Process Flow for Tessellated Microstructures in BioMEMS

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***Abstract*—The study of origami folding techniques and tessellated patterns as a means to solve fitting problems involving conformity to complex, organic topologies is of great relevance to the design of flexible micro electromechanical systems (MEMS), with particular relevance to bioMEMS applications. As a consequence of Gauss's Theorema Egregium, conventional flexible electronics implemented on flexible printed circuits (FPC) cannot conform to surfaces of varying Gaussian curvature. By corrugating a flexible substrate with tessellated patterns, conformity to an organic shape with varying Gaussian curvature across its surface can be approximated. A process flow compatible with existing nanofabrication techniques for fabricating pyramidal truss tessellated microstructures on polypropylene fumarate (PPF) is achieved by exploiting anisotropic etching. Several implications of the material properties of tessellated microstructures are discussed in the context of bio-inspired MEMS.**

***Index Terms*—bioMEMS, origami, tessellation, auxetic**

I. Introduction and Background

A. Defining Curved Surfaces

The curvature of a surface can be defined in two ways: extrinsically by the average curvature, and intrinsically by the Gaussian curvature. The average curvature is given by the mean of the curvatures along each of the principal axes of curvature:

$$\bar{\kappa} = \frac{1}{2}(\kappa_1 + \kappa_2) \tag{1}$$

The average curvature provides an extrinsic measure of how the object displaces space in a three-dimensional environment. For instance, a paper laid flat on a surface has zero-curvature in both principal axes, so $\bar{\kappa} = 0$. However, when the paper is picked up and deformed such that both ends of the paper are brought closer together, the bulk of the material forms a "wave-like" pattern. In this case, the principal axis transverse to the direction of compression remains at zero-curvature, while the radii of curvature at regions on the surface along the longitudinal axis become non-zero. The average curvature is changed depending on how an external observer sees the object in their environment. A second measure of curvature, the Gaussian curvature, is given by the product of the principal curvatures:

$$K = \kappa_1 \kappa_2 \tag{2}$$

Contrary to the average curvature, the Gaussian curvature provides an intrinsic measure of curvature from the perspective of a two-dimensional observer embedded in the surface of the object. The "test" for curvature is as follows: if the sum of the angles within a triangle drawn on the surface at the region in question is deemed to equal 180° by an intrinsic observer, the region has $K = 0$. Otherwise, if the sum is deemed to be less than or greater than 180°, then the region has negative and positive Gaussian curvatures, respectively. According to Gauss's Theorema Egregium, which states that the Gaussian curvature of a surface is preserved through bending operations where stretching is not involved [1], a surface that has a zero Gaussian curvature to begin with cannot conform to surfaces with a non-zero Gaussian curvature, no matter how it is bent. Taking the previous example of a deformed paper, since at least one principal curvature is zero at every point on the surface, the Gaussian curvature will always remain zero, even though the average curvature changes. Inelastic bending operations that comply with the Theorema Egregium are called *isometric* because they leave the metric imposed on the surface unchanged, preserving Gaussian curvature. Surfaces with a Gaussian curvature of $K = 0$ are called *developable.* For MEMS devices, a problem with conventional flexible substrates is that, because they are developable surfaces, they cannot conform to a non-developable surface with a non-zero Gaussian curvature $K \neq 0$ without creasing.

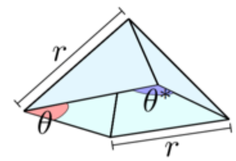

Fig. 1. Facet for pyramidal truss tessellation [3]

B. Tessellated Patterns

Folding a developable surface is defined as a bending operation with a very high radius of curvature [1]. As per Gauss's theorem, such an operation is isometric and cannot achieve conformity to shapes with inconsistent Gaussian curvatures. While tessellation origami does not change the intrinsic Gaussian curvature of the surface, what this folding technique can achieve is a change in the *apparent* Gaussian curvature of the surface tangent to the vertices of the tessellation [2].

Tessellation patterns are characterized by fundamental units called facets. A tessellated surface is deemed conformable to a local surface region as long as the largest protruding dimension r of the facet is sufficiently small to satisfy the following fitting criterion given in Nassar [3]:

$$r \ll R \tag{3}$$

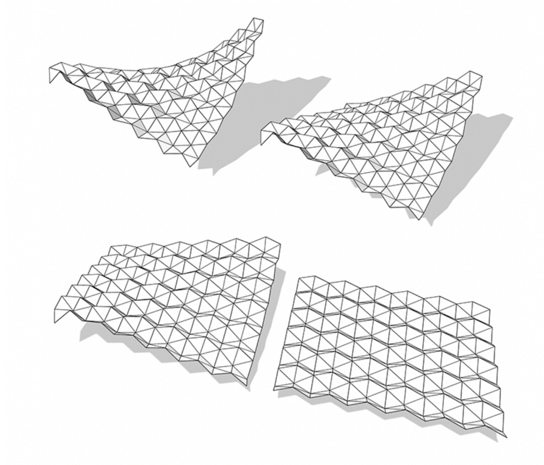

Fig. 2. Tessellated substrate demonstrating double curvature

The tessellation can approximate, to a sufficient degree, conformity to a local surface region with radius of curvature R. Although far superior conformity may be achieved through irregular tessellation, only periodic tessellation patterns are considered in this paper. There exist many algorithms in computer-aided design that minimize the fitting error of a tessellated pattern by using non-periodic and irregular facets. Non-uniform rational B-spline (NURBS) is a common method to represent organic curves as meshes. However, fitting error should not be reduced so much as to undermine the generalizability of the pattern in maintaining conformity despite movement. Tessellations should be able to conform to non-developable surfaces, consist of topologically periodic facets, and be feasible to produce.

Among many popular folding techniques that abide by these criteria such as the waterbomb [1] and eggbox [3] tessellations, the following sections focus on the pyramidal truss tessellated structure (Fig. 3). This tessellation pattern uses the three-dimensional facet shown in Fig. 1 as its tessellation unit and tiles this feature over a compliant substrate. The result is a substrate that is able to conform to a variety of non-developable surfaces and maintain its conformity through reasonable movement.

A convenient consequence of this particular tessellated origami approach is that these patterns contain vertices that, for non-extreme deformations compliant with fitting condition (3), are fixed points on the surface to which the substrate is conforming. For instance, an electromyography (EMG) based orthosis that both records local EMG signals and writes stimulation patterns to induce muscle movement may require certain electrodes to be placed at specific locations along a subject's arm. A tessellated "smart-skin" enveloping the subject's arm may be designed such that electrodes or small MEMS-based sensors are cradled within fixed nodes. Due to the geometric properties of the tessellated surface, those fixed nodes remain throughout any deformation of the substrate. Additionally, because the edges of each facet maintain a length r throughout deformation, these edges are suitable for

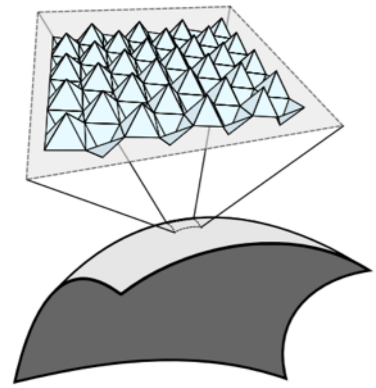

Fig. 3. Pyramidal truss tessellation conforming to surface of positive Gaussian curvature [3]

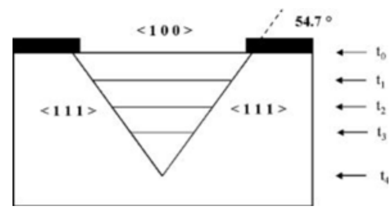

Fig. 4. Anisotropic etching on silicon performed to completion

placement of conductive traces connecting each electrode.

II. Fabrication

A. Process Flow for In Situ Pyramidal Truss MEMS

The pyramidal truss tessellation can be reproduced at both the macroscale and microscale due to its simple and repeatable pattern. The process flow describing the latter uses established nanofabrication techniques to create a mold to form the tessellated pattern on a flexible substrate. For microscopic *in situ* biomedical sensing applications, polypropylene fumarate (PPF) is a recommended substrate material. A flexible polymer, PPF is an ideal choice due to its injectability (useful for molding) and biodegradability.

To form the PPF into a pyramidal truss pattern, a simple approach is to create a negative mold that forms PPF into the desired shape. Fortunately, the pyramid shape arises as a convenient byproduct of anisotropically etching silicon, a property which can be exploited to form the negative mold.

To create the cast for the pyramidal truss pattern, a silicon wafer is anisotropically etched to completion, leaving the three-dimensional imprint of an inverted pyramid in the substrate (Fig. 4). Under the completed etching condition (i.e. the etching forms a vertex), the dimensions of each side of the mask opening obey

$$M_O = 2z \cot 54.74^\circ \tag{4}$$

or equivalently

$$M_O = \sqrt{2}z \tag{5}$$

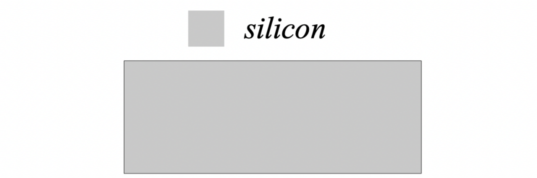

Fig. 5. Blank ⟨100⟩ silicon wafer

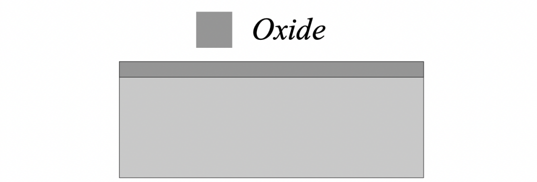

Fig. 6. SiO_2 is grown on wafer via thermal oxidation

where z is the desired height of each pyramidal facet. The above relation assumes ideal anisotropy and ignores undercutting effects. Lateral undercutting amount in anisotropically etched silicon behaves as follows:

