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

Advancements In Electrode Design and Laser Techniques for Fabricating Micro-Electrode Arrays as Part of a Retinal Prosthesis

C.W.D. Dodds, *Member, IEEE*, M. Schuettler, *Member, IEEE*, T. Guenther, *Student Member, IEEE*,
N.H. Lovell, *Fellow, IEEE* and G.J. Suaning, *Member, IEEE*

***Abstract*— Retinal micro-electrode arrays (MEAs) for a visual prosthesis were fabricated by laser structuring of platinum (Pt) foil and liquid silicone rubber. A new design was created using a folding technique to create a multi-layered array from a single Pt sheet. This method allowed a reduction in both the electrode pitch, and the overall width of the array, while maintaining coplanar connection points for more stable interconnections to other components of the system. The design also included a section which could be rolled to create a cylindrical segment in order to minimise the size of the exit in the sclera after implantation. A picosecond mode-locked 532 nm laser system was investigated as a replacement for the nanosecond Q-switched 1064 nm laser currently in use. Trials showed that the ps system could produce high quality electrode tracks with a minimum pitch of 30 μm, less than 40 % the pitch achievable with the ns laser. A method was investigated for the cutting of Pt foils without damaging the underlying silicone by laser machining to a depth just below the thickness of the foil. Initial samples showed promise with full penetration of the foil only occurring at cross points of the laser paths. The ps laser was also used to create roughened surfaces, in order to increase the electrochemical surface area of the electrodes. Surfaces were imaged using a scanning electron microscope, and compared to surfaces roughened with the ns laser. The ps laser was seen to offer a reduction in feature size, as well as an increase in control over the appearance of the electrode surface.**

I. INTRODUCTION

With constant advances in retinal prostheses, device developers are including larger numbers of electrodes in order to improve visual acuity. This requires a reduction in MEA feature sizes, and optimization of design to best utilize available space. Miniaturization is also advantageous as it reduces trauma to the patient during implantation.

A method for laser fabrication of MEAs from polydimethylsiloxane (PDMS) and platinum foil was developed by Schuettler et al. [1]. MEAs produced using this method have been shown to be safe for long-term implantation [2] and to elicit a response in the feline cortex when used to stimulate from the supra-choroidal space [3], making them well suited for use in a retinal prosthesis.

Our retinal prosthesis, currently under development, utilizes a hermetic capsule containing a custom-built neurostimulator, located on the outside of the sclera. The MEA penetrates through the sclera to the supra-choroidal space. In order to use laser fabricated arrays with our system, they needed to be able to be bonded effectively to the neurostimulator capsule, and be designed such that surgical implantation minimizes the exit in the sclera, both during the operation, and in the permanent trans-scleral wire bundle.

A multi-layered fabrication process was developed using alternate layers of Pt foil and PDMS [4]. This method has the advantages of decreasing the minimum pitch of the electrode openings, and the overall width of the MEA, thereby reducing the size of the incision required for insertion.

A number of methods for connecting MEAs produced in this manner to the other electrical components were investigated [5], [6]. However these interconnection technologies are made difficult by the use of a multi-layered design, as the distance between subsequent layers makes it difficult to ensure the intimate contact needed for bonding. Other methods, currently under development, require that the connection points be on a single plane, rather than staggered on different layers. To retain the spatial benefits of a multi-layered approach, while using these interconnection technologies, a method for creating a multi-layered MEA from a single planar sheet of Pt foil was needed.

While much space can be saved through changes to the design of the array, to reduce this even further it is necessary to improve laser structuring techniques in order to minimize the feature sizes of individual electrodes and wires. At these smaller feature sizes the quality of the laser cut becomes increasingly important, as small defects and imperfections could lead to the failure of an electrode track by concentrating force at a single point.

