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REDUCING STIFFNESS AND ELECTRICAL LOSSES OF HIGH CHANNEL HYBRID NERVE CUFF ELECTRODES

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Abstract-**For restoration of grasp in disabled people by means of functional electrical stimulation of peripheral nerves, 18polar *Hybrid Cuff Electrodes* were developed. These electrodes consisted of a micromachined polyimide-based thin-film structure with integrated electrode contacts and interconnection lines which was glued to a silicone cuff. Interconnection lines were made of only 300 nm of sputtered gold, which led to high line drops. Gold electroplating was used to thicken the lines to 3 µm, which reduced the mean track resistance from 480 Ω to 10 Ω. Furthermore, the electrode material was changed from sputtered platinum to electroplated platinum black in order to decrease the phase border impedance of stimulation sites. Applying these techniques, the overall electrode impedance could be reduced from 7.78 kΩ to 624 Ω (at 1 kHz). Additional to the electrical optimization of the cuff electrodes, mechanical properties were enhanced by changing the method of joining silicone and polyimide from using one part silicone adhesive to plasma activation of surfaces: Plasma-treated surfaces were simply pressed face to face. The result was a bondage without any additional layer of glue, which led to a very high mechanical flexibility and higher yield of the overall *Hybrid Cuff Electrode.***

Keywords **- FES, cuff electrode, electroplating, gold, platinum, platinum black, polyimide, silicone, polymer bonding**

I. INTRODUCTION

Cuff-type electrodes are probably the most commonly used neural interfaces for restoration of lost neuro-muscular functions by means of functional electrical stimulation (FES), at least since the early 70ies. Veraart *et al.* showed that a single cuff electrode having multiple stimulation contacts installed on a peripheral nerve allowed selective activation of different muscles [1]. In order to gain high selectivity, a high number of stimulation contacts was assumed to be mandatory. Applying traditional fabrication methods, based on stimulation contacts made of platinum foils embedded in a silicone cuff [2], the integration density of contacts (and cables) was limited by the skill of the manufacturer. Stieglitz *et al.* introduced a fabrication method for cuff-type electrodes based on micromachined polyimide thin-film substrates, that offer a very high possible integration-density of electrode contacts [3]. Because of mechanical properties and also cost-effectiveness, these thin-film cuffs are restricted to small diameters, up to 3 mm. *Hybrid Cuff Electrodes*, consisting of a micromachined, scaffold-like polyimide-substrate glued to a silicone cuff appeared to be a good combination of advantages of both technologies: traditional silicone and micromachining [4]. This technology also proved to be suitable for the realization of smart neural electrodes, integrating a some intelligence by electronics, e.g. multiplexer circuits [5]. A drawback of the micromachined substrates was the high electrical resistance of thin (300 nm) and narrow (down to 10 µm) gold interconnection lines, that was found to be in the range several 100 Ω, depending on the length and width of the tracks. Even worse was the influence of the phase-border impedance of dot-shaped electrode contacts (Ø=500 µm) to the overall power loss during stimulation: using sputtered platinum, an impedance magnitude of several kilo-ohms at 1 kiloherz was measured in saline solution. Among the electrical efficiency, also the mechanical properties could be improved. Using silicone adhesive to join silicone sheets and polyimide caused a stiffening of the overall device, that was hard to predict in its extend. This affected the reproducibility of the fabricated *Hybrid Cuff Electrodes.*

The here presented study is about reducing the electrical losses of a *Hybrid Cuff Electrode* by thickening integrated interconnection lines using gold electroplating and by changing the electrode material and deposition process. In order to overcome the mechanical problems related to gluing, a new method for joining silicone to silicone and silicone to polyimide was investigated.

II. METHODOLOGY

To optimize the properties of the *Hybrid Cuff Electrode,* two different approaches were investigated, independently described in subchapters A (electrical) and B (mechanical).

