33rd Annual International Conference of the IEEE EMBS
Boston, Massachusetts USA, August 30 - September 3, 2011

Mechanical Characterization of Neural Electrodes based on PDMS-Parylene C-PDMS Sandwiched System

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***Abstract*—Manufacturing of neural electrodes based on metal foil and silicone rubber using a laser is a simple and promising method. A handicap of such electrode arrays is the mechanical robustness of the thin metal tracks that connect the electrode sites with the interconnection pads. Embedding of structured parylene C foil in silicone rubber turned out to be an interesting method to increase the robustness. Test samples with 12.5 µm thick platinum tracks and a 15 µm thick embedded and RIE-structured parylene C foil showed more than 800 % higher ultimate strength until breakage of the tracks. Different structured parylene C foil showed increasing robustness with increasing hole-spacing.**

I. Introduction

Neural interfaces, more precisely electrocorticography (ECoG) electrodes, have a wide range of medical applications. They can be used for presurgical epilepsy monitoring, as aid for tumor resections or for providing brain-computer interfaces [1]. A manufacturing technology for electrodes with a high spatial resolution based on laser structuring was first described by Schuettler et al. in 2005, using exclusively medical grade silicone rubber (PDMS) as insulation material and metal foil as electrode material [2]. To get a high spatial resolution the laser method allows us manufacturing electrode tracks of 12.5 µm platinum foil with a pitch down to 80 µm [3].

A disadvantage of small metal foil structures embedded in flexible silicone rubber is the mechanical robustness and flexibility, which is required for several medical applications. In order to increase the flexibility of an electrode array, the tracks can be meander-shaped. However, this increased flexibility compromises the mechanical robustness [4]-[6]. Regarding mechanical forces, standards for as far as possible similar medical devices like the cochlear implant demands for the leads to withstand tensile forces of minimum 1 N [7]. Cables of cardiac pacemakers have to withstand tensile forces of 5 N [8].

For increasing the mechanical robustness an option is to embed a thin and stable polymer foil in a sandwiched-like way between to layers of silicone rubber. As material we selected parylene C because of the excellent biocompatibility properties [9], the mechanical robustness and the transparency of thin foils. Furthermore, it can be easily integrated into the existing manufacturing and sterilization process [10], [11]. Perforations in the parylene C foil should enable mechanical interlocking in the silicone-parylene C-silicone sandwich system since chemical bond between parylene C and silicone rubber is weak [11].

This paper describes the fabrication process of parylene C-stabilized electrode test samples and the investigation of the mechanical robustness of different parylene C layer layouts and the electrode materials platinum and MP35N (CoNiCrMo) via pull tests.

II. Materials And Methods

A. Parylene C foil Layout and Fabrication Process

The design and fabrication of the parylene C foil seem to be the most crucial points on the way to reach higher mechanical robustness. For all test samples 15 µm thick layers of parylene C were deposited at a deposition pressure of 20 mTorr with a PDS 2010 LAB-COTER™, using DPX-C as dimer (both Speciality Coating Systems, Indianapolis) according to the standard Gorham process [12]. As substrate we used silicon wafers from which the parylene C can be peeled off easily afterwards.

The patterning of the parylene C layers was realized in two different ways: a 1064 nm Nd:YAG marking laser (DPLGenesisMarker by cab, Karlsruhe, Germany), the same laser as used for the electrode fabrication process; and by reactive ion etching (RIE) in oxygen plasma using the RIE Multiplex (Surface Technology-Systems, Newport, England). The masking was realized by a standard photo-lithography process. Avoiding stress peaks in the parylene C foil, round perforations in a hexagonal arrangement were patterned.

