ON-DEMAND NEURAL PROBES

Maria G. Kindlundh[a], Peter Norlin[a] and Ulrich G. Hofmann[b]
[a]Acreo AB, Electrum 236, SE-164 40 Kista, Sweden
[b]Institute for Signal Processing, Medizinische Universität zu Lübeck, Seelandstr. 1a, D-23569 Lübeck, Germany
Tel.: +46 8 632 77 34, Fax: +46 8 793 94 83, e-mail: maria.kindlundh@acreo.se

ABSTRACT

We demonstrate a method to vary recording site distribution on Si neural probes with a maskless finishing process. The concept is based on the use of a direct write laser (DWL) lithography on one mask layer thus enabling relatively fast on-demand processing of wafers with semi-custom designs at a reasonable cost.

Up till now, neural probes have only been produced with fixed standard mask sets, which is straightforward but very costly for small production volumes and inflexible for electrode distribution redesigns.

Using a DWL machine enables us to selectively choose which electrodes, from a standardised electrode array, should be active. We propose a probe model with eight shafts and 64 recording electrodes distributed in 11 different ways. The process was evaluated on some of our standard Acreo neural probes, and showed as a proof of concept. Impedance characterisation was performed on active and inactive electrodes, and on electrodes with varying active area.

INTRODUCTION

Micro system technology is well suited to batch-fabricate fork-like probes with multiple electrodes, intended for recording or stimulation in neural tissue [1, 2, 3]. However, a fundamental problem is that the desired spatial electrode distributions are usually differing between separate neuroscience experiments. Neural probes that are available today are designed according to specifications from specific scientific user groups or offered as fixed standard designs.

Our company, for example, has recently started a small-scale prototype service with a number of different models with up to 64 microelectrodes distributed on one to eight shafts. The Center for Neural Communication Technology at the University of Michigan offers 12 different models on their web site [4]. Bionic Technologies, a spin off company from the University of Utah also offers neural probes, in an alternative "bed-of-nails" configuration [5].

A commercial setting prohibits custom made designs for individual researchers due to the associated costs and lead times. In this paper we report on a concept to generalise the probe design and modify the production process, so that relatively fast on-demand processing of a limited number of wafers with semi-custom / semi-standard probe designs will be possible.

BASIC CONCEPTS AND DESIGN

The main elements of fork-like structures are described in figure 1. From a user perspective or from the anatomical requirements respectively, the main design parameters of the neural probes are: (1) the electrode site centre-to-centre (c/c) distance a, (2) the shaft c/c distance b and (3) the shaft length L, see figure 1.

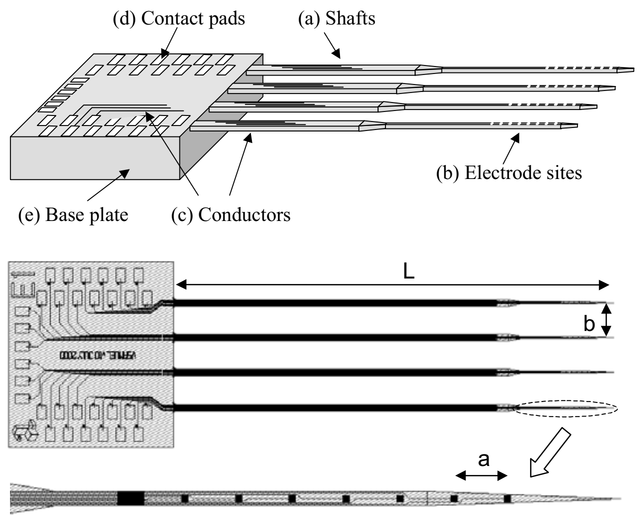

Figure 1. Schematic illustration of a neural probe (top) and a CAD layout showing the design parameters a, b and L (bottom).

Together the parameters a and b define a 2-dimensional array of electrode sites at which individual recordings (or stimulations) can take place. To limit the design space a standardised electrode grid may be useful. After analysis of several probe designs, we suggest a standardised 8 × 32 coordinate "snap grid" with a = 50 µm and b = 250 µm. The grid then defines 256 possible positions for the electrode sites, see figure 2. However, limitations on silicon area and shaft dimensions make 256 bond pads and conductor traces impractical. In our case, we have worked with 32 or 64 connected sites. In the case of 64 sites on a 256-point grid, we have found that 11 different main designs suffice to approximate most other permutations well enough.

Multiple shaft lengths, L, could in principle also be implemented, but that would increase the design complexity. Experimental results have shown that a standard shaft length of 7 – 8 mm would be a good compromise for most end users.

The number of conductors on each shaft is limited by the shaft width and conductor line width. The shaft width

0-7803-7731-1/03/$17.00 ©2003 IEEE

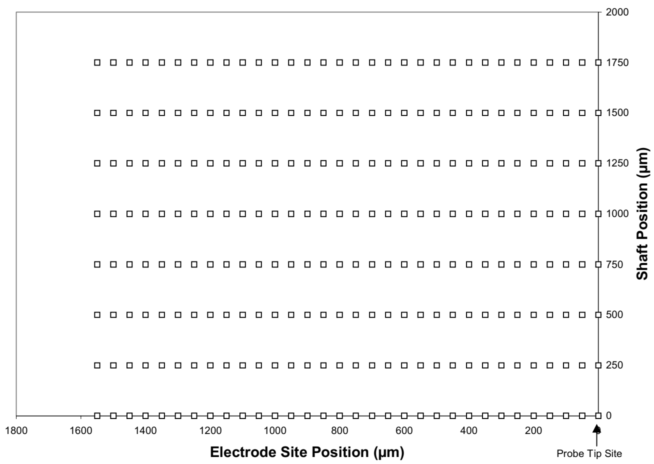

Figure 2. Proposed snap grid for on-demand probes.

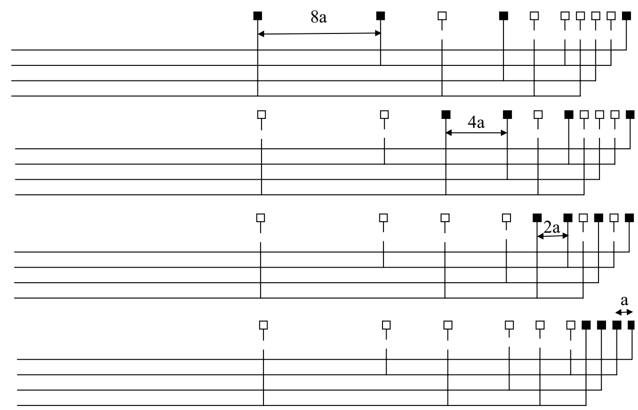