Surface roughening of electrodes in order to increase the electro-chemical surface area (ESA) to geometric surface area (GSA) ratio has been shown to offer improved charge carrying capacity and to decrease the impedance of electrodes [7]. Electrodes with a high ESA:GSA ratio can therefore be made smaller than smooth electrodes with the same charge carrying capacity. For a retinal prosthesis this is important as it allows a denser packing within the electrode array, potentially offering an increase in visual acuity.

Ultra-short wavelength laser pulses have been shown to offer a high degree of flexibility for creating micro-structures on surfaces of various materials, as well as cutting of metal foils [8]. Integration of a ps laser into existing fabrication techniques should offer improvements in both achievable electrode pitch and quality, as well as the ability to design high ESA electrodes with a great degree of accuracy.

C.W.D. Dodds, T. Guenther, N.H. Lovell and G.J. Suaning are with the Faculty of Engineering, Graduate School of Biomedical Engineering, The University of New South Wales, Kensington, NSW, 2052, Australia `c.dodds@unsw.edu.au`

M. Schuettler is with the Laboratory for Biomedical Microtechnology, Department of Microsystems Engineering, University of Freiburg, Germany

This research was supported by the Australian Research Council (ARC) through its Special Research Initiative (SRI) in Bionic Vision Science and Technology grant to Bionic Vision Australia (BVA).

978-1-4244-4122-8/11/$26.00 ©2011 IEEE

II. METHODS

A. Electrode Array Design and Fabrication

Fig. 1 outlines the steps in producing a multi-layered MEA from a single sheet of Pt foil. Our existing electrode design was modified to allow for a folding technique during the fabrication process. A glass carrier was used with a laser machined hole which matches the size and shape of the neurostimulator capsule. The carrier is coated with PDMS and a piece of Pt foil is applied, covering the hole. The electrode design is then laser cut in the Pt, and the waste material is manually removed. The capsule is positioned in the hole in the carrier from below, and the connections of the MEA to the implant made from above. A second layer of PDMS is then spin-coated on and cured. One half of the MEA is removed from the carrier, and folded over the other half, producing a two-layered structure. Bonding of the two layers can be done by either gluing with silicone adhesive or oxygen plasma activation of the surfaces. The electrode openings, and the outline of the MEA, are cut through the silicone layers using a laser and the array is removed from the carrier. Finally, one section is rolled around a fine mandrel, held in position with silicone adhesive and back filled to produce a narrower exit through the sclera.

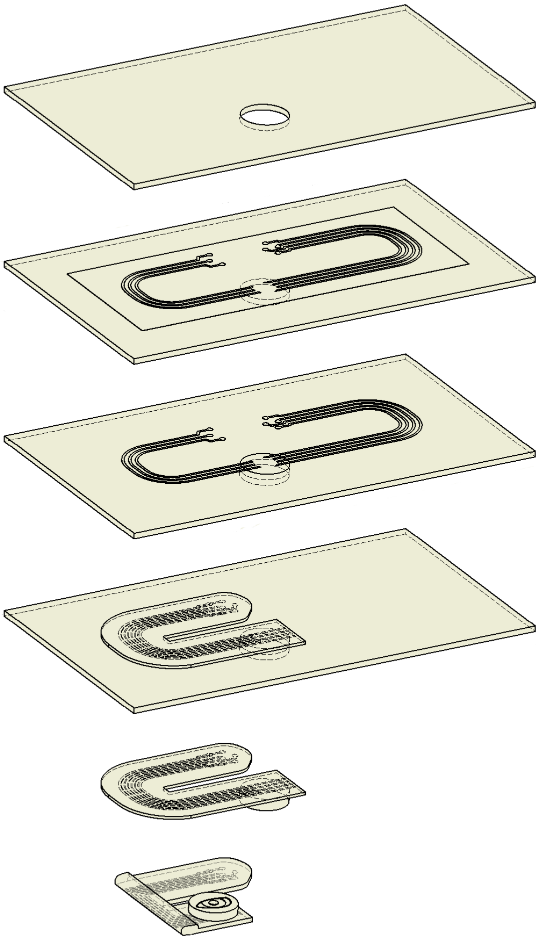

Fig. 1. Production of a folded supra-choroidal micro-electrode array attached to an implantable neurostimulator.