$$\delta_{uc} = \frac{\sqrt{6}z}{2S} \tag{6}$$

As shown above, in order to minimize lateral undercut δ_{uc}, it is essential that the wet etching process maintain high selectivity S. Selectivity S is a dimensionless quantity that represents the rate ratio in the ⟨100⟩ direction to that in the ⟨111⟩ direction; the higher this ratio, the lesser the undercut in the ⟨111⟩ direction. Potassium hydroxide is an ideal choice as a wet etchant due to its selectivity of $S_{KOH} \approx 400$, favorable compared to other common anisotropic silicon etchants like ethylenediamine pyrocatechol ($S_{EDP} \approx 17$) and tetramethylammonium hydroxide ($S_{TMAH} \approx 37$). For the mask material, both silicon nitrate (Si_3N_4) or silicon dioxide (SiO_2) are good choices for KOH etchant, and may be deposited on the wafer via thin film deposition.

A modified equation describing the mask opening M_O while taking into account undercutting effects is

$$M_O = \left(\sqrt{2} - \frac{\sqrt{6}}{2S}\right) z \tag{7}$$

or equivalently,

$$M_O = \left(1.41 - \frac{1.22}{S}\right) z \tag{8}$$

The fabrication process begins with a blank ⟨100⟩ silicon wafer at least as thick as the desired height of each pyramidal facet (Fig. 5). A thin film of SiO_2 is then grown on the wafer via thermal oxidation (Fig. 6). An etch stop layer may also be deposited on the backside of the wafer. This is done to provide a durable mask layer through which KOH etching occurs. Because of the high etching rate of KOH, the photoresist cannot reasonably act as a robust etching mask. Alternatively, Si_3N_4 may be deposited onto the surface via plasma enhanced

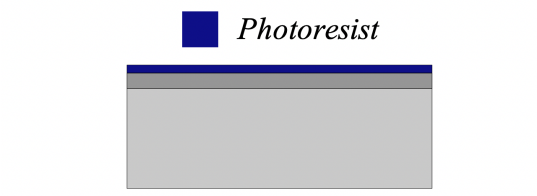

Fig. 7. Photoresist layer spincoated on oxide

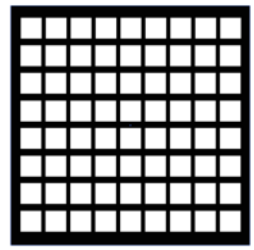

Fig. 8. Photomask for pyramidal truss tessellation

chemical vapor deposition (PECVD). A photoresist layer is then spin coated on top of the mask layer (Fig. 7). The mask used is patterned with squares of side length M_O; the spacing between each square hole is $2\delta_{uc}$ (Fig. 8). The photomask is then aligned on the wafer and the mask pattern transferred via photolithography. The wafer is developed (Fig. 9). Deep reactive ion etching (DRIE) is then used to etch through the mask layer and expose the underlying silicon layer, providing a durable channel through which etching may occur (Fig. 10). Diluted KOH is used to anisotropically etch the silicon *to completion,* timing the etching such that a pyramidal structure with a pointed vertex is formed in the negative space of the substrate (Fig. 11). Polypropylene fumarate (PPF) is then injected into the silicon mold and released to create the desired pyramidal truss microstructure (Fig. 12). The procedure outlined above creates facets with filled volume. Often times, shell facets are desired. This reduces the mass of the substrate, as well as

Fig. 9. Cross section of facet; exposed photoresist removed

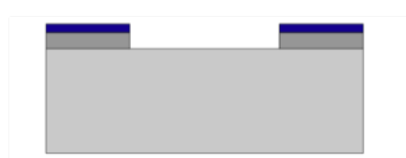

Fig. 10. DRIE through oxide layer

Fig. 11. Anisotropic etching

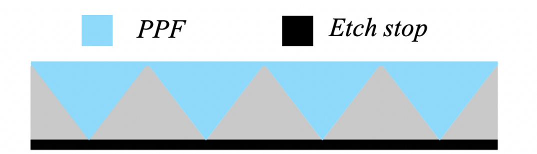

Fig. 12. PPF is deposited into negative mold

enables more in-plane bending capability, due to the various ways in which each facet may be deformed (Fig. 13). A negative silicon mold is created as before. Polysilicon is then deposited into the mold. Backside etching may then release the polysilicon from the underlying silicon substrate. The resulting positive mold may be used to press the PPF into the negative mold, creating a shell structure (Fig. 14). The rigidity of the shell structure may be controlled by the dimensions of the mask opening of the press mold.

