretchable electronics systems allows the design of new reconfigurable macro-electronics, that extends a device capability to function as a distributed sensor network which can potentially be used for wearable electronics. Stretchable electronics, are getting more scientific and commercial relevance because of the wide applications in the wearable electronics industry [1, 2]. Interesting ways to engineer materials are continuously emerging in order to achieve required characteristics needed in this kind of devices, such as: light-weight, tunable-shape, and a conformable electronic system [3, 4].

At the moment such devices are primarily based on polymeric materials such as PDMS or Polyimide [4–13]. Research on organic/polymer-based electronics has taken the lead, providing good mechanical properties and cost advantages over other materials. Even though great advancements have been made on display technologies and great flexibility and stretchability can be achieved,the electrical properties of these devices are far from silicon technology standards. Nevertheless, silicon has been the predominant material in electronics for decades. For this reason, we selected silicon as the base material structure for a hexagonal islands network, which are connected through spiral springs to form an ultra-stretchable arrangement [1, 2].

In this work we simulated a spiral tether structure for stretchable and adaptable electronic systems. The spirals interconnect several hexagonal islands as show in Fig. 1.

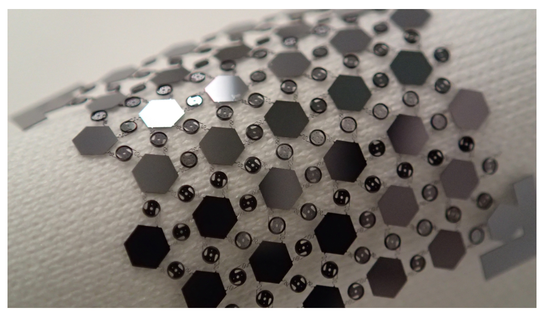

Figure 1: Digital photograph of an array of 800um-side-hexagons interconnected by single 5um- arm spirals

2. Computational Methods

The Solid Mechanics interface solves the equations of motion together with a constitutive model for a solid material. From these solutions, COMSOL can compute results on the structure displacements, strains and stresses [14]. The MEMS and Structural Mechanic modules provide several features, like geometric nonlinearity and advanced boundary conditions such as contact, follower loads, and nonreflecting boundaries [14].

2.1 Governing Equations

The analysis of deformation describes the local deformation in a material suitable for use in a constitutive relation, which frequently derives to a strain tensor.

The formulation used for structural analysis in COMSOL Multiphysics for bot small and finite deformation is a Total Lagrangian formulation. Which means, that the computed stress and deformation state is referred to as the material configuration and not to the current position in space [14].

Consider a certain physical particle, with an initial position at the coordinate $\mathbf{X}$. When the particle is deformed, it follows a path

$$\mathbf{x} = \mathbf{x}(\mathbf{X}, t) \tag{1}$$

where, $\mathbf{x}$ is the spatial coordinate and $\mathbf{X}$ is the material coordinate.

To simplify, COMSOL assumes that undeformed and deformed position are measured in the same coordinate system [14]. It uses the displacement $\mathbf{u}$ in order to be possible to use the following equation

$$\mathbf{x} = \mathbf{X} + \mathbf{u}(\mathbf{X}, t) \tag{2}$$

The displacement is a function of the material coordinates (X, Y, Z), without being an explicit function of the spatial coordinates (x, y, z). Therefore, it is only possible to compute derivatives with respect to the material coordinates [14].

In the following equation (3), the gradient operator is to be assumed as a gradient with respect to the material coordinates, unless it is stated different.

$$\nabla = \nabla_X = \left[\frac{\delta}{\delta X} \frac{\delta}{\delta Y} \frac{\delta}{\delta Z} \right] \tag{3}$$

The gradient of the displacement is always computed with respect to the material coordinates. In 3D:

$$\nabla \mathbf{u} = \begin{bmatrix} \frac{\delta u}{\delta X} & \frac{\delta u}{\delta Y} & \frac{\delta u}{\delta Z} \\ \frac{\delta u}{\delta X} & \frac{\delta u}{\delta Y} & \frac{\delta u}{\delta Z} \\ \frac{\delta u}{\delta X} & \frac{\delta u}{\delta Y} & \frac{\delta u}{\delta Z} \end{bmatrix} \tag{4}$$

The deformation gradient tensor F can show how an infinitesimal line element, $d\mathbf{X}$ is mapped to the corresponding deformed line element $d\mathbf{x}$ by

$$d\mathbf{x} = \frac{\delta \mathbf{x}}{\delta \mathbf{X}} d\mathbf{X} = F\, d\mathbf{X} \tag{5}$$

The deformation gradient $\mathbf{F}$ contains the complete information about the local straining and rotation of the material [14]. The deformation gradient $\mathbf{F}$, can also be written in terms of the displacement gradient as

$$d\mathbf{x} = \frac{\delta \mathbf{x}}{\delta \mathbf{X}} = \nabla \mathbf{u} + I \tag{6}$$

When a material stretches it will cause changes in the material density. The ratio between the current and the initial mass density is given by

$$\frac{dV}{dV_0} = \frac{\rho_0}{\rho} = det(F) = J \tag{7}$$

In Equation (7), ρ_0 is the initial density and ρ is the current density after deformation. The determinant of the deformation gradient tensor F is related to volumetric changes with respect to the initial state [14].

