35th Annual International Conference of the IEEE EMBS
Osaka, Japan, 3 - 7 July, 2013

# Spiral Peripheral Nerve Interface; Updated fabrication process of the regenerative implant

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*Abstract*— **The spiral peripheral nerve interface (SPNI) has been developed to record neural activity by utilizing the body's own ability to regenerate axons after injury. The implantable device is capable of providing a chronic recording array for use with technology designed to compensate for a loss of motor function. The SPNI offers a good route to establishing an effective interface to the peripheral nervous system (PNS) as the signals are enclosed within an insulating array that amplifies the axon signals for the neural recording, and reduces the amount of current necessary for stimulation. This paper presents an updated fabrication process that addresses the problems of previous designs and allows for an easier integration to external electronics via a ball-bonding technique. The updated device has been tested electrically *in vitro*, to show that it is capable of providing a reliable electrical interface to the regenerated tissue.**

## I. Introduction

A peripheral nerve interface is an implantable device that is capable of coupling the PNS to electronic circuitry. The aim of establishing such an interface is to provide assistance to a patient via muscle stimulation or prosthetics to compensate for a loss of function through injury. Many designs have been proposed to record signals from axons in the PNS [1] [2] [3] and a neuroelectric interface that relies on the PNS's natural ability to regenerate after injury [4] offers a good route to establishing a bioelectric coupling [5].

The action potentials from individual axons within the PNS give rise to extremely small signals in the extracellular space (≈10μV), which are difficult to detect in the low resistive medium that surrounds the axons. Furthermore, for myelinated axons, the current flows into the extracellular space from the regularly inter-spaced 'nodes of Ranvier', that propagates the transfer of the signal along the nerve. By surrounding the regenerated axon with an insulating medium, the axon signals can be increased for neural recording and the amount of current required for stimulation is reduced [6]. The spiral peripheral nerve interface (SPNI) [7] has been developed to provide a microchannel array into which regenerating axons grow [8], where electrodes integrated into the channel cavity are capable of recording from the regenerated tissue. The microchannel array has previously been shown to be capable of recording from, and stimulating, regenerated nervous tissue *in vivo* [9] [10].

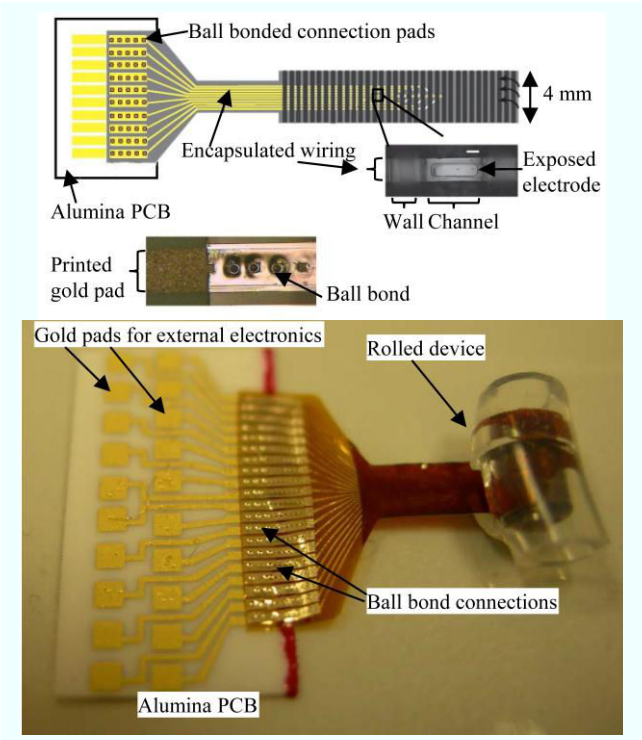


Figure 1. Updated design of the spiral peripheral nerve interface including the Ball Bonded connections; Top: Basic schematic of an unrolled SPNI device with 100 micron wide channels to allow for axon regeneration, exposed electrode sites for recording and gold ball bonded connections to an alumina PCB. Bottom: Rolled SPNI electrode array bonded to alumina PCB.

Establishing a durable and practical connection to external electronics has been a long term concern in the progression of the SPNI, as many standard interconnection methods are not suitable for applications inside the human body, either due to biocompatibility problems or due to degradation of the coupling as a result of biological fluids in the PNS. This paper presents an updated fabrication process that addresses the problems of the earlier devices and allows an easier

* Funding for this work came from the Defence Science and Technology Laboratory (DSTL: X1000048489) and the Engineering and Physical Sciences Research Council- MR Basic Technology Program under the Grant EP/C52330X on "Bioelectronics Interfaces for Peripheral Nerve Repair."

