

PARYLENE ORIGAMI STRUCTURE FOR INTROCULAR IMPLANTATION

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ABSTRACT

This paper presents the use of origami technique to construct a 3D spherical structure from a 2D parylene-C (PA-C) film with designed folding crease patterns. This origami technique is developed or intended for intraocular epiretinal implant application, which requires a “curved” electrode array to match the curvature of the macula. The folding method and process are described here using silicone oil as a temporary glue to hold the folded structures through meniscus force. The temporary origami is then thermally set into permanent 3D shapes at 100 °C for 30 minutes in vacuum utilizing parylene-C’s viscoelastic properties. The reported origami technique enables the possibility of first making an extended device in 2D format and, after a possible minimal surgical cut and insertion, then folding it into a 3D device inside the eye for necessary geometric matching with host tissues.

KEYWORDS

Origami, parylene-C, intraocular implantation

INTRODUCTION

Origami is an art of paper folding, which generates 3D structures from 2D paper. Recently this ancient paper folding art has been applied in Engineering. For examples, scientists have been exploring new folding methods to meet technological challenges for solar energy generation [1]. In the MEMS/NEMS field, researcher has proposed a self-folding cell origami, taking advantage of cell traction force (CTF) to fold flat microplates into diverse three-dimensional (3D) cell-laden microstructures [2]. Others came up with different ideas, including DNA origami [3], capillary origami [4], and origami using ion-induced plastic strain to achieve self-folding [5]. However, to form a perfect “spherical” origami structure with precisely controlled radius from a 2D film has been difficult and has not yet been demonstrated in MEMS/NEMS.

Here, this work presents our way of folding a fully-released 2D parylene-C thin film with a special folding crease patterns to a 3D spherical origami structure. Fig.1 shows the SEM image of the device. Our long-term goal is to achieve an origami retinal implant. Such an implant must fit the original curvature of the retina inside the eyeball (Fig.2) [6]. Therefore, the origami implant design enables the possibility of first making an extended device in 2D format and, after a possible minimal surgical cut and insertion, then folding it into a 3D device inside the eye for necessary geometric matching with host tissues. In this work, parylene-C is chosen to be the material for the

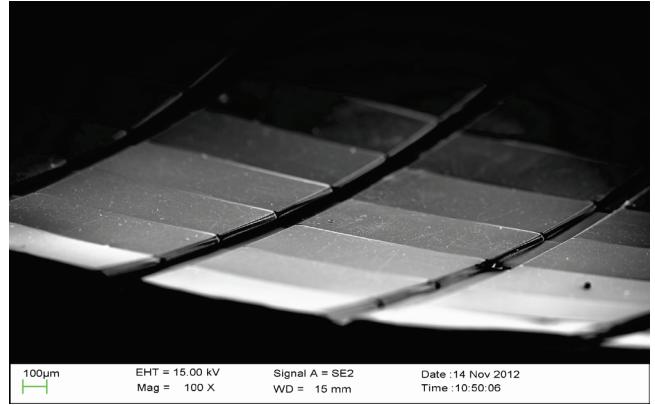


Fig.1: SEM image of parylene-C origami structure

origami structure. Due to its high biocompatibility, good mechanical strength and machinability, parylene-C has become a good candidate as the material for implantable devices. Recently, studies of parylene-C based retinal implantable devices have been reported for the treatment of age-related macular degeneration [7, 8]. This paper then reports the first 3D spherical PA-C origami folded from a 2D film with pre-designed folding crease patterns.

