THERMOFORMING OF PARYLENE C TO FORM HELICAL STRUCTURES

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ABSTRACT

Microfabricated, thin film, Parylene C helices down to a 0.25 mm diameter were achieved using a post-fabrication thermoforming process. This overcomes the planar configuration imposed by MEMS fabrication techniques. By utilizing a thermoplastic, Parylene C backbone, planar devices can be fixtured into a desired 3D geometry and thermoformed, permanently transforming the device into the fixtured shape. This work characterizes the thermoforming process and necessary parameters to achieve 0.25 to 2.6 mm diameter helices in bare Parylene strips and microfabricated Parylene and metal devices without insulation (Parylene) or electrical (metal) failure.

KEYWORDS

Parylene C, thermoforming, three-dimensional, fabrication.

INTRODUCTION

Microfabrication can be used to build complex MEMS devices on a flat substrate. These planar devices can be assembled into 3D structures via stacking or linkages, however biomedical applications often require more complex 3D geometries to produce seamless, intimate interfaces with anatomical features. By using flexible polymer substrates instead of a traditional silicon backbone, planar, thin film, microfabricated devices can be transformed into intricate 3D geometries through post-processing, achieving a conformation matching the targeted and surrounding tissue and thereby minimizing the body's immune response to implanted devices [1].

Several polymers are compatible with existing microfabrication techniques (the most common of which are polydimethylsiloxane (PDMS), polyimide, and Parylene C) and are significantly less stiff than silicon, resulting in flexible devices that can be transformed from a planar formation into 3D shapes. Parylene C (here on referred to as Parylene) is particularly useful due to its thermoplasticity, which allows it to be transformed permanently into complex geometries by thermoforming against a template [1]. PDMS and polyimide are thermoset polymers, so their shape cannot be easily modified; non-planar structures fabricated using these materials are achieved by attachment to a supporting structure or plastic deformation [2]–[5] (which can damage the device).

Thermoforming is performed by fixturing a Parylene film or microfabricated device into a desired shape and heating it above the glass transition temperature (approximately 60-90 °C [1], [6], [7]), which softens the amorphous regions of the polymer while the film is still in a solid state. As the film cools back to room temperature it re-hardens and more crystalline regions form, holding the Parylene permanently in the fixtured shape and increasing the stiffness and insulative properties [1].

Parylene is commonly used in microfabricated medical devices, with most devices consisting of multiple layers of Parylene and metal to form sensors, electrodes, or microfluidic channels. Several thermoformed Parylene devices have been developed to match anatomical features, to provide mechanical strain relief, or to form a mechanical anchor to interface with another device (Table 1). One of the most common and useful geometries is a helix, which can be used for strain relief, to interface with features such as nerves, muscle fibers, and blood vessels, or can be mounted on cylindrical supports (such as catheters, stents, or probes) to produce "smart" devices.

Table 1: Examples of microfabricated Parylene medical devices formed into 3D geometries via thermoforming.

Device	Curvature Shape	Curvature Diameter
This work	Helix	0.25-2.6 mm
Cable strain relief [1], [8]	Helix	1.1-5 mm
Cuff electrode [9]	Tube	3 mm
Retinal electrode array [1], [10], [11]	Sphere section	5 mm
Retinal electrode array [12]	Cylinder section	1 mm
Penetrating cortical electrode array [1], [11]	Cylinder or cone (between Parylene layers)	0.25 mm

An evaluation of the design space for thermoformed helices (and other shapes) is presented towards enabling novel device geometries. The smallest Parylene helix reported in literature is 1.1 mm in diameter [8]. The smallest thermoformed Parylene feature reported is a 0.25 mm cylinder on a Parylene-metal-Parylene electrode array, however features at this size exhibited cracking in both the Parylene and metal layers, rendering the device non-functional [1], [7]. This work describes a method for thermoforming Parylene helices down to 0.25 mm (a 4× improvement) while maintaining electrical conductivity in the metal layer of a Parylene-metal-Parylene device.

MATERIALS AND METHODS

Bare Parylene Helix Fabrication

Bare Parylene strips of varying thickness were fabricated and thermoformed into 0.25, 1.6, and 2.6 mm diameter helices. First, Parylene was deposited via chemical vapor deposition (CVD) onto a bare 4" silicon wafer. For some wafers, a second coat of Parylene was deposited using the same procedure (after breaking vacuum, removing the samples, and re-loading the samples) to produce thicker layers and/or to evaluate the effects of multi-layered Parylene. Thicknesses of 5.4 to 26.3 μm were achieved by varying the amount of dimer loaded into the machine and the number of coating runs.

After Parylene was deposited, the film was removed from the wafer by cutting around the edge of the wafer with a scalpel and peeling the film off the wafer surface. The

freed film was then cut into strips (300 µm width by 20 mm length) using a cutting plotter.