The mass density should be constant when using the material formulations used in the structural mechanics interface. This is because the equations are formulated for fixed material particles. Therefore, temperature-dependent material date for the mass density should not be used. The changes in volume caused by temperature changes are incorporated using the coefficient of thermal expansion in the material model, when combined with the Thermal Expansion module [14].

3. Results

To validate the chosen designs, we used COMSOL Multiphysics to evaluate the structures strain distribution in order to identify possible weak points in the design. For simplicity we omitted the hexagonal islands, to focus only in the stretchable spiral structure.

The structure layout design was exported from Tanner Tools L-edit software as a DXF file. Using the CAD import module of COMSOL. The 2D drawing was imported to a work-plane and then extruded to the specific thickness needed. A Union command was applied to make sure that the structure is a single object. For the material used in the structure, Silicon (single-crystal) was selected from the materials library. The physics being used for this simulation is the Solid Mechanics interface. Therefore, the material properties required are: Density (rho) of 2330[kg/m3], Youngs modulus (E) of 169[GPa] and Poissons ratio (nu) of 0.22.

For the boundary conditions the material was defined as a Linear Elastic Material. All the faces of the 3D model were free to move in the virtual space except for the end of the spiral that was given a Fixed Constraint boundary condition.

To deform the structure a Prescribed Displacement condition was set to the other end of the spiral structure and the value was set to a predefined parameter to be able to perform an extended study. For the mesh settings the top face of the spiral was selected to create a Free Triangular mesh, which then was used in a swept function to propagate the structure elements.

The simulation was performed using a Stationary Study (including the geometric nonlinearity of the system) with an Auxiliary sweep to help the solver converge contemplating the large deformation of the structure. Finally the Auxiliary sweep was set up using the predefined parameter and solved for a range of values from 0m of displacement to 2mm in steps of 5m.

In Fig. 2 we show the simulation results of a fully extended spiral.

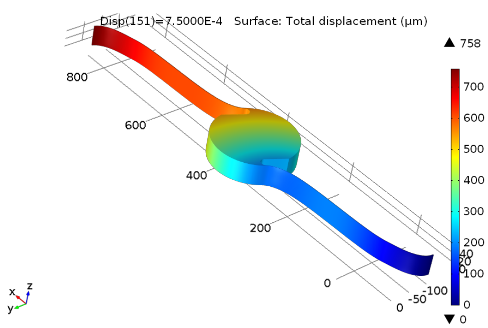

Figure 2: Simulated displacement of the stretched spiral structure.

Fig. 3, shows the corresponding strain. The maximum strain and stress point are foudn at the beginning o f the arms and in both cases is aroudn 1.2%.

Von Mises stress is also shown in Fig. 4, showing the stress in the spiral, when is extended to

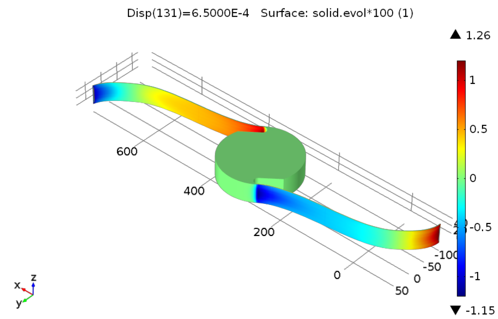

Figure 3: Expanded spiral showing the strain in the structure after a displacement of 650μm.

different horizontal displacement of up to 675m. Its maximum is approximatelty 4000MPa, which is much lower than the ultimate tensile strength of the silicon.

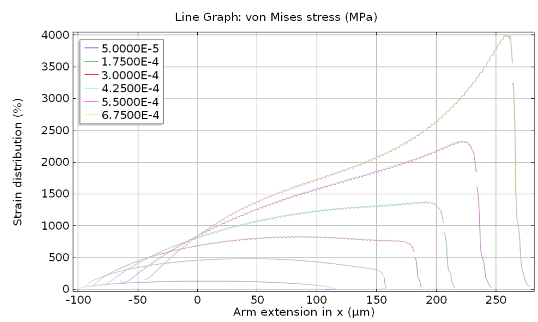

Figure 4: Strain distribution vs Arm extension for different displacements of the structures, from 50μm to 675μm.

The maximum stress and strain location are at the beginning of the arms. The Von Mises stress has a maximum of 4000 MPa, which is much lower than the tensile strength of the silicon.

4. Conclusions

We were able to localize the weakest point of the structure. From this results we were able to modify the design to include a design feature at the beginning of the arms to reinforce its stability.

Furthermore, we decided to include a serpentine-shaped tether to help mitigate the force induced in this area.

We have presented an area efficient design to achieve ultra-stretchability in monolithic single-crystal silicon. After the optimization of the design, we fabricated the structures with a 5-steps fabrication process flow, more details in [1]. The fabrication process is simple accomplish and the measured stretchability was of up to approximately 1000% for single spirals, and an area expansion of up to 30 fold in arrays.

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