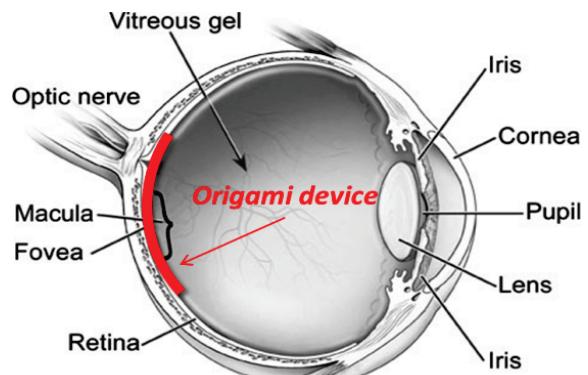


Fig.2: Origami device for intraocular implant: curvature needed to closely appose device to the retina

EXPERIMENTS

Design of the 2D Parylene-C Origami Film

As shown in Fig.3, the crease patterns consist of curved lines. Once folded along the curved lines with the right sequence, the designed 2D film can turn into a spherical structure. These crease lines are designed by mathematics and computer simulation. The simulation is run within a multi-objective optimization loop, which minimizes the contact pressure on the retina by changing parameters such as width and thickness of crease regions.

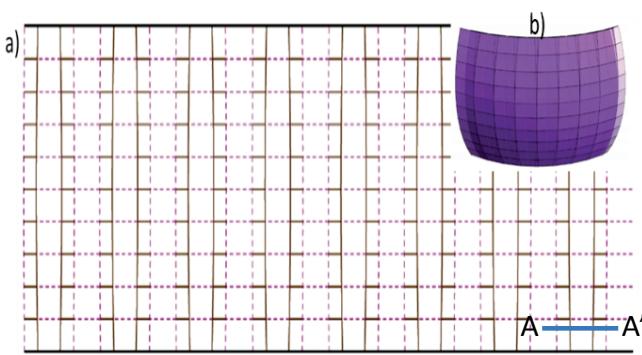


Fig.3: a) The crease pattern: crease lines are curved; b) conceptual model of final device

The extended 2D film is a 20- μm -thick PA-C film with 3- μm -thick crease region (i.e., Fig.4f). Since we need both convex fold and concave fold, the width of right crease region is set to be 30 μm (for concave fold), while the width of left crease region is set to be 10 μm (for convex fold). The left crease region folds in the opposite direction of the right crease region, forming a Z-shaped stack as shown from Fig.4f to Fig.4g.

Fabrication of the Parylene-C Origami Film

Fig.4 shows the fabrication process of the origami film. A 4-inch wafer is prepared for fabrication after piranha plus buffered hydrofluoric acid (BHF) cleaning, and then hexamethyldisilazane (HMDS) treatment respectively. A 17- μm -thick PA-C film is then deposited over the wafer (Fig.4a). Next, a 0.1 μm -thick aluminum (Al) is thermally evaporated over the PA-C and the photoresist to pattern Al as a plasma etching mask is exposed and developed (Fig.4b). Oxygen plasma (400W, 300mT) is used to etch through the openings on PA-C film all the way down to silicon surface (Fig.4c). The openings on the PA-C film define the crease lines. After removing Al etching mask in Al etchant (Fig.4d), another run of oxygen plasma (50W, 200mT, 1 minute) is used to roughen the surface of PA-C, followed by a 30-second BHF cleaning to make the surface hydrophobic. A final 3- μm -thick layer of PA-C is deposited over the device (Fig.4e). Finally, a dicing saw is used to cut the origami wafer into dies and the PA-C origami films are peeled off from silicon in DI water.

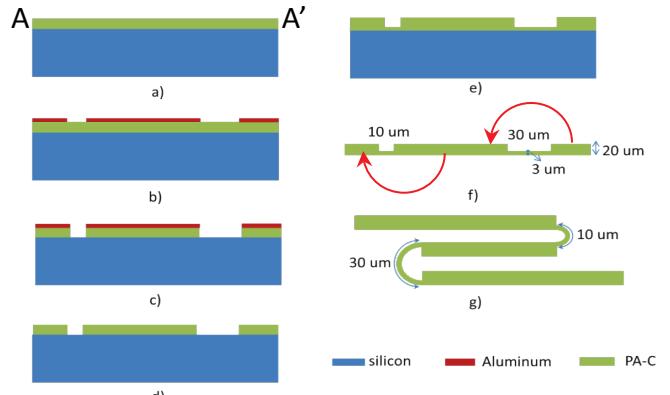


Fig.4: Fabrication process referring to the cross-sectional view of A-A' in Fig.3: a) deposition of 1st PA-C layer; b) Al patterning; c) oxygen plasma etching; d) getting rid of Al; e) deposition of the 2nd PA-C layer; f) Origami film separated from the silicon wafer; g) mechanical folding of the origami film. Note the difference between the convex and concave folds.