Cut Parylene strips were fixtured into a helical shape by wrapping around a stainless steel mandrel and held in place using non-adhesive, 10 µm thick Teflon tape. Parylene strips with two layers were tested wrapping in both directions (i.e., one sample with the base Parylene layer towards the inside of the helix, and a second sample with the base Parylene layer towards the outside of the helix). Helix diameter (0.25, 1.6, 2.6 mm) was defined by the mandrel and helix angle (angle between the axis of the helix and the long edge of the Parylene strip, Figure 2; 15°, 30°, 45°) was imposed by using a template.

After fixturing, parts were baked at 200 °C (~0.7 °C/min ramp) for 12 hours under vacuum in a programmable oven. After cooling to room temperature, parts were removed from the oven and separated from the mandrel. Some samples were also thermoformed at 100 and 150 °C using the same method to determine the impact of lower temperature thermoforming.

The resulting Parylene helices were visually inspected using a microscope for their ability to retain the desired helical shape/size and for cracking failure in the Parylene.

Parylene-Metal-Parylene Helix Fabrication

After optimizing the thermoforming method on bare Parylene strips, devices with a functional metal layer were evaluated. Three-layer devices were fabricated, with a base Parylene layer, a metal layer patterned with electrodes on one end, bondpads on the other end, and traces connecting each electrode to a single bondpad, and a top Parylene layer with etched openings to expose the metal bondpads and electrodes. Two groups of devices were fabricated, one with asymmetric Parylene layers (layers of different thicknesses) and one with symmetric Parylene layers.

Parylene-metal-Parylene (PMP) devices were fabricated by first depositing a base Parylene layer (3.4 µm thickness for the asymmetric group, 4.4 µm for the symmetric group) via CVD onto a bare 4" silicon wafer (Figure 1A). In the symmetric group only, the base Parylene layer was annealed under vacuum with nitrogen flow at 150 °C for 4 hours (which causes minor shrinkage (<2%) of the Parylene [1]). Next, 15 nm titanium and 200 nm platinum were deposited via e-beam evaporation and patterned into electrodes, traces, and bondpads using a lift-off technique (Figure 1B). A top Parylene layer (11.5 µm for the asymmetric group, 4.7 µm for the symmetric group) was deposited via CVD. Openings in the top Parylene for exposed metal electrodes and bondpads were etched using O_2 reactive ion etching and the outer edge of the device (through both Parylene layers) was etched using the same method (Figure 1C). Devices were manually released from the wafer using water and tweezers (Figure 1D).

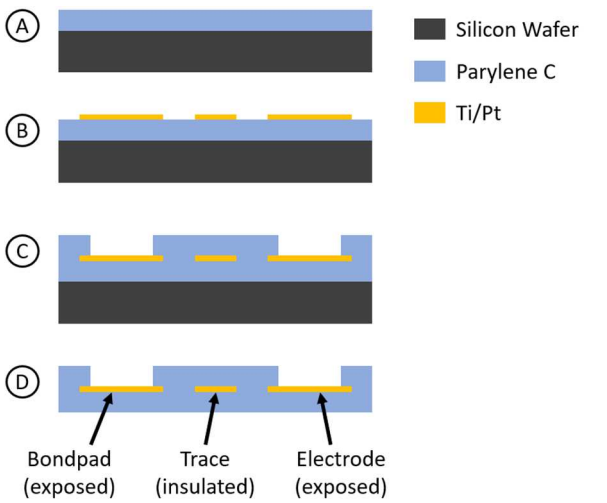

Figure 1: Fabrication process flow for Parylene-metal-Parylene devices.

Released devices were thermoformed into 1.6 and 0.25 mm helices (Figure 2) at a 45° helix angle using the same thermoforming method as was used for bare Parylene strips. PMP helices were visually inspected for their ability to retain the desired helical shape/size and for cracking failure in the Parylene and electrically tested for continuity between the exposed bondpads and electrodes using an LCR meter before and after thermoforming.

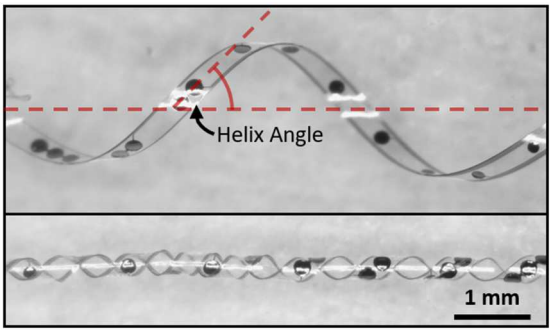

Figure 2: Photos of (top) 1.6 mm and (bottom) 0.25 mm Parylene-metal-Parylene device helices.