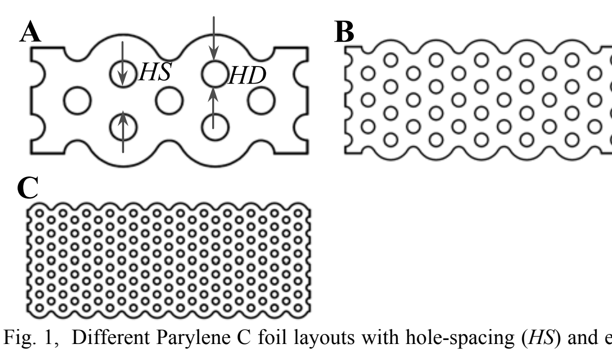

Fig. 1, Different Parylene C foil layouts with hole-spacing (*HS*) and equal hole diameters (*HD*) of: **A**: 2 mm , **B**: 1 mm, **C**: 0.5 mm.

Manuscript received April 15, 2011. This work was supported in part by the German Federal Ministry of Education and Research (BMBF Grant: ExistGo Bio 01GQ0830 to BFNT Freiburg/Tübingen).
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Since it was not clear which perforation density would be provide the best robustness, three different layouts were created with hole-spacing *HS* and hole diameter *HD* = *HS* of 2 mm, 1 mm and 0.5 mm (Fig 1). As last step of the fabrication process the patterned foils were peeled off the silicon wafer substrate using tweezers.

B. Metal Track Design

As materials for the metal tracks 25 µm thick MP35N foil (Hamilton Precision Metals, Lancaster, Pennsylvania, USA) and 12.5 µm thick platinum foil (Goodfellow Cambridge Ltd, Huntington, UK) was chosen. The track structures were designed in a meander-shaped structure with an opening angle $\theta = 60°$ and a radius/width (r/w) ratio of 3 for all samples [6]. The MP35N tracks had a width of w = 150 µm and the platinum foil a width of w = 70 µm (Fig 2).

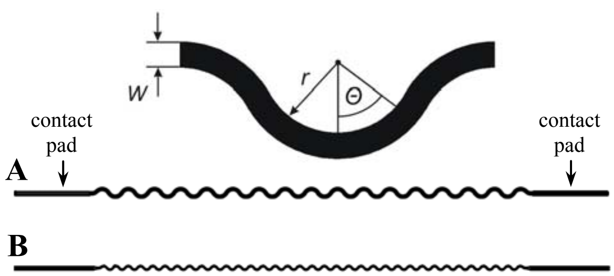

Fig. 2, Two different metal track layouts and materials. **A**: MP35N foil with a width (w) = 150µm. **B**: Platinum foil with a width (w) = 70µm.

C. Sample Fabrication Process

The sample fabrication process steps are basically described in [6]. Here, an additional layer of structured parylene C foil and silicone rubber was set in.

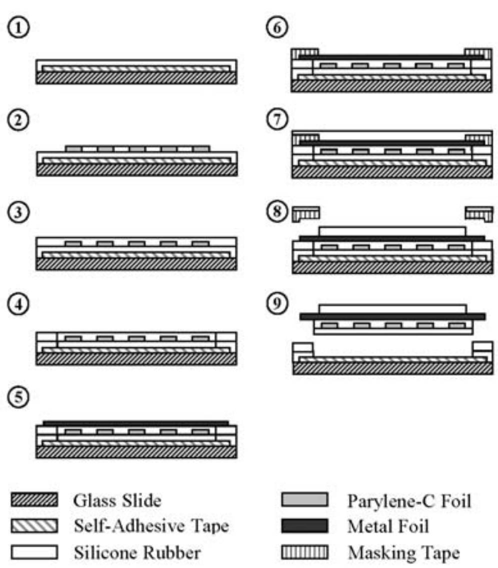

Fig. 3, Fabrication process steps for PDMS-embedded parylene C foil and metal tracks.