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integration to external electronics via ball-bonding to printed circuit boards. This 'Microflex' technology [11] creates an electrical coupling by the thermosonic bonding of a gold ball through the substrate of the implant to a gold surface underneath. The gold-gold bond is biocompatible and durable in the physiological environment and has been successfully incorporated into other nerve interfaces [12] [13].

The updated SPNI is designed to utilise this interconnection technique and the impedance of the new design has been tested *in vitro* before, during and after a prolonged exposure to a simulated physiological environment.

## II. Updated Design

To make the SPNI compatible with the Microflex technology, the substrate layers were made of photosensitive polyimide and designed to have a 60µm diameter hole through which the connection could be made. During the development of the current SPNI device, it was found that, to achieve a reliable ball bond through the connection hole, the photosensitive polyimide (PSPI) substrate layer should be no thicker than 20µm. This conflicts with the requirement that the gold wiring layer should be on the neutral plane of the structure to avoid stress on the thin gold film during rolling [7]. Earlier work had suggested that a substrate thickness of 37µm should be used.

To meet both of these requirements, the new device was designed to have a 20µm-thick, first substrate layer, which contained the connecting area. On top of this, a 17µm-thick layer was defined that did not cover the connecting area.

This creates a 17µm high step which the gold tracks must cross before they enter the rolled section of the device, however the slope in this region is relatively gentle under the processing conditions that we used, see Figure 2. It was found that there was no problem in maintaining the electrical continuity, or patterning the thermally evaporated gold track over the step.

Finally, whilst it is necessary to use PSPI as a substrate to create connection holes for ball bonding, PSPI adheres very well to a silicon carrier wafer, which is used in the preferred method of fabrication, so it was not possible to peel the devices mechanically. Thus, a suitable sacrificial material needed to be chosen that was compatible with other fabrication processes associated with the original SPNI process. Polymethylmethacrylate (PMMA) was found to be a suitable material for this purpose, as it has been demonstrated to be a compatible sacrificial material with photosensitive polyimide PSPI and is simple to use with standard clean-room processes [14].

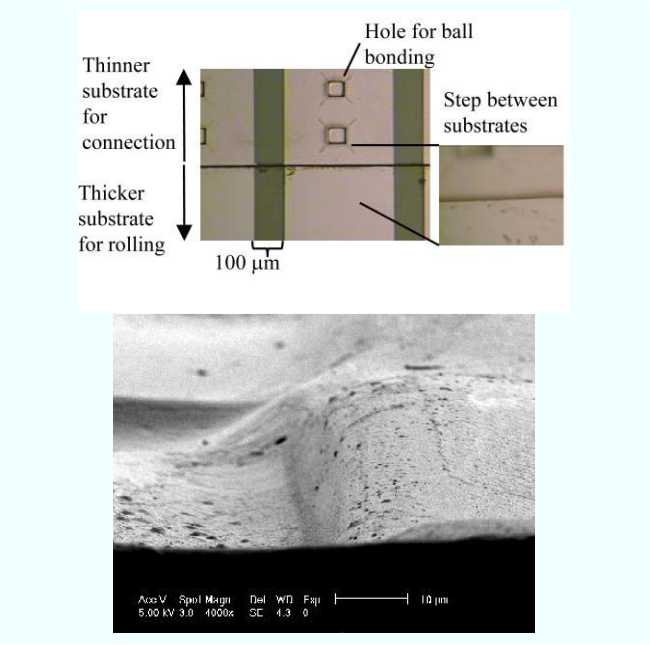


Figure 2. Top: Step between the connection area and wiring area of the device. Bottom: Scanning Electron Microscope image, to show that step is sloped. The dark particles on the surface of the sample are fragments of dirt.

## III. Fabrication

The devices were fabricated according to the process flow illustrated in Figure 3.

