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Parylene-Coated Metal Tracks for Neural Electrode Arrays – Fabrication Approaches and Improvements Utilizing Different Laser Systems

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***Abstract*—In the past we developed a method for the fabrication of neural electrodes based on laser-structuring metal foil to form tracks and electrode sites within a silicone rubber substrate. Here, this process was refined by an additional coating of the laser-patterned metal tracks to improve their mechanical properties. Parylene C has been found to be the coating material of choice due to excellent electrical and mechanical characteristics and its well known biocompatibility. An almost ten times increased tensile strength compared to uncoated tracks could be achieved. Investigating the electrical properties of parylene C and silicone rubber attested both materials excellent insulating capabilities by withstanding voltages of more than 400 V_{DC} for layer thicknesses as intended to be used in electrode array fabrication (some 10 µm). This paper outlines the feasibility of the manufacturing process using a 1064 nm Nd:YAG laser in the nanosecond pulse regime. However, an improvement of the whole processing was demonstrated when a 355 nm Nd:YVO_4 laser in the picosecond regime is used. Benefits of this short pulse duration range from ablating materials independent of their optical properties to increased manufacturing speed and superior processing quality.**

I. Introduction

THE demand for highly sophisticated neural prostheses has dramatically increased over the past years. Applications range from cochlear electrodes with less than 25 contact sites to arrays with high-density and large number of contacts up to some 100. Here, electrocorticogram (ECoG) electrode arrays for invasive brain activity recording in e.g. epilepsy diagnostics are of great interest. Fabrication methods utilizing laser technology and biocompatible materials such as high purity platinum foil and medical grade silicon rubber were developed since 2004 [1]. Based on that, processes implementing a Nd:YAG laser with a wavelength of 1064 nm and pulse durations in the nanosecond regime were introduced which led to an improvement in speed, quality and use as rapid prototyping technology for manufacturing electrode arrays. Subsequently the technology was expanded by integrating and characterizing materials such as stainless steel or platinum iridium for a new neural interface [2]. Scaling limitations of the Nd:YAG laser process were found to be close to 80 µm for the track to track pitch which allowed acceptable spatial resolutions for many applications [3]. One major disadvantage is the fragility of electrode designs implementing straight conductive paths. To overcome this hurdle, meander-shaped structures substituted the previous designs and allowed electrode arrays of greater flexibility [4]. However they were still not robust enough for the rough handling during implantation, attributable to the fact that the very soft silicone substrate does not provide enough mechanical protection for the delicate metal tracks. The introduction of an either laser- or chemically structured parylene C layer turned out to be a promising step for enhancing the mechanical strength of the arrays [5]. An example of this state-of-the-art manufacturing is depicted in Figure 1. However the desired softness of the electrode array is compromised by this method.

Figure 1: Electrode design implementing meander shaped tracks and an intermediate parylene C layer. 1: Electrode contact sites 2: Meander-shaped tracks 3: Silicone rubber with embedded parylene C foil 4: Transition electrode to cable (welded).

For this study a laser-based manufacturing process was developed in order to create tracks individually coated with parylene C. An additional polymer besides the silicon rubber should benefit both, the mechanical and the electrical properties of the array. In contrast to the intermediate parylene layer in [5], arrays with coated integrated tracks spare at least three silicone layers compared to our state-of-the-art method. Thus the whole electrode array remains more flexible while the fragile metal tracks are individually protected. The current technological bottleneck of laser-manufacturing electrode arrays with high spatial resolutions is the nanosecond pulse duration of the Nd:YAG system. Ablation in this pulse regime is always linked to extensive heat development and hence thermally induced damage. This leads to mechanically weak spots in the patterned metal where the track is likely to break. Moreover, precise structuring is not possible, since molten metal may shortcut adjacent structures. Hence, a certain minimal distance between two tracks has to be ensured in order to electrically separate them. Structuring polymers is even harder because

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of their optical properties i.e. reduced absorption at 1064 nm. Accordingly, laser-polymer interaction rather burns the material than precisely ablates it. Utilizing laser ablation in the picosecond regime lacks all these shortcomings. First benefits for this kind of electrode processing were demonstrated in [6, 7]. Further results are presented in this paper.