RESULTS AND DISCUSSION

Bare Parylene Helices

In bare Parylene strips thermoformed into 1.6 or 2.6 mm diameter helices, no cracking was observed at any thickness. In 0.25 mm helices, thinner Parylene strips (≤11.1 µm thickness) exhibited no cracking (Figure 3A) or minor cracking (cracks not spanning the full film thickness; Figure 3B). The thinnest samples (5.6 µm thick) did not exhibit any cracking at either helix angle, while thicker samples (9.9 and 11.1 µm thicknesses) yielded minor cracking in some samples. All thicker samples (≥13.3 µm thickness) exhibited full thickness cracking (Figure 3C) at all helix angles. Number of Parylene layers and uneven layer thicknesses did not impact shape retention or cracking of bare Parylene strips.

Parylene strips thermoformed at a 30° or 45° helix angle held the desired shape at all helix diameters (except for one outlier), while several parts formed at a 15° helix angle did not. Loose helix shape (Figure 3D) was not correlated to Parylene thickness or helix diameter, suggesting a fixturing issue (i.e., more difficulty wrapping Parylene strips around the mandrel at a 15° helix angle).

These results demonstrate that Parylene thickness must be considered when thermoforming to smaller helix diameters (thin Parylene is less likely to crack but is fragile and requires careful handling). When thermoforming to a larger diameter, thicker Parylene can be safely used without cracking failure. When producing helices with

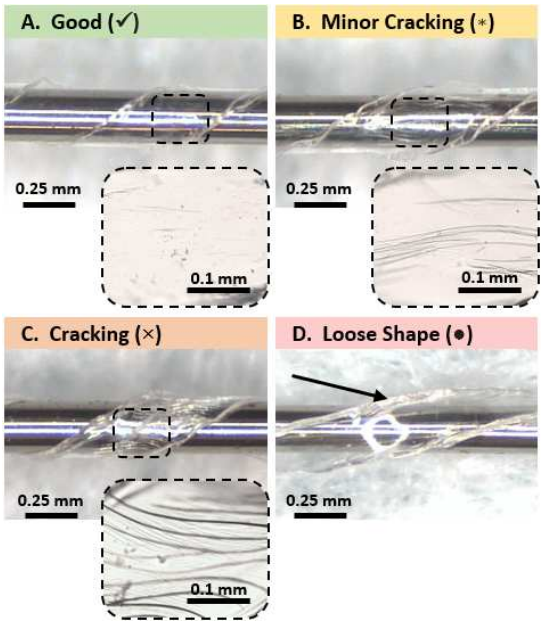

Figure 3: Examples of bare Parylene strips thermoformed into 0.25 mm helices, showing (A) a good result, (B) minor (partial-thickness) cracking, (C) cracking, and (D) loose shape, with detailed views of good and cracked Parylene.

small angles, devices should be tightly fixtured to ensure the desired shape is achieved.

Thermoforming tests were repeated on Parylene strips of 13.3 µm (single layer) and 18.5 µm (two asymmetric layers) thickness at 100 and 150 °C. Temperature did not impact the results at any helix diameter or angle. Full results for bare Parylene strip thermoforming are summarized in Table 2.

Parylene-Metal-Parylene Helices

PMP devices exhibited similar cracking results to bare Parylene strips: no cracking (Figure 4A) at 1.6 mm helix diameter, no cracking or minor cracking (Figure 4B) in thin devices (9.1 µm total thickness) at 0.25 mm helix diameter, and cracking (Figure 4C) in thick devices (14.9 µm total thickness) at 0.25 mm helix diameter. In thin/symmetric devices when the pre-annealed base Parylene layer was oriented to the inside of the helix, most regions of the device exhibited no cracking, with minor cracking visible in some areas. Thin/symmetric devices were curled towards the base layer when released off the carrier wafer due to pre-shrinkage of the base Parylene. This natural curvature likely alleviated bending stress in the Parylene during fixturing, leading to minor cracking only in localized areas on the device.

All traces were conductive between bondpads and electrodes when thermoformed to 1.6 mm diameter. Trace continuity was maintained in thin/symmetric devices thermoformed with the pre-shrunk base layer towards the inside of the helix. All other devices had discontinuous traces after thermoforming to 0.25 mm diameter.

Thin/symmetric devices did not retain the desired shape in some areas when formed into 1.6 mm helices, likely due to the high-stress interposing metal layer (centered in the device when symmetric Parylene layers are used, or off-center when asymmetric Parylene layers are used). Thick/asymmetric devices formed to the desired shape at all diameters, and thin/symmetric devices formed to the desired shape at 0.25 mm diameter. Thicker Parylene layers can counteract the forces in the metal film more effectively (and thus are more likely to hold the desired thermoformed shape).