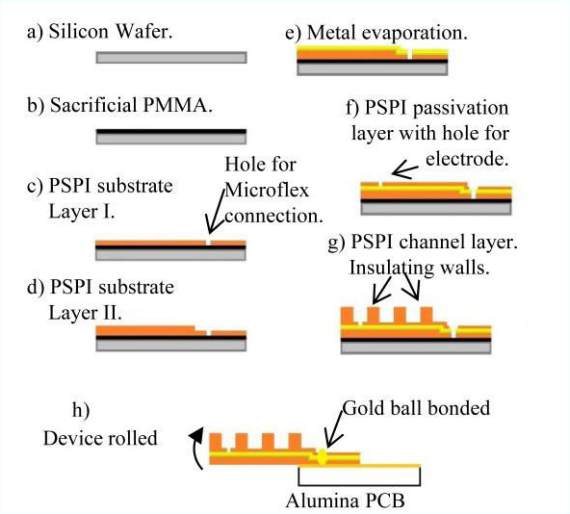


Figure 3. Representation of the fabrication process; a) a Standard Silicon Wafer, Cleaned, b) 5µm Sacrificial PMMA Layer, c) first substrate layer is spun and developed to leave a hole through the substrate for bonding, d) second substate is spun and developed to have gold layer on the neutral plane for rolling, e) an ≈80nm Chrome adhesion layer and ≈200nm Gold electrode layer are thermally evaporated after plasma etching, f) a 5µm PSPI passivation layer is spun onto the metal layer, g) a 100µm-thick PSPI layer is soun to form the insulating walls of the microchannel array, h) after release, sample is rolled, inserted into silicone tube and ball-bonded to an alumina PCB.

### A. Sacrificial and Substrate Layers

The device was built up in layers starting with the PMMA sacrificial layer. A 4" silicon wafer was cleaned and a layer of 5µm PMMA was spun and baked at 180°C for 10 minutes on a conventional hot plate.

The first substrate layer was prepared by spinning a 20µm-thick layer of PSPI (Durimide 7020, Fujifilm) onto the PMMA. After a softbake the layer was exposed under a g-line Ultra- violet lamp using a Canon Mask aligner. The photosensitive polyimide was developed in HTRD-2 (Fujifilm) and RER600 (Fujifilm) to define the overall footprint of the device, and via holes for the ball-bonded connections. The first substrate was partially hard baked at 180° C for 10 minutes, to improve adhesion to the second substrate layer. In Figure 2, small stress cracks can be seen at the corners of the holes. These were not present on every sample.

The region that supports the gold tracks is fabricated using a second PSPI layer of 17µm, which was spun directly on top of the first substrate layer. The subsequent development procedure of the first layer was repeated to create the dual layer substrate as described. The substrate is baked at 180°C for 1 hour and placed in oxygen plasma barrel etcher (Diener Electronics, Femto) for 10 minutes to 'de-scum' any remaining PSPI from the connection windows and to activate the surface of the substrate to aid adhesion to the subsequent metal layers.

### B. Metal Evaporation

A thin Chrome adhesion layer (≈80nm) was thermally evaporated onto the substrate followed by a layer of Gold (≈200nm) (Polaron Vacuum Evaporator, E6100) to provide the metal for the integrated electronics of the recording interface. The gold was structured into connection pads, electrode sites and the wiring that connects the two via a photolithographic, wet etch process. This uses a 12µm layer of SPR220 (Shipley) photoresist, and to remove the unwanted metal the wafer was then immersed in gold etchant (Pottasium Iodide, Chestech) for 40 seconds and chrome etchant (Chrome Etch, Chestech) for 15 seconds.

### B. Passivation and Channel Layers

Electrode leads were encapsulated with a 5µm layer of PSPI (Durimide 7505, Fujifilm), baked and exposed in the same way as the other PSPI layers. The electrodes and the connection pads are left open to form a 30µm x 100µm electrode site and a 400µm x 1mm pad to allow for neural recording and connection see Fig.1 and Fig.2. The passivation layer was then de-scummed and further cleaned in an ozone etcher (Jelight, UVO Cleaner) to remove any remaining organic matter from the metal surfaces.

A 100µm PSPI layer was spun and baked at 0.5°C per minute between 30°C and 70°C, and then at 1°C per minute up to 100°C where it was held for 10 minutes. The solvent of the polyimide cannot evaporate too quickly otherwise bubbles and other defects form in the PSPI layer. The layer was allowed to cool for at least 30 minutes before exposure. This final layer was exposed and developed as before, except to help the development process of the thick layer the wafer is immersed into the RER600 and agitated using ultrasound for 30 seconds at the end of the development cycle. The thick PSPI layer forms the insulating walls of the device and once rolled provides the microchannel array into which the regenerating axons grow.

After the final layer has been developed the wafer was again de-scummed and UV-Ozone cleaned. The processed wafer was cured in $N_2$ at 350°C for 1 hour in a convection oven, and was left for at least 5 hours to cool to room temperature before the sample can be released from the carrier wafer.

### B. Release, Rolling and Bonding

To release the device the samples were submerged in MIBK(Methyl-isobutyl Ketone) and IPA at a ratio of 3:1 and left for at least 24 hours. Using IPA and a razor blade the samples are peeled from the wafer and cleaned using acetone and IPA ready for rolling.