II. Materials and Methods

A. Manufacturing process

As a variation of the fabrication process described in [4], a few steps are introduced which serve the realization of a proper coating of the metal tracks.

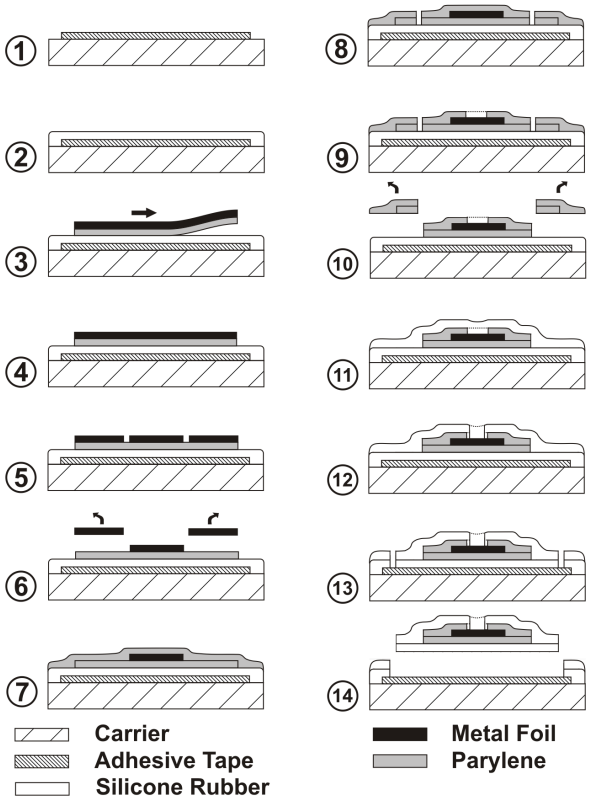

Figure 2: Cross-sectional process flow for parylene C coated electrode tracks.

In a first step (Fig. 2-1), an adhesive tape (No 4124, tesa Ag, Hamburg, Germany) which serves as release layer is laminated onto a mechanical carrier (either a glass slide or an alumina ceramic substrate) and afterwards covered by a 25 µm thin layer of n-heptane-diluted MED-1000 silicone adhesive (NuSil, Carpinteria, CA, USA) by means of spin coating (Fig. 2-2). For the next step, a piece of high purity 12.5 µm platinum foil (Goodfellow, Friedberg, Germany) in the designated size is coated with a 10 µm layer of parylene C. Parylene is deposited from the gas phase with a PDS 2012 LABCOTER™ (SCS, Indianapolis, USA). The platinum-parylene C stack is carefully laminated onto the substrate with the parylene facing towards the rubber (Fig. 2-3/4). Next, the metal is laser-patterned (Fig. 2-5). The processing parameters have to be chosen in such a way that the parylene C beneath the metal foil is left unharmed. Excessive platinum foil is then removed manually with forceps (Fig. 2-6) and the whole substrate is covered with another 10 µm layer of parylene C (Fig. 2-7). The laser is used for cutting the contour of the electrode into the parylene (Fig. 2-8) and for opening the contact sites (Fig. 2-9). Excessive parylene is peeled-off with forceps (Fig. 2-10). A subsequent spin-coating step covers the array in silicon rubber (Fig. 2-11). Again, the laser is used to remove the rubber from the previously opened contacts sites (Fig. 2-12) and also for cutting the electrode array's perimeter (Fig. 2-13). Droplets of ethanol diminish the adhesion to the tape and facilitate the final removal of the array from its carrier (Fig. 2-14).