B. Laser Cutting of Platinum Foils

Samples consisting of Pt foil sheets applied to PDMS-coated microscope slides were prepared. A simple design was created in AutoCAD 2010 (Autodesk) consisting of straight electrode tracks of varying widths and pitches. As with all our electrode designs, adjacent tracks were separated by a strip of platinum foil which is removed after cutting. By removing this strip of waste material between all tracks, we ensure they are not short-circuited. Single laser cuts are not considered to be adequate gaps between the electrodes, as they can be bridged by molten or redeposited platinum particles [9].

A DPL GenesisMarker Q-switched ns laser (ACI, Nohra, Germany) and a frequency doubled, Duetto mode-locked ps laser (Time-Bandwidth, Zurich, Switzerland) were used to cut the design into the Pt foil. The waste material between the tracks was then manually removed.

In order to reduce the spot size, the picosecond laser was fitted with a second harmonic generation device to half the wavelength from 1064 to 532nm, as the spot size of a laser is proportional to its wavelength. A third harmonic generation device was also avaible to reduce this to 355nm, however this was not used as the apsorption of UV light by the PDMS may have led to unwated cutting of the substrate.

Samples were inspected under a Leica MZ75 optical microscope, and a JEOL Neoscope bench-top scanning electron microscope (SEM) to both measure the minimum achievable pitch and assess the quality of the cuts. Roughness of the cut edges (Rt) was calculated using the SEM images to measure the maximum deviation along the laser path. Roughness measurements were taken on three wires cut with each laser.

C. Incomplete Cutting of Platinum Foil

In order to produce electrode tracks without damaging the underlying PDMS, an attempt was made to laser machine to just shallower than the thickness of the Pt foil. The same parameters were used as for regular cutting, but with a reduction of approximately 8 % in the number of passes, with the aim of leaving an amount of Pt which was thin enough to allow for the removal of waste Pt, but prevented exposure of the underlying PDMS to the laser beam.

Electrode arrays were assessed using optical microscopy with back lighting to determine any points where the laser had cut completely through the Pt foil. The waste material was then removed manually to demonstrate that the cut was deep enough to allow removal of waste material. SEMs of the cuts were taken to inspect the cut depth.

D. Surface Roughening

The ps laser was used to produce roughened Pt surfaces by cutting a cross-hatched pattern with line separations approximately equal to twice the spot size of the laser beam. The parameters used for roughening were the same as those used for cutting, however the number of passes was reduced from 130 down to 30 in order to reduce the depth of the hatched pattern. This depth was measured using a laser scanning microscope, and SEMs were taken of the surface.

III. RESULTS

A. *Size Advantages of Current Design*

The distance between electrode sites in the array depends not only on the achievable feature sizes of the laser, but also on the number of electrode tracks to be routed in between adjacent electrodes. By using a folded design rather than a strictly planar design for our MEA, this number was reduced from three to two, which in turn reduced the achievable center to center spacing of electrodes from 653 μm to 553 μm. This, combined with the space saved from having overlaying routing, reduced the width of the entire MEA from 15.57 mm down to 9.74 mm, a 37 % saving[1].

Rolling the section of the array exiting the sclera resulted in a reduction of the scleral wound from 10 mm to less than 4 mm. Fig. 2 shows a model of a 98 channel device produced using the method described above.

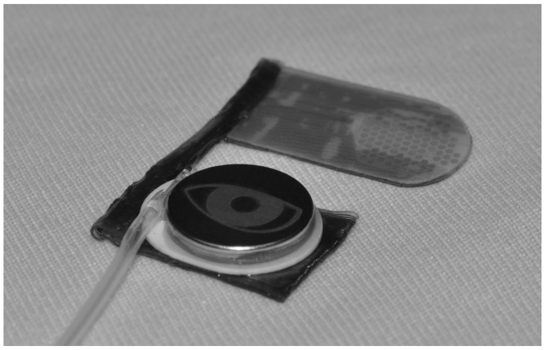

Fig. 2. A model 98 channel electrode array and attached neurostimulator.