As carrier a microscope glass slide was used. Self-adhesive tape (No. 4124 by tesa AG, Hamburg, Germany) was laminated on top of the glass slide acting as release layer. A first layer of silicone rubber MED-1000 (NuSil, Carpinteria, USA) was spin-coated, diluted with n-heptane in a volume ratio of 1:1 (Fig. 3-1). Further, the pre-processed parylene C foil was laminated (Fig. 3-2) and embedded with a second layer of spin-coated silicone rubber (Fig. 3-3). Preparing the contact pads for a free-standing structure, the silicone rubber was cut with the marking-laser (Fig. 3-4). The metal foil was laminated and structured with the laser as described in section *B* (Fig. 3-5). Tape (type 5413 Kapton® Tape, 3M, Neuss, Germany) is laminated to mask the future contact pads (Fig. 3-6). The last layer of diluted silicone rubber was spin-coated (Fig. 3-7), and the masking tape was manually removed, locally lifting off the covering silicone (Fig. 3-8). After curing of the silicone rubber and laser-cutting of the boundary, the test sample was removed from the carrier (Fig.3-9).

All samples had just one metal track. Also samples without parylene C were fabricated, exactly the same process only without step 3-2.

Both contact pads were soldered to copper-clad printed circuit boards (PCBs), and fixed with epoxy adhesive in order to protect the gap between parylene C foil and solder point. All samples were steam sterilized using the SUPERIOR B23 autoclave (Mammooth, Bibbiano, Italy) at 134°C and a pressure of 2.06 bars for 20 minutes (prion-program).

The fabricated test samples and the layout and material combinations are shown in Table. 1. For each combination five test samples were manufactured.

TABLE I
SAMPLE AND MATERIAL COMBINATIONS

Parylene C structuring	Hole-Spacing	Material
without parylene C	--	MP35N
without parylene C	--	Platinum
Laser	2 mm	MP35N
Laser	2 mm	Platinum
RIE	2 mm	MP35N
RIE	2 mm	Platinum
Laser	1 mm	Platinum
RIE	1 mm	Platinum
Laser	0.5 mm	Platinum
RIE	0.5 mm	Platinum

D. Pull Test

The pull tests were carried out using a bond tester (type 4000 with WP10kg measurement cartridge, Dage, Aylesbury, Buckinghamshire, UK). The samples were stretched with a velocity of 50 µm/s while recording force and elongation *L*. Using a four-wire setup, the electrical resistance of the metal track was monitored during the stretch process with a sample rate of 10 Hz, and afterwards low pass filtered (100 measurement points window). The yield strength was calculated at 102 % of the initial value of the averaged resistance. The ultimate strength was calculated at the breakage of the track when a resistance larger than 10 MΩ was measured.

III. RESULTS

Regarding the fabrication of the parylene C foil, RIE-etching showed excellent cut quality. Laser-structuring of parylene C could be easily integrated in the existing manufacturing infrastructure, but the cut quality was worse (Fig. 4). The parylene C was melted by the laser beam on a cut width of 130 µm and had irregular cut edges.

A test sample with MP35N and laser-structured parylene C foil with 2 mm hole-spacing is shown in Fig. 5. It is assembled to the PCBs and the resistance measurement system and ready for the pull test. The layer thickness was about 270 µm for all samples.

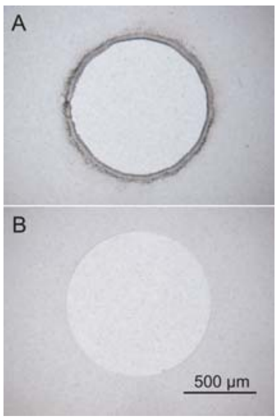

Fig. 4, Structured parylene C foil. **A**: laser-structured; **B**: RIE-etched.

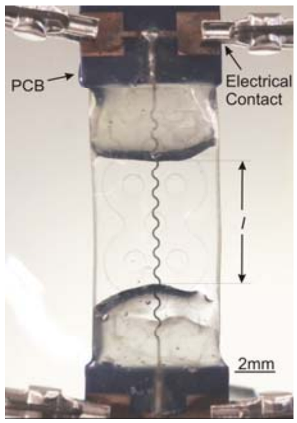

Fig. 5, Fabrication process steps for PDMS-embedded parylene C foil and metal tracks.