A. Reduction of Electrical Losses

Electrical losses were caused by ohmic resistance of thin-film tracks and complex impedance of electrode phase-border. The only way to decrease the resistance of a track with a given planar layout was to increase its thickness. Sputtering and vapor depositing was not suitable to obtain layers thicker than a few 100 nm because of mechanical stress and high costs. Electroplating of gold was assumed to be a much more suitable to get tracks of a few µm thickness. Electrode impedance, in general, is determined by effective electrode area and properties of electrode material. Holding on platinum as soft material that stands bending of flexible polyimide substrate (in contrast to iridium) and keeping the geometrical area predetermined by electrode design, the effective area had to be increased to reduce the impedance. A large effective area could be gained by platinum black deposition. Platinum black is platinum with a very high micro-roughness inhibiting reflection of visual light causing a characteristic black appearance.

1) *Gold Electroplating:* One requirement for the electroplating process was to fit into the established processing procedure for polyimide micro-structures, e.g. no additional photolithographic mask should be needed. The new process for fabrication of polyimide-structures, including electroplating of tracks, is illustrated in Fig. 1.

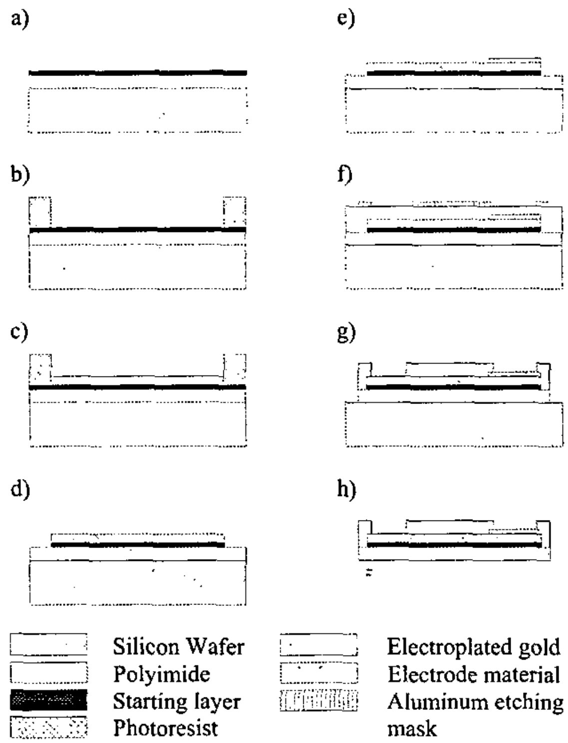

Fig. 1. Processing of polyimide thin-film substrate with electroplated gold interconnection lines. a) Spinning polyimide resin on silicon wafer, curing, deposition of Ti/Au starting layer. b) Patterning photoresist and c) gold electroplating of interconnection lines. d) Removing resist and wet-etching of starting layer. e) Deposition of electrode material and f) spinning on polyimide resin, curing, deposition and patterning of aluminum etching mask. g) Dry-etching of electrode and pad openings, removing etching mask by wet-etching. h) Release of substrates from silicon wafer.