B. Fitting Criterion

Tessellated surfaces should satisfy the fitting criterion given in [3], where the side length of each three-dimensional facet r is sufficiently small with respect to the radius of curvature R of the local surface being fitted. This fitting criterion imposes highly application-dependent constraints when creating tessellated substrates. For instance, applications at the macroscale, such as an EEG device that uses tessellated patterns to conform to a patient's head, seem realistically achievable. However, microscale applications such as conforming to the inner lining of a capillary may not be feasible to implement using this process, since it would be difficult to achieve feature sizes small enough to realize the fitting condition given in (3) at this scale. Anisotropic wet etching is inadequate to reliably produce features on the submicron order. By conservative estimates this process flow can produce tessellated facets with $r \approx 100\mu\text{m}$, sufficient to conform to features with $R \approx 1\text{mm}$. Fabrication processes for MEMS-based designs employing tessellated microstructures are limited by this fitting criterion.

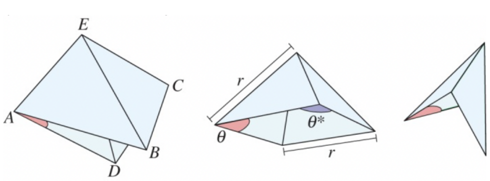

Fig. 13. Bending modes for pyramidal truss facet [3]

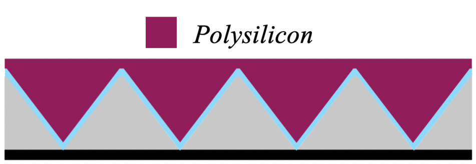

Fig. 14. Tessellated shell microstructure formed with press and negative molds

III. Auxetic Microstructures

Auxetic microstructures have many potential use cases in bioMEMS such as expanding microstructures that internally conform to cavities, and immediate applications in inertial MEMS sensors, where the simultaneous expansion of MEMS components in multiple axes given a single mechanical control input is often desired. Rigid auxetic microstructures have already been verified experimentally and shown to be compatible with existing nanofabrication processes [4].

Tessellations can enable flexible auxetic structures at the microscale through kirigami, a variant of origami whose primary operation is cutting instead of folding. In addition to providing biomimicry capabilities, such polymer-based microstructures retain substantial mechanical resilience [5] and can be implemented with biocompatible materials such as PPF. While the micromold design will differ, kirigami microstructures may be fabricated through conventional nanofabrication techniques using the process described here.

IV. Conclusion

The study of tessellated topologies is of particular interest to medical device designers and bioMEMS researchers, where close conformity to organic shapes is desired. Conventional flexible electronics often consist of MEMS sensors and ICs implemented on flexible printed circuits (FPC). Because FPCs have at least one null principal axis of curvature, they are unable to conform to simple non-developable surfaces such as a head, let alone more complex organic topologies. This fitting problem may be solved by corrugating a compliant substrate in a tessellated pattern. Specifically, the implementation of a pyramidal truss microstructure is achieved by exploiting the natural pyramidal indentations created by anisotropically etching silicon to completion. The fabrication processes proposed here is compatible with existing nanofabrication methods and can be used to create flexible microstructures which, depending on the mold design, can conform to organic surfaces and exhibit auxeticity.

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References

[1] Y. Zhao, Y. Endo, Y. Kanamori, and J. Mitani, “Approximating 3d surfaces using generalized waterbomb tessellations,” *Journal of Computational Design and Engineering*, vol. 5, no. 4, pp. 442–448, 2018.

[2] S. J. Callens and A. A. Zadpoor, “From flat sheets to curved geometries: Origami and kirigami approaches,” *Materials Today*, vol. 21, no. 3, pp. 241–264, 2018.

[3] H. Nassar, A. Lebée, and L. Monasse, “Curvature, metric and parametrization of origami tessellations: theory and application to the eggbox pattern,” *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences*, vol. 473, no. 2197, p. 20160705, 2017.

[4] V. Zega, A. Nastro, M. Ferrari, R. Ardito, V. Ferrari, and A. Corigliano, “Design, fabrication and experimental validation of a mems periodic auxetic structure,” *Smart Materials and Structures*, vol. 28, no. 9, p. 095011, 2019.

[5] M. Humood, J. Lefebvre, Y. Shi, M. Han, C. D. Fincher, M. Pharr, J. A. Rogers, and A. A. Polycarpou, “Fabrication and mechanical cycling of polymer microscale architectures for 3d mems sensors,” *Advanced Engineering Materials*, vol. 21, no. 3, p. 1801254, 2019.