Folding Method and Process

The method and process of the parylene origami is presented here. The PA-C film is peeled off from the wafer and attached on a stainless steel ball (20 mm in diameter). To enable the attachment and the following folding, the ball surface is first covered with silicone oil. This silicone oil serves as a temporary glue to provide surface tension to allow the PA-C film to stick to the ball through meniscus force. Then a one-dimensional “tent” (with the apex to be a convex fold) is picked up from the film (Fig.5a). The segment on the left of the tent is then pushed inward as in Fig.5b and the convex fold is finished. Because of the silicone oil, the left part can be pushed inside easily, while the right segment remains unmoved. Then, the closed tent is tilted to the left side to finish the concave fold on the ball surface (Fig.5c). The process repeats itself until the whole origami film is folded. Fig.6a shows the origami structure before and after folding. In fig.6b, spherical origami device (A) is compared to PA-C film without crease patterns folded onto a ball (B). (A) can fit the surface curvature precisely while (B) cannot. Wrinkles and bad contacts with the ball surface can be observed on (B).

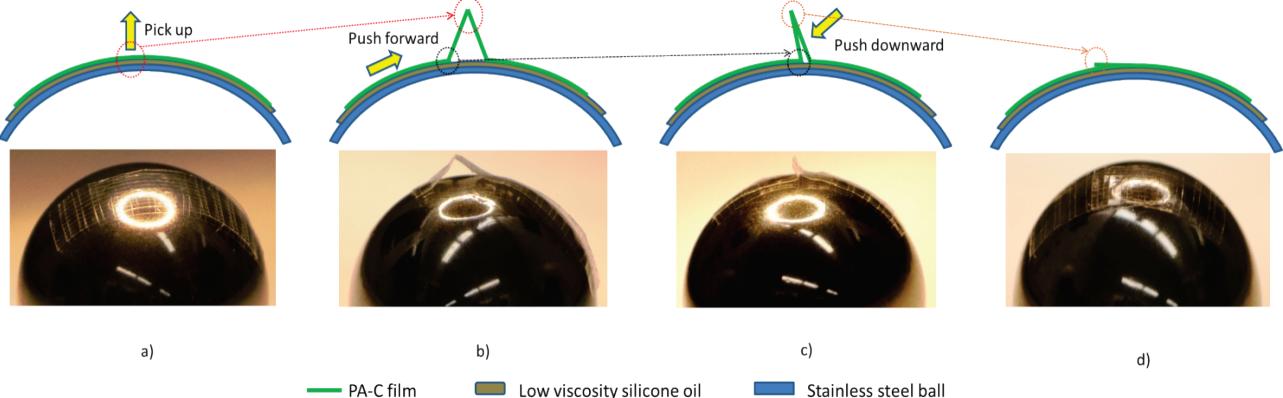


Fig.5: The folding process: a) start a segment with a convex fold on the right; b) form a tent by pushing the left part to the right while the right part stays unmoved; c) tilt the squeezed tent to left on the ball surface