B. *Laser Cut Platinum Wires*

For the laser cut wires, we defined an acceptable track to be one which was continuous throughout its length, and maintained a bond to the PDMS without lifting off the substrate. An acceptable gap was defined similarly, with the added criteria that the waste material between the tracks must be strong enough to be removed manually without breaking.

Using the ns laser the smallest producible features were 24 μm Pt tracks with a 56 μm separation distance, bringing the total achievable pitch to 80 μm. The ps laser offered a significant reduction, with 14 μm tracks and 16 μm separation distances possible. This gives a total pitch of 30 μm, a reduction of 62.5 % when compared to the ns laser. These minimum sized features are shown in Fig. 3.

Inspection of the laser cuts under both optical microscope and SEM showed the quality of cuts produced by the ps laser to be far superior to those from the ns laser. The average measured roughness of the cuts was 4.55 μm for the ns laser. The ps cuts were 0.85 μm, 17.7 % of the ns laser value. Wires produced using the ps laser also had almost no visible heat affected zone (HAZ), whereas with the ns laser, the HAZ extended across the entire width of the wires in the worst cases. Fig. 4 shows a comparison of the laser cuts with SEMs taken at the same magnification.

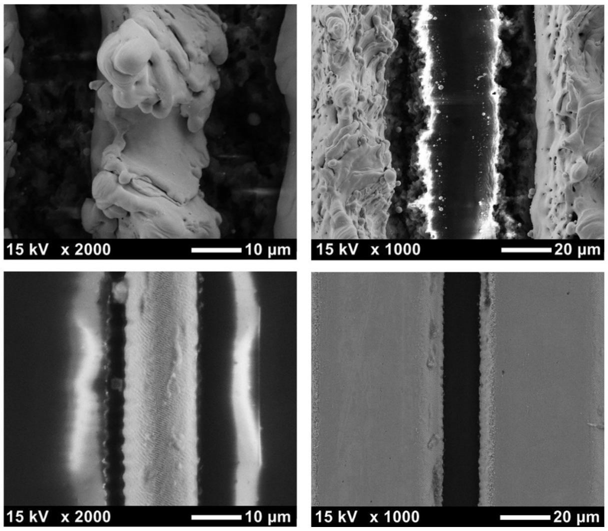

Fig. 3. A comparison of minimum feature sizes using the two lasers. Top Left: Smallest electrode track cut with ns laser (24 μm). Top Right: Smallest gap with ns laser (56 μm). Bottom Left: Smallest electrode track with ps laser (14 μm). Bottom Right: Smallest gap with ps laser (16 μm).

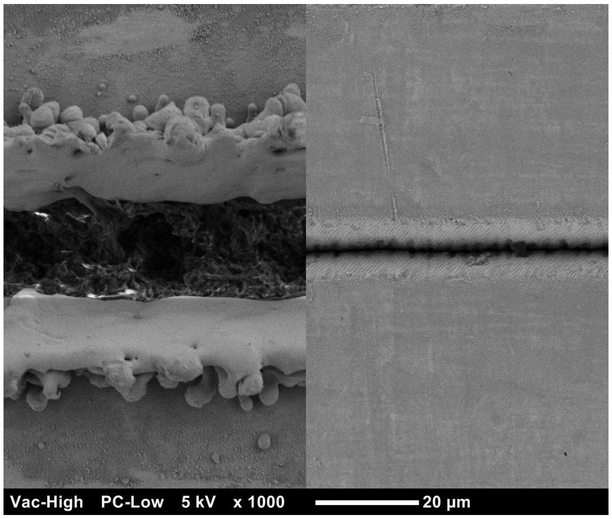

Fig. 4. Laser cuts in 12.5 μm platinum foil. Left: Cut using ns laser. Right: Cut using ps laser.