First, a 5 µm layer of polyimide resin (Pyralin 2611, HD-Microsystems, Bad Homburg, Germany) was spun on a silicon wafer and imidized. 50 nm Ti/Au was sputtered (reactor: L400 SP, Leybold, Dresden, Germany) onto it as a starting layer for electroplating (Fig. 1, a). 5 µm of photoresist ma-N 440 (Micro Resist Technology, Berlin, Germany) was patterned to protect specific parts from electroplating (Fig. 1, b). The starting layer was electrically contacted and the whole wafer was put upside-down into a gold-sulfite bath (Imabrite 24, Schloetter, Stuttgart, Germany), heated to 40 °C. An electrical current was applied to the starting layer and a platinum counter electrode in order to deposit gold from the electrolyte (Fig. 1, c). The amperage was calculated by total surface area of all interconnection lines to be thickened on the wafer multiplied by a current density of 30 A/m². The thickness of the electroplated gold layer was predetermined by processing time. After electroplating, the photoresist was removed and the starting layer was wet-etched (Fig. 1, d). The following steps remain unchanged to former polyimide microprocessing: sputtered electrode metal (200 nm Pt) was patterned on the electroplated gold by a lift-off process (Fig. 1, e), a second polyimide layer (5 µm) was spun on and imidized. A 200 nm aluminum etching mask was patterned onto it (Fig. 1, f). Using oxygen-based reactive ion etching (reactor: STS 320 PC, Surface Technology Systems, Newport, UK), pad and electrode sites were opened, structure separation were etched down to the silicon wafer (Fig. 1, g). As a final step, the structures were released from the wafer (Fig. 1, h). The electrical resistance of electroplated tracks were measured by four-wire ohms measurement using a probe needle station (PM5, Karl Suss, Dresden, Germany) and a precision multimeter (HP 3458 A, Hewlett Packard, Palo Alto, CA). Thickness of the electroplated structures were measured with an optical surface profiler (RM 600-S, Rodenstock, Munich, Germany), structure quality was visualized by scanning electron microscopy (SEM).

2) *Deposition of Platinum Black:* An electrolyte was mixed as follows: 5 g H_2PtCl_6 was dissolved in 357 ml ultra pure water. Subsequently, 71.4 mg $Pb(NO_3)_2$ were added (Merck KGaA, Darmstadt, Germany). Voltage-controlled electroplating was carried out, using a platinum counter electrode and an Ag/AgCl reference electrode, connected to custom-made potentiostat. A DC signal was applied between counter electrode (anode) and starting layer of electrode structure (cathode) for a specific time period. During the deposition process, ultra sound was applied to the electrolyte in order to immediately remove bad adhesive platinum black particles from the electrode structure.

Electrode surfaces were characterized by three electrode impedance spectroscopy (0.9% saline solution at room temperature) using a commercially available setup (model 1260 impedance/gain-phase analyzer and 1287 electrochemical interface, Solartron, Farnborough, England). Surfaces were inspected by SEM and optical microscopy.

B. Enhancement of Mechanical Properties

Jo *et al.* reported a method for bonding two parts of PDMS elastomers by simply pressing two plasma-activated surfaces together [6]. We applied this method for joining silicone to silicone and also polyimide to silicone in order to assemble fixed diameter cuff electrodes as well as spiral cuff electrodes.

1) *Spiral Cuff Electrodes:* Two sheets of medical grade silicone (4 cm x 8 cm, 127 µm thickness, Speciality Silicone Fabricators, Paso Robles, California) were treated by oxygen plasma, generated in a sputter reactor (L400 SP). Subsequently, one sheet was mounted in a stretching tool and stretched. The second sheet was laid onto it - activated surfaces faced each other - and slightly pressed on. After a specified period of time, the tool was opened and the two layer silicon sheet was taken out, and curled by itself to a spiral. This spiral cuff was fixed

with tape in opened position and treated again with plasma, together with a polyimide thin-film structure. Subsequently, the cuff was allowed to curl while the thin-film structure was slightly pressed to the inner side of its wall.

2) Fixed Diameter Cuff with Piano-Hinge Closure: A sheet of silicone and a polyimide thin-film structure was plasma-treated. Subsequently, the thin-film structure was slightly pressed to the silicone sheet in planar position. A piano-hinge closure [7] was made by gluing (MED-1000, NuSil, Carpinteria, CA) eight pieces of medical grade silicone tubing (1 mm length, $Ø_{outer}$=0.7 mm, $Ø_{inner}$=0.5 mm, HM Medical Engineering, Binzen, Germany) to the edges of the silicone sheet.

To estimate the maximum processing time, activated surfaces were put together 10, 30 and 60 minutes after plasma treatment. In case of silicone-silicone junctions, the quality of bonding was estimated 20 hours after plasma-treatment by trials of manual separation of two bonded sheets. Also after 20 hours, polyimide-silicone adhesion was measured by 180° peel tests, using a modified bond tester (PC 2400 tester with DS100KG sensor unit, Dage Precision Industries, Aylesbury, England) that was actually intended to characterize wire bonds of electronic assemblies.