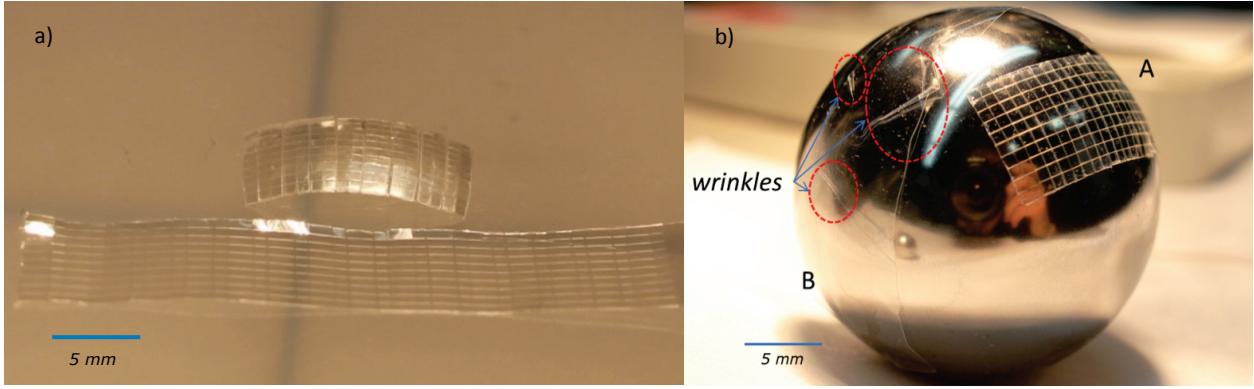


Fig.6: a) spherical parylene-C structure after folding (top) and 2D patterned parylene-C film before folding (bottom); b) A and B have the same dimensions in 2D. A has crease pattern while B does not. When folded to sphere surface, A can fit the surface curvature precisely while B cannot

Thermal Fixation of the Folded Origami

After folding, the silicone oil can only hold the folded origami temporarily. We then use thermal annealing to achieve the fixation of the folded origami. The glass transition temperature (T_g) for as-deposited PA-C is 50°C and viscoelasticity happens to fix the shape when $T > T_g$ [9]. However, high temperature annealing larger than 100°C in air makes PA-C brittle. Thus tensile tests of parylene-C stripes after various annealing conditions have been done to determine the suitable temperature of thermal annealing. DMA (dynamic mechanical analysis) Q 800 from TA Instruments is used for the tensile tests. Fig.7 presents DMA setup for tensile test of PA-C film. Procedures are described as follows. First, raise the environment temperature to 37°C; maintain isothermal for 30 minutes; finally ramp the strain at 0.5%/minute up to 250% (PA-C samples break before reaching 250% elongation). Fig.8 shows the nominal stress/strain curves of PA-C films annealed at different temperatures (as-deposited, 100°C, 150°C and 200°C) for 30 minutes. The sample annealed at 100°C shows 76.3% elongation, while 150°C and 200°C show 10.1% and 2.5%, respectively. Therefore, PA-C films annealed at 150°C and 200°C become too brittle. Considering stretching and bending in practical surgery process, 100 °C annealing is appropriate. In addition, since the time constant of PA-C crystallization is shorter than 1 minute [10], so a 30 minutes thermal annealing is sufficient. Therefore, all our folded origami devices are annealed at 100 °C for 30 minutes in vacuum. There is no damage to the silicone oil we used and it can be easily removed using organic solvents such as acetone.

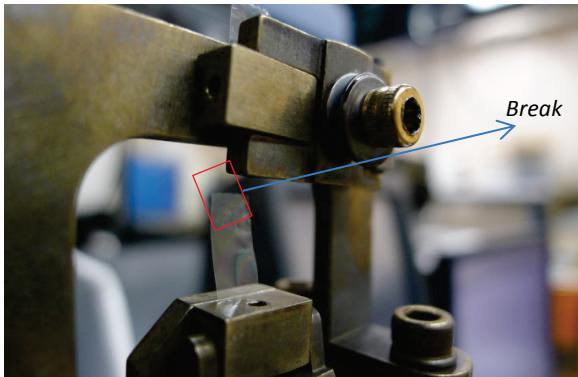


Fig.7: DMA setup for tensile test of PA-C film. Shown in the figure is a 200°C pre-annealed sample but broken after the tensile test.