B. Laser Systems

Two different laser systems were utilized. First, a Q-switched Nd:YAG nanosecond marking laser for evaluating the feasibility of the process itself. This laser operates at 1064 nm (infrared, IR) wavelength. Because of its long pulse duration, the resulting heat-affected-zone (HAZ) is large for processing both, metals and polymers. Hence the ablation mechanism is predominantly of thermal nature. Further processing optimizations and possibilities for the individual materials were assessed with a passively mode-locked Nd:Vanadate picosecond laser. Due to frequency tripling its native wavelength is shifted to 355 nm. An increased absorption of polymers in this near ultraviolet (UV) range and a strongly diminished thermal influence of the laser-solid interaction facilitate processing all intended materials. Specifications of both systems are summarized in Table 1.

TABLE I. Specifications of utilized laser systems

	Nanosecond Laser	Picosecond Laser
Model	DPL Genesis Marker	Super Rapid
Supplier	Cab GmbH, Karlsruhe, Germany	Lumera Laser, Kaiserslautern, Germany
Active medium	Nd:YAG	Nd:YVO_4
Pulse duration	30 – 60 ns	< 15 ps
Repetition frequ.	1 Hz – 40 kHz	80 kHz – 1 MHz
Wavelength	1064 nm	355 nm

In order to find suitable processing parameters to obtain smooth cutting edges and short processing times, simple test structures were cut into the materials. Furthermore the smallest track width and pitch were determined as well as the electrical isolation of two adjacent structures after separating them by a lased trench. A hatching test (multiple repetition of the same trajectory with small lateral offsets) was performed to see whether it is possible to remove an area of material layer by layer by laser cutting parallel trenches with a pitch of 5 µm. Processed materials were investigated by means of scanning electron microscopy (SEM).

C. Mechanical Tests

Pull-tests utilizing a multi-purpose bond tester (Type 4000, Dage, Aylesbury, UK) and a WP10kg measurement cartridge were performed to compare coated and uncoated platinum tracks, fully embedded in silicone rubber. Preliminary investigations identified a design implementing parylene wings to be advantageous over slender coated tracks concerning mechanical stability and manufacturing issues. Test samples with three different cross sections were fabricated, featuring coating 'wing-widths' *w2* of 100 µm and 150 µm. Additionally, a straight coating which contour does not follow the actual meander shape was designed as depicted in Fig. 3. For the meander design an opening angle θ of 60° was chosen in accordance with actual electrode designs [5].

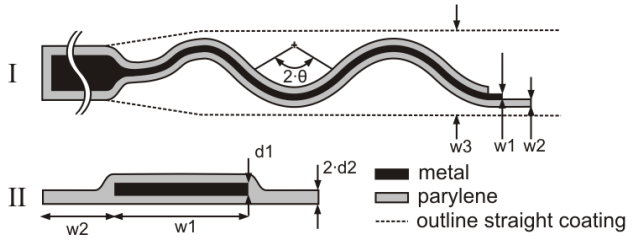

Figure 3: Parameters defining the dimensions of coated tracks. I: Top view II: Cross section

Other dimensions for the specimens were: Straight coating width *w3* = 1.1 mm, track width *w1* = 150 µm, metal foil thickness *d1* = 12.5 µm and coating thickness *d2* = 10 µm. Note that these values indicate design parameters, the actual dimensions differ due to the influence of the laser beam. During the pull-test a four-wire measurement setup was used in order to monitor the resistance of the tracks to determine the point of electrical failure. For this purpose the samples were soldered to small pieces of printed circuit board which were connected to the electrical measurement setup and then mounted in the pull tester. The pull-test itself was performed at 150 µm/s within a measurement range of 5 N.