C. *Incomplete Cutting of Platinum Foil*

Inspection of samples under back-lit microscopy showed only pin points of light at the points in the design where the laser paths intersect. In all other areas no light was seen to penetrate the Pt layer. Removal of the waste material was performed without any of the electrode tracks lifting from the silicone. This indicated that the cut depth was adequate for proper separation of tracks, and that the underlying bond between Pt and PDMS remained intact (a particular difficulty with fine ns laser tracks owing to the heat effects on the PDMS.

---

[1] These figures are based on process optimization using the ns laser. Further miniaturization will be possible after integration of the ps laser into our system.

SEM imaging, as seen in Fig. 5, clearly showed the remaining Pt which had sheared as the waste material was removed. This confirmed that full depth cutting had occurred at the intersections, and revealed that approximately 1 μm of Pt foil remained along the laser paths, which was sufficiently weak to allow removal.

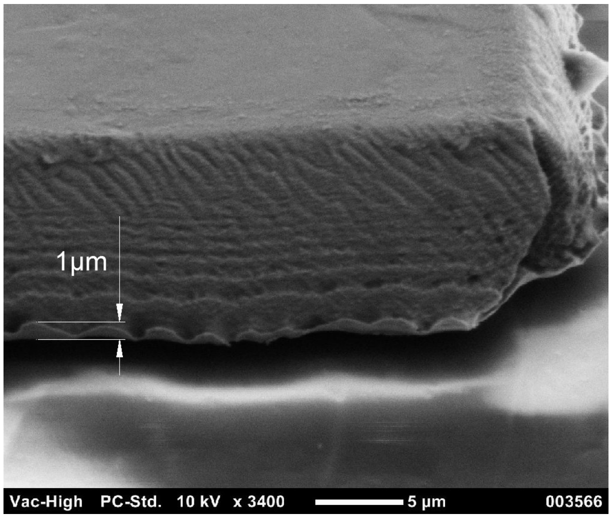

Fig. 5. An incomplete cut through a 12.5 μm sheet of platinum foil, showing the tear line with a maximum thickness of 1 μm.

D. Surface Roughening of Electrodes

Inspection of the ps laser roughened surface using the SEM, as displayed in Fig. 6, showed a well-ordered surface with a high degree of structure compared to that produced with the ns laser.

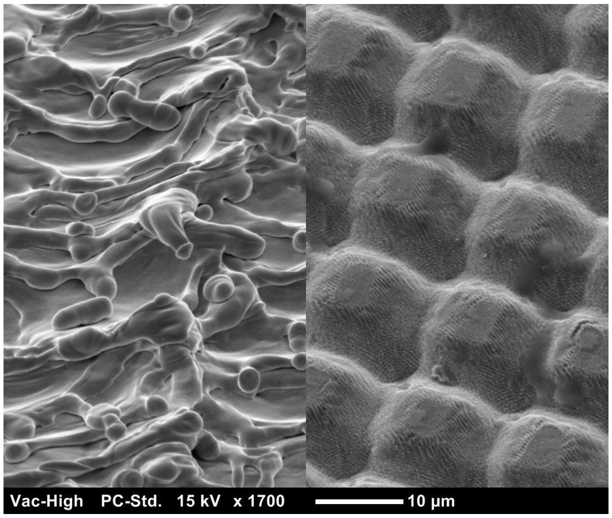

Fig. 6. Laser roughened surfaces in Pt foil. Left: Produced using a ns laser. Right: Produced using a ps laser.

IV. DISCUSSION AND CONCLUSIONS

Utilization of a folded MEA design has shown the ability to combine the size advantages of a multi-layered structure with the superior connectivity of co-planar wiring.

Laser cutting using ps laser pulses produced smaller and higher quality cuts than possible with the ns laser. Further studies on the tensile strength of wires produced with these methods will assess the advantages of the smoother cuts and smaller HAZ.