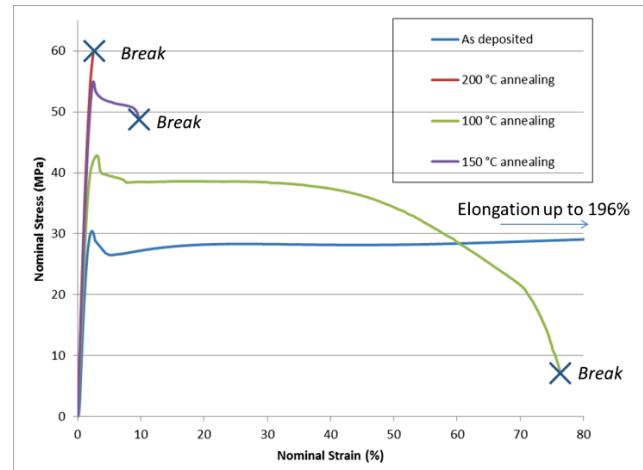


Fig.8: Tensile test at 37 °C to choose annealing temperature: 100, 150, 200 °C annealed samples (for 30 minutes) show 76.3%, 10.1%, 2.5% elongation respectively. Considering stretching and bending in practical surgery process, 100 °C is appropriate.

CONCLUSION

An origami technique to construct a 3D spherical structure from a 2D parylene-C (PA-C) film with designed folding crease patterns is presented. This origami technique includes design, folding and fixation to complete final origami devices. The reported origami technique enables the possibility of first making an extended device in 2D format and then folding it into a 3D device. In our case, this new origami technique is intended for retinal implant application that requires a curved electrode array. This technique, however, can also be applied to other applications.

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REFERENCES

- [1] M. Bernardi, N. Ferralis, Jin H. Wan, R. Villalon, Jeffrey C. Grossman, "Solar energy generation in three dimensions", *Energy Environ. Sci.*, vol. 5, pp. 6880-6884, 2012.
- [2] Kurabayashi-Shigetomi, K., H. Onoe, S. Takeuchi, "Self-folding cell origami: Batch process of self-folding 3d cell-laden microstructures actuated by cell traction force", in *Micro Electro Mechanical Systems (MEMS), 2012 IEEE 25th International Conference*, Paris, January 29-Feberary 2, pp. 72-75, 2012.
- [3] H. T. Maune, S. Han, R. D. Barish, M. Bockrath, W. A. Goddard, P. W. K. Rothemund, E. Winfree, "Self-assembly of carbon nanotubes into two-dimensional geometries using DNA origami templates", *Nature Nanotechnology*, vol. 5, pp. 61-66, 2010.
- [4] C. Py, P. Reverdy, L. Doppler, J. Bico, B. Roman, C. N. Baroud, "Capillary Origami: Spontaneous Wrapping of a Droplet with an Elastic Sheet", *Phys. Rev. Lett.*, vol. 98, pp. 156103, 2007.
- [5] K. Chalapat, N. Chekurov, H. Jiang, J. Li, B. Parviz, G. S. Paraoanu, "Self-Organized Origami Structures via Ion-Induced Plastic Strain", *J. Adv. Mater.*, vol.25, pp. 91-95, 2013.
- [6] J. H. Chang, Huang, R., Y.C. Tai, "High Density 256-Channel Chip Integration with Flexible Parylene Pocket", in *Digest Tech. Papers Transducers'11 Conference*, Beijing, June 5-9, 2011, pp. 390-393.
- [7] B. Lu, Z. Liu, L. Liu, D. Zhu, D. Hinton, M.S. Humayun, Y.C. Tai, "Semipermeable parylene membrane as an artificial Bruch's membrane", in *Digest Tech. Papers Transducers'11 Conference*, Beijing, June 5-9, 2011, pp. 950-953.
- [8] B. Lu, D. Zhu, D. Hinton, M.S. Humayun, Y.C. Tai, "Mesh-supported submicron parylene-C membranes for culturing retinal pigment epithelial cells", *Biomedical Microdevices*, vol. 14, pp. 659-667, 2012.
- [9] J.C.-H. Lin, P. Deng, G. Lam, B. Lu, Y-k Lee, Y.C. Tai, "Creep of Parylene-C Film", in *Digest Tech. Papers Transducers'11 Conference*, Beijing, June 5-9, 2011, pp. 2698-2701.
- [10] J.C.-H. Lin, "MEMS for glaucoma", Dissertation (Ph.D.), California Institute of Technology, 2012.

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