A typical pull test measurement for a platinum foil sample without an embedded parylene C foil is shown in Fig. 6. It shows the measured force over the strain *L*/*l* in %, and the measured and averaged resistance. Every peak in the force graph illustrates a breakage of the platinum metal track. 3.7 ohm was detected as 2 % increase of the low pass filtered resistance at a force of 398 mN (yield strength) and a strain of 18.5 %. The first breakage was measured at a force of 546 mN (ultimate strength) and a strain of 24.3 %. A calculation of the yield strength at samples with parylene C foil was not possible. The resistance-change was always below 2 % until breakage.

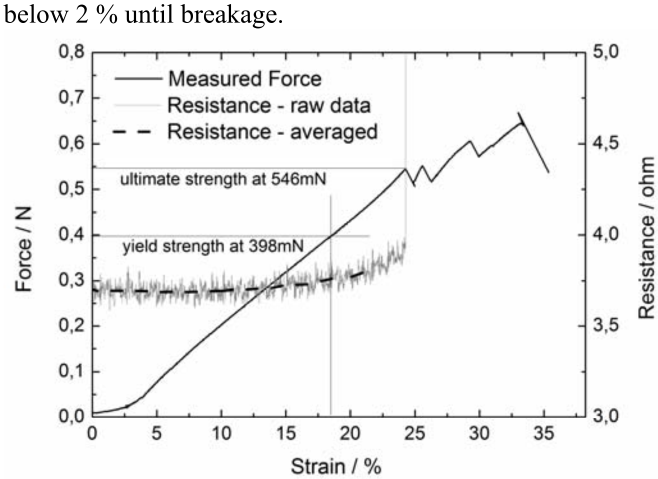

Fig. 6: Force–Strain diagram of a typical platinum foil sample without parylene C foil. Measured and averaged resistance.

The averaged forces of 5 platinum samples without parylene C foil were calculated 381 mN for yield strength and 534 mN for ultimate strength. Samples with embedded parylene C foil and a 2 mm hole-spacing have an averaged ultimate strength of 4.38 N for laser-structured and 4.5 N for RIE-etched parylene C foil. The values are shown with minima and maxima (Fig. 7).

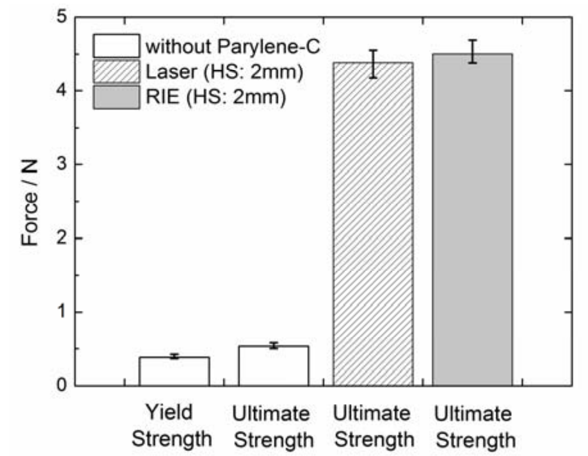

Fig. 7, Averaged values of yield and ultimate strengths of platinum-samples without parylene C-, laser-cut parylene C- and RIE etched parylene C foil, 5 samples each plus minima and maxima.

Regarding MP35N samples, the averaged yield strength was calculated 0.93 N and the ultimate strength 1.62 N for samples without parylene C foil. Samples with parylene C foil and a 2 mm hole-spacing have an averaged ultimate strength of 5.39 N for laser-structured and 5.49 N for RIE-etched parylene C foil. These results are shown in Fig. 8 with minima and maxima.

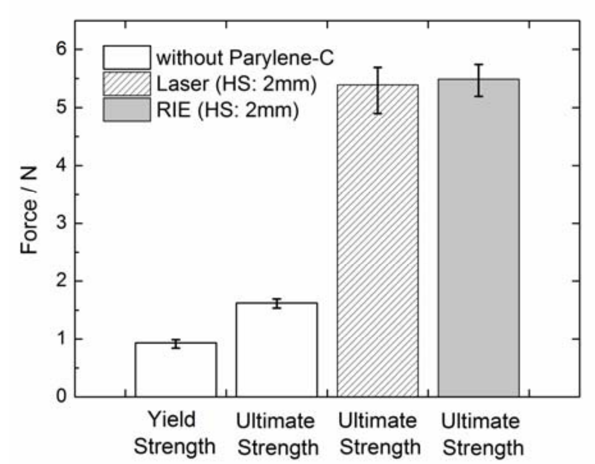

Fig. 8: Averaged values of yield and ultimate strengths of MP35N samples without parylene C-, laser-cut parylene C- and RIE etched parylene C foil (hole-spacing 2 mm), 5 samples each plus minima and maxima.