To roll the device into the spiral configuration the end of the device was clamped into a pair of tweezers that were connected to a hand operated rotating mechanism. The tweezers were gently turned to form a tight spiral in the direction perpendicular to the channels and so that the channels were on the inside of the roll, as indicated by the red arrow in Fig.3. The rolled device was inserted into a silicone tube (1.5mm internal diameter and 3mm external diameter) which provides a number of useful functions; it stops the channels from unravelling, allows for easier handling for implantation and provides an initial guide that leads the nerve stump into the microchannel array.

To make external connections to the electrodes the samples were ball bonded through the hole on the connection pads to alumina printed circuit boards underneath (ESL Europe) using 25 micron gold wire and a manual ball bonder (Kulicke and Soffa, Model 4522). Each electrode pad is connected using at least 6 bonds to provide both an electrical coupling and a mechanical support for the device.

## IV. *In Vitro* Testing

*In vitro* testing has been carried out to investigate the chronic durability of the implant with respect to the physiological environment of a human patient. To simulate the devices ability to provide a long-lasting and stable recording platform impedance testing was carried out, over a period of one month, on an SPNI device. At the start of the *in vitro* test sequence, impedance spectra for ten electrodes on one unrolled device were measured at room temperature using a platinum counter electrode in saline solution. An Agilent 4924A impedance analyzer was used for this measurement with a 5mV excitation. An additional PCB, made of a conventional laminate, was required to make connections for the impedance analyzer and was wire-bonded to the alumina PCB. At 1kHz, the mean value of the impedance of the electrodes was 352kΩ (N=10) with a range of 120kΩ to 600kΩ before prolonged exposure to saline.

The device was then exposed to a saline solution (8.6g of NaCl, 0.3g of KCl and 0.33g of $CaCl_2$ per one litre of deionised water) held at 40°C, and impedance spectra were measured at a number of timepoints up to 30 days. To perform the measurement, the sample was removed from the saline and tested in the same way as the first measurements, which required the repeated disconnection and connection of the additional PCB mentioned above. The variation of the spectra of a typical electrode between 0 and 30 days is shown in Figure 4. At the end of the 30 days the mean value of the electrodes was 358kΩ, with a range of 98kΩ to 585kΩ. There was some variation in the spectra between the first and last recordings, suggesting that the there had been minor changes in the surface properties of the electrode sites. But there was no evidence that the quality of thee interconnecting ball bonds had been dramatically affected by the saline solution.

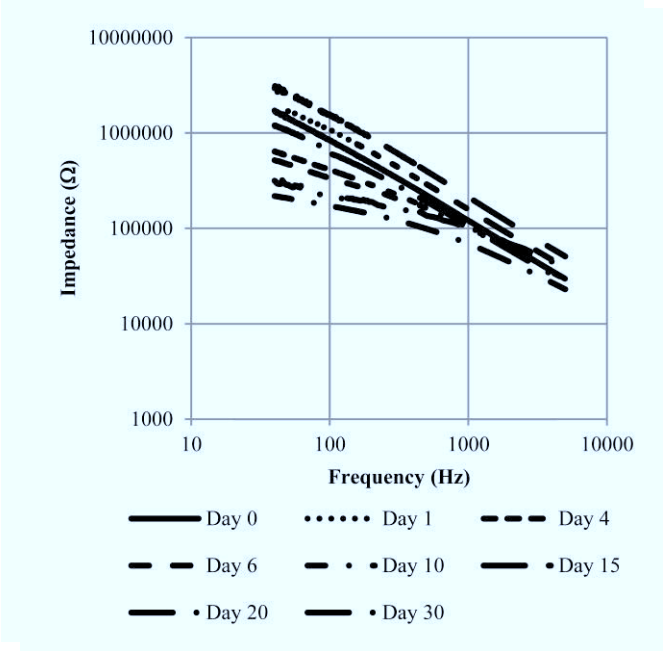


Figure 4. The impedance of a typical electrode of the SPNI after exposure to a simulated physiological environment.

The variation seen across the exposure period is most likely caused by the necessity of removing and replacing the connecting PCB needed to perform the impedance test. Care was taken to ensure that the SPNI was undamaged and replaced in the same position after handling. There was no evidence of swelling or other structural degradation of the device over this period.

## V. Conclusion

The updated fabrication process is capable of producing peripheral nerve interfaces that have a robust integration to external electronics. The dual layer substrate successfully solves the fundamental problems with of the earlier devices, without losing the mechanical integrity of the electrode layers. We have successfully updated the SPNI device to allow for an external connection regime via Microflex technology, which provides both mechanically and electrically robust connections that could withstand chronic implantation. Also, this paper further demonstrates the ability of PMMA as a sacrificial material for use with photosensitive polyimide, opening the range of possible uses of the photosensitive polyimide.

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