Thermoforming tests were repeated on thin/symmetric PMP devices (9.1 µm total thickness, formed in both directions) at 100 and 150 °C. Temperature did not impact the results at either diameter. Full results for PMP device thermoforming are summarized in Table 3.

CONCLUSION

Microfabricated Parylene devices are most commonly in a planar configuration. Biomedical devices, however, benefit from a 3D structure that can more closely interface with complex anatomical features. By utilizing thermoforming, intricate, Parylene-based, planar devices can be transformed into 3D geometries.

The thermoforming method described here produces mm- and sub mm- sized helices (0.25 to 2.6 mm diameter)

Table 2: Thermoforming results over varying thicknesses, helix angles, and helix diameters for bare Parylene strips treated at 200 °C for12 hours.

✓ *good result*	∗ *minor cracking*	× *cracking*	● *loose shape*

Parylene Thickness (µm)			30°, 45° Helix Angle Helix Diameter (mm)			15° Helix Angle Helix Diameter (mm)		
Inner Layer	**Outer Layer**	**Total**	**2.6**	**1.6**	**0.25**	**2.6**	**1.6**	**0.25**
5.6	n/a	5.6[1]	✓	✓	✓	✓	✓	✓
9.9	n/a	9.9[1]	✓	✓	∗	●	✓	∗
5.5	5.6	11.1	✓	✓	∗	●	●	✓
13.3	n/a	13.3[2]	✓	✓	×	✓	✓	×
5.3	13.2	18.5[1,2]	✓	✓	×	●	●	×
13.2	5.3	18.5[1,2]	✓	✓	×	●	✓	× ●
20.9	n/a	20.9[1]	✓	✓	×	●	✓	×
5.4	20.4	25.8	✓	✓	× ●	✓	✓	× ●
20.4	5.4	25.8	✓	✓	×	✓	✓	∗ ●
11.9	14.4	26.3[1]	✓	✓	×	✓	✓	× ●
14.4	11.9	26.3[1]	✓	✓	×	●	●	×

[1] *Only the indicated parts were tested at a 30° helix angle (all parts were tested at 15° and 45°).*
[2] *Indicated parts were also tested at 100 and 150 °C thermoforming temperature; temperature did not impact results.*

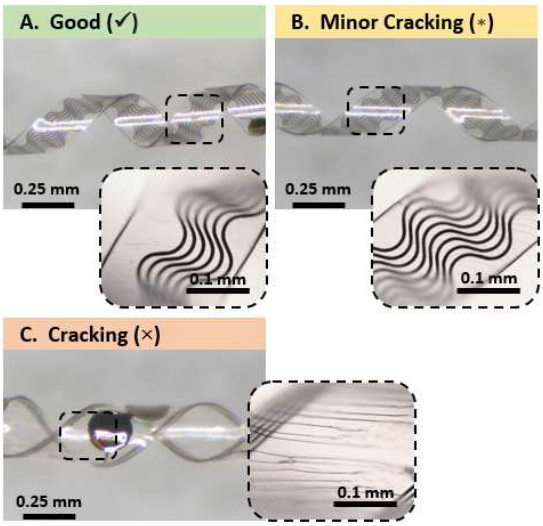

Figure 4: Examples of PMP devices thermoformed into 0.25 mm helices, showing (A) a good result, (B) minor (partial-thickness) cracking, and (C) cracking, with detailed views of good and cracked Parylene

Table 3: Thermoforming result for varying thicknesses and helix diameters for PMP devices at 45° helix angle and treated at 200 °C for 12 hours.

✓ *good result*	∗ *minor cracking*
× *cracking*	● *loose shape*

Parylene Thickness (µm)			Helix Diameter (mm)			
Inner Layer	Outer Layer	Total	1.6		0.25	
4.4[1]	4.7	9.1[2]	✓	●	✓	∗[3]
4.7	4.4[1]	9.1[2]	✓	●	∗	–
3.4	11.5	14.9	✓		×	–
11.5	3.4	14.9	✓		×	–

[1] *4.4 µm layer was deposited and annealed (150 °C, 4 hours) before adding metal and top Parylene.*
[2] *Indicated parts were also tested at 100 and 150 °C; temperature did not impact results.*
[3] *Most regions had no cracking; some minor cracking was visible in a few areas.*

from microfabricated Parylene films and devices, a 4× improvement from prior published work. When thermoforming into small helices (0.25 mm diameter), thin Parylene must be used to prevent cracking failure. Devices with interposing metal layers are sometimes unable to hold the desired shape due to high film stress in the metal, however thicker Parylene can more effectively overcome the metal stress and hold the desired shape.

More work is necessary to elucidate the relationship between Parylene thickness, film stress, and thermoforming process parameters on PMP devices. In addition, device regions with exposed metal (such as electrode sites, where Parylene is selectively removed) must be evaluated to determine the impact of large, unbalanced stress on thermoforming capability.

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