Results of investigations on platinum samples with different hole-spacing in embedded, laser-cut and RIE-etched parylene C foil are shown in Fig. 9.

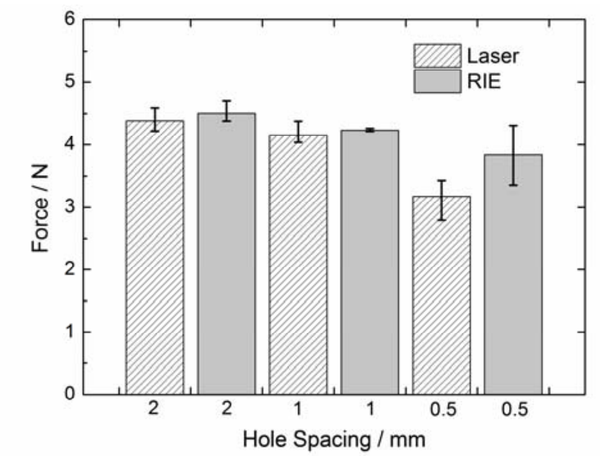

Fig. 9: Averaged values, minima and maxima of ultimate strength of platinum samples (5 each) with different hole-spacing in embedded, laser-cut- and RIE-etched parylene C foil.

The averaged values of 5 platinum samples each for the ultimate strength with different hole-spacing and parylene C process technologies are listed in Table 2.

TABLE II
SAMPLE AND MATERIAL COMBINATIONS

Parylene C structuring	Hole-Spacing	Averaged Ultimate Strength
Laser	2 mm	4.38 N
RIE	2 mm	4.50 N
Laser	1 mm	4.15 N
RIE	1 mm	4.23 N
Laser	0.5 mm	3.17 N
RIE	0.5 mm	3.83 N

IV. DISCUSSION

Comparing the two methods of parylene C structuring, RIE-etched samples showed higher values of calculated averaged ultimate strength than laser-structured samples. Conspicuously samples with 0.5 mm hole-spacing showed better results with RIE-etching of 17.2%. However, laser-structuring is a much more simple process, does not require photolithography, photomasks, cleanroom environment, etc. and hence minimizing the manufacturing costs.

Obviously samples are more stable with increasing hole-spacing. However, this advantage comes with the drawback of increased inhomogeneity of silicone rubber interlocking.

A reason for potentially imprecise measurements could be the mounting of the test sample into the bond tester. Also non-uniform application of the epoxy adhesive may have influence on the different results within one sample design.

A comparison between MP35N and platinum samples is outside the focus of this paper. We rather wanted to investigate to which extend embedding of a parylene C foil improves the performance for each single layout of the metal tracks. Regarding the application, thicker MP35N foils would be the material of choice for bigger ECoG-electrodes with lower spatial resolution. Thinner platinum foil is better for small electrodes with high resolution [3].

V. CONCLUSION

The results show considerably higher robustness of samples with embedded parylene C foil than samples without extra foil. The larger the hole-spacing the higher the robustness is at least valid for hole-spacing’s up to 2 mm. Regarding the manufacturing process and the biocompatibility, sandwich-like embedding of structured parylene C foil in silicone rubber turned out to be an almost perfect method to increase the robustness of silicone rubber based ECoG-electrodes. Using a parylene C foil, different electrode materials then have subordinate influence on the robustness.

ACKNOWLEDGMENT

This work was funded by the German Federal Ministry of Education and Research (BMBF grant 01GQ0830 to BFNT Freiburg/Tübingen).

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