D. Electrical Tests

Representative for the coating, thin membranes of each material were investigated for electrical insulation properties. Circular (diameter: 1.5 cm) Parylene C membranes of 5 and 10 µm thickness and silicone membranes of 30 and 70 µm thickness were produced and centered to a 1 cm diameter hole in an Al_2O_3 carrier, to which the membranes were then glued to. The parylene pieces were glued with epoxy EPO-TEK 302-3M (Epoxy Tech. Inc., Billerica, USA) whereas the silicone was glued with MED-1000. The fixated membranes are mounted in a fluid chamber in such a way that two segments are created only separated by the thin membrane. The chamber was filled with 0.01 mol/L phosphate buffered saline (PBS) solution at 37°C. For the measurements a platinum electrode is placed in each chamber segment and impedance and phase in the range from 10 Hz to 1 MHz are recorded utilizing a Solartron 1260 impedance/gain phase analyzer (Solartron Analytical, Hampshire, UK). The measurements were repeated frequently within a timeframe of 7 months till submission of this paper to see whether the impedance of the polymers changes in a body like environment over time. Therefor the membranes were stored in PBS at 37°C in an incubator between the recordings. To determine the dielectric strength of the membranes a voltage up to 420 V_{DC} was applied between the two segments and the current passing the membrane was recorded.

III. Results

A. Processing with Different Laser Systems

All intended materials could be processed with almost no visible thermal effects when the picosecond laser was used. As already reported in [7], compared to the nanosecond laser technology, manufacturing speed, smoothness of edges in terms of profile roughness and feature sizes could be dramatically improved. The latter is possible because no molten metal splashes into the laser-cut trenches and hence cannot short-circuit them. In Fig. 4 SEM pictures of patterned platinum foil and polymers with both laser systems are depicted.

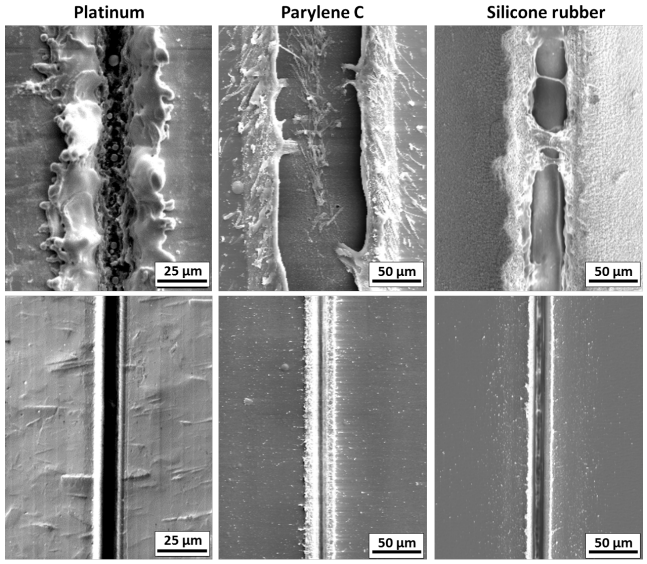

Figure 4: Processing platinum foil, parylene C and silicone rubber - Top: Nanosecond regime - Bottom: Picosecond regime

Moreover the feasibility of simply ablating material with the picosecond laser was demonstrated. It was possible to remove either parylene C or silicone from the platinum surface leaving the metal unharmed. This hatching process is exemplarily depicted in Fig. 5 for parylene C. First trials showed the possibility to also ablate metal in a defined way. However, this step still needs further parameter optimization.

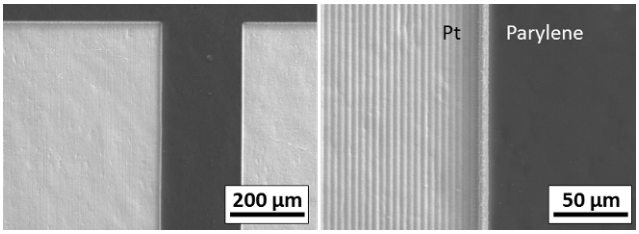

Figure 5: Removing parylene from the platinum surface by applying a hatching pattern with the picosecond laser.

B. Mechanical Tests

Pull-testing revealed that coatings with design wing widths of 100 and 150 µm increased the tensile strength by a factor of nearly ten compared to uncoated tracks. Straight coatings delivered even more promising results of withstanding almost 2.5 N till track breakage.