III. Results

Presentation of results was divided into electrical characterization (subchapter A) and description of mechanical improvements (subchapter B).

A: Reduction of Electrical Losses

Electroplating of gold for a duration of 18 min, 42 sec at 30A/m² resulted in interconnection lines with a thickness of 3 µm. Mean track resistance was reduced from 480 Ω to 10 Ω, varied by track length and width. Figure 2 shows a SEM of a representative test structure.

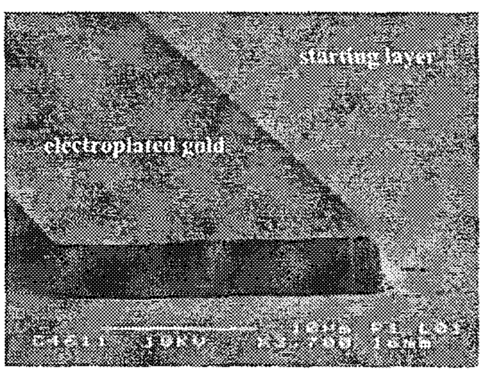

Fig. 2: SEM of a 20 µm wide and 3 µm high test structure on Ti/Au starting layer, made by electroplating of gold.

Well adherent, uniform layers of platinum black were achieved by application of 0.5 V for a duration of 30 sec. A comparison of four investigated combinations of materials and depositing processes (Fig. 3) led to the following ranking, referring to impedance measured at 1 kHz, 100 mV sine excitation at room temperature, using 0.9% saline solution as electrolyte: best results were obtained by platinum black electrodes on electroplated tracks (624 Ω / -1.9 °), followed by platinum black on thin-film tracks (1002 Ω / -2.0 °). Electrochemical properties of sputtered platinum on electroplated tracks (3302 Ω / -58.8 °) were found to be better than that of sputtered platinum on thin-film tracks (7784 Ω / -60.6 °), which was the candidate with the highest impedance.

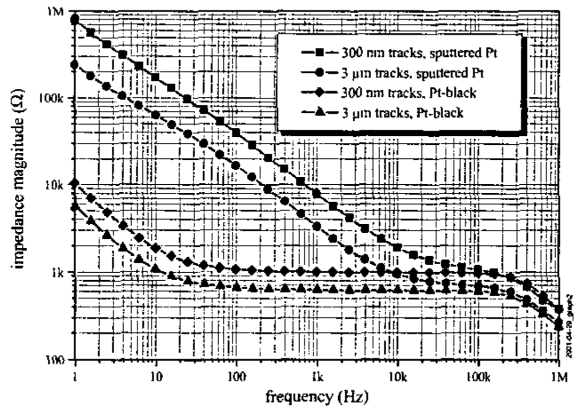

Fig. 3: Spectra of impedance magnitudes of dot-shaped electrodes (Ø=500 µm, connected to integrated interconnection lines), made of different material combinations: sputtered platinum on sputtered tracks (square), sputtered platinum on electroplated tracks (dot), platinum black on sputtered tracks (diamond), and platinum black on electroplated tracks (triangle). Measured in 0.9% NaCl solution, 100 mV sine excitation at room temperature.

B. Enhancement of Mechanical Properties

Successful silicone to silicone bonding proved to be uncritical in respect to plasma parameter variation. Bonding of polyimide to silicone was more delicate. A set of parameters was found, that enabled bonding of both material combinations: an oxygen-plasma (75 % O_2 at 10^{-7} bar), generated for 10 sec with a RF-power of 200 W at 13.56 MHz. Neither silicone-silicone nor polyimide-silicone junctions were reversible, independent from time of contact (10, 30, 60 minutes after plasma treatment). Peeling trials led to destruction of silicone, the adhesion was better than the cohesion of silicone. Applying that bonding technology, the wall-thickness of a *Hybrid Cuff Electrode* was determined only by the thickness of used the silicone sheets and additional 10 µm of the polyimide-inlay. A fixed diameter cuff electrode was assembled, consisting of a 127 µm thick silicone sheet (cuff) and a polyimide-microstructure with 18 stimulation sites. A piano-hinge like closure was realized as shown in Fig. 4. Because of the thin silicone wall, this cuff electrode was extremely flexible and soft. A spiral cuff electrode was manufactured by bonding a sheet of silicone to another one that was stretched. This resulted in a silicone spiral with a wall thickness of 254 µm. To the inside of this spiral, a polyimide structure was bonded (Fig. 4).