Incomplete cutting of the Pt foil showed promise as a method for protecting the substrate from laser exposure. However, further optimization is required compensate for points in the design where lines intersect, as these areas were cut through prematurely. Breaks could be inserted into one of the intersecting lines in order to remove this effect.

Surface roughening of Pt foil using ps laser pulses showed of a high degree of control of the micro-structure of the surface with an added advantage of a small nano-scale roughness absent from ns laser samples. A possible reason for this is that when roughening with a ps laser, material is being ablated away from the surface, whereas when using a ns laser, the material is melted and re-solidified. During this molten phase, surface tension will act to smooth out these nanostuctures. A later study will investigate the effect of different ps laser surface topologies on the electrical characteristics of the electrodes.

REFERENCES

[1] M. Schuettler, S. Stiess, B. V. King, and G. J. Suaning, "Fabrication of implantable microelectrode arrays by laser cutting of silicone rubber and platinum foil," *Journal of Neural Engineering*, vol. 2, no. 1, p. S121, 2005.

[2] R. A. Green, J. S. Ordonez, M. Schuettler, L. A. Poole-Warren, N. H. Lovell, and G. J. Suaning, "Cytotoxicity of implantable microelectrode arrays produced by laser micromachining," *Biomaterials*, vol. 31, no. 5, pp. 886 – 893, 2010.

[3] G. J. Suaning, S. Kisban, S. C. Chen, P. J. Byrnes-Preston, C. W. D. Dodds, D. Tsai, P. Matteucci, S. Herwik, J. W. Morley, N. H. Lovell, O. Paul, T. Stieglitz, and P. Ruther, "Discrete cortical responses from multi-site supra-choroidal electrical stimulation in the feline retina," in *Engineering in Medicine and Biology Society (EMBC), 2010 Annual International Conference of the IEEE*, 31 2010.

[4] G. J. Suaning, M. Schuettler, J. S. Ordonez, and N. H. Lovell, "Fabrication of multi-layer, high-density micro-electrode arrays for neural stimulation and bio-signal recording," in *Neural Engineering, 2007. CNE '07. 3rd International IEEE/EMBS Conference on*, pp. 5 –8, May 2007.

[5] M. Schuettler, C. Henle, J. S. Ordonez, W. Meier, T. Guenther, and T. Stieglitz, "Interconnection technologies for laser-patterned electrode arrays," in *Engineering in Medicine and Biology Society, 2008. EMBS 2008. 30th Annual International Conference of the IEEE*, pp. 3212 – 3215, 2008.

[6] T. Guenther, M. Schuettler, J. S. Ordonez, C. Henle, J. Wilde, and T. Stieglitz, "A novel interconnection technology for laser-structured platinum silicone electrode arrays," in *4th European Conference of the International Federation for Medical and Biological Engineering* (R. Magjarevic, J. Sloten, P. Verdonck, M. Nyssen, and J. Haueisen, eds.), vol. 22 of *IFMBE Proceedings*, pp. 2392–2395, Springer Berlin Heidelberg, 2009.

[7] S. S. Thanawala, D. G. Georgiev, A. Khan, R. J. Baird, and G. Auner, "Fabrication and characterization of platinum-iridium electrodes with micro-structured surfaces for neural stimulation applications," in *MRS Proceedings*, vol. 820, 2004.

[8] B. Neuenschwander, G. F. Bucher, C. Nussbaum, B. Joss, M. Muralt, U. W. Hunziker, and P. Schuetz, "Processing of metals and dielectric materials with ps-laserpulses: results, strategies, limitations and needs," vol. 7584, p. 75840R, SPIE, 2010.

[9] C. Henle, M. Schuettler, J. S. Ordonez, and T. Stieglitz, "Scaling limitations of laser-fabricated nerve electrode arrays," in *Engineering in Medicine and Biology Society, 2008. EMBS 2008. 30th Annual International Conference of the IEEE*, pp. 4208 –4211, aug. 2008.