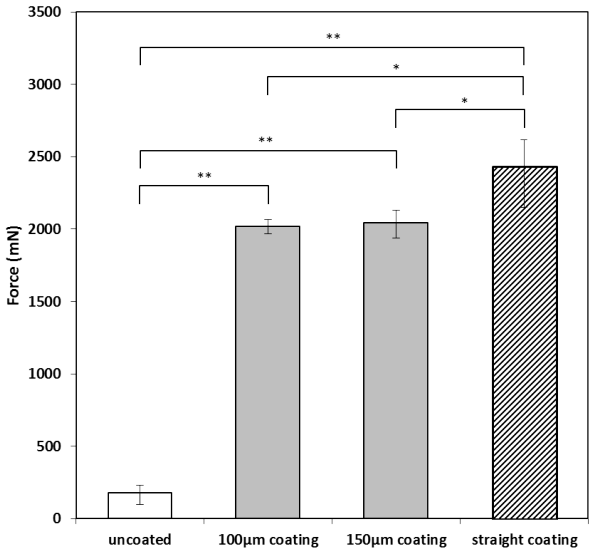

Figure 6: Pull-test of differently coated and uncoated meander structures. * Probability value between 1% and 5%, if a difference between the data sets is assumed. ** P-value <1%. Test size N = 5, error bars indicate min and max values.

C. Electrical Tests

The impedance and phase of all investigated polymer membranes (Parylene C and silicone rubber) did not show any alteration over the period of 7 months as shown in Fig. 7.

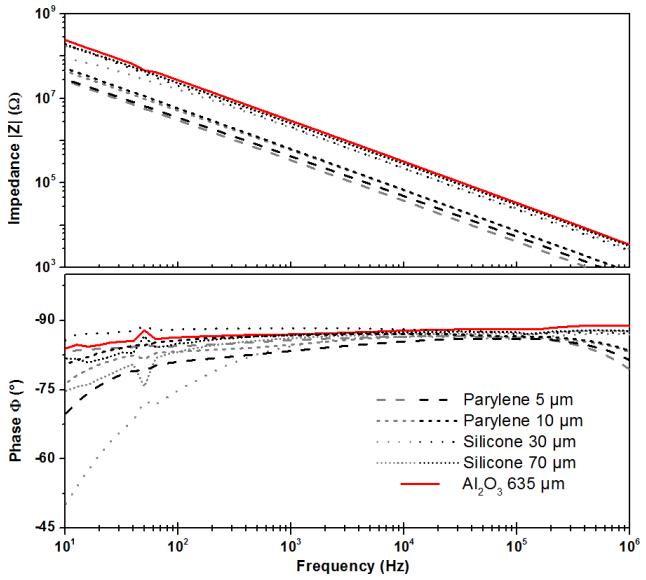

Figure 7: Impedance and phase recordings of processed polymers. Grey lines indicate initial measurements and black lines represent the same material after 7 months storage in PBS. The Al_2O_3 ceramic was used as reference.

The characteristic can be considered as completely capacitive and there is no evidence of any ion uptake from the PBS solution into the membrane material within this timeframe. No electrical breakthrough could be observed for any of the membranes even when 420 V_{DC} (limited by our set-up) were applied for several seconds. Calculated minimal dielectric strengths for the thinnest membranes were 84 kV/mm for parylene C and 14 kV/mm for MED-1000.

IV. Discussion

Fabricating first samples with the newly developed process showed the feasibility of manufacturing parylene coated electrode tracks in general. On the other hand the mechanical benefit of this approach could be demonstrated, too. However, because of the thermal influence of the Nd:YAG laser a precise and defined realization of the coating was not possible. Burned edges and molten material increase the minimal feature size and make the process unsuitable for high density electrode arrays. Despite this drawback, the picosecond laser technology was identified as technology to overcome this hurdle. Processing the individual materials with pulses in the picosecond regime revealed that all aforementioned side effects could be omitted and a precise structuring of metals and polymers could lead to high density electrode arrays with individually coated tracks.

Acknowledgment

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