IV. DISCUSSION

Electroplating of 3 μm gold reduced track resistance by a factor of about 48, compared to 300 nm thin-film, which did not correlate to the factor 10 of track thickening. Possible reasons for that could be the well-known differences between bulk-material and thin-film properties of metals and different ratios of deposited gold and titanium layer heights. Titan, which was used as adhesive layer between polyimide and gold, might be diffused into the gold tracks, formed an alloy and modified electrical properties. This effect was assumed to be negligible in electroplated tracks but not in thin-films.

Differences of impedance spectra between electrodes on thin-film and electroplated tracks could not be explained only by different track resistance but by a much rougher surface of electroplated tracks that also led to a rougher surface of the stimulation site (larger effective electrode area caused smaller impedance).

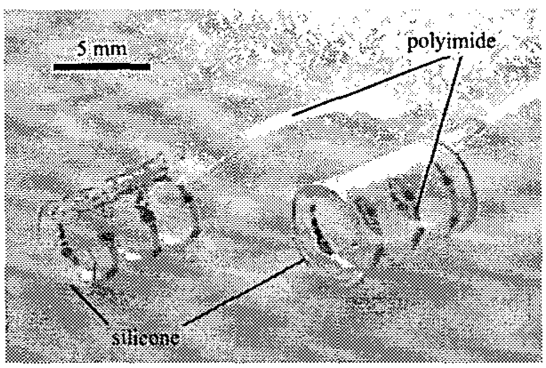

Fig. 4: *Hybrid Cuff Electrodes*, fitting to 4 mm diameter peripheral nerves, assembled by plasma-activated bonding. Left: fixed-diameter cuff with piano-hinge closure, locked by a piece of suture (2.5 metric). Right: spiral cuff.

The initial trials of bonding silicone to silicone and polyimide to silicone using oxygen plasma activation were very encouraging (and might be interesting for a couple of different applications). Wall-thickness of silicone cuffs were only predetermined by thickness of used polyimide and silicone sheets, which are in general not restricted to the sheets of 127 μm thickness that were used here. Not using silicone adhesives increased yield in electrode assembly because stimulation sites could not get covered accidentally by glue. Possible processing time of at least one hour after plasma activation gave a lot of space for assembling, in contrast to silicone glue that had to be processed within a few minutes. The time of completion of bonding remains to be explored. In this study, bonding was allowed to last 20 hours but it might be finished much earlier.

To ensure safety for chronic implantation of the improved *Hybrid Cuff Electrode*, biocompatibility of the new processing steps has to be proved, e.g. by cytotoxicity testing; *in vitro* tests have to be carried out investigating long-term reliability of electrical and mechanical properties.

V. CONCLUSION

Impedance of multichannel *Hybrid Cuff Electrodes* - and as a consequence: electrical loss during stimulation - was lowered by up to two decades (lower frequency spectrum) by electroplating of gold tracks and platinum black electrodes. Now, even CMOS-based stimulators can drive reasonable currents through this device. A new technology was established for bonding silicone and polyimide thin-film based on plasma activation. Adhesion between two bonded bodies was found to be stronger than the cohesion of silicone. Applying this new bonding method, extremely flexible cuff electrodes were manufactured. However, biocompatibility of the new process steps and long-term reliability of electrical and mechanical properties remain to be demonstrated until patients may gain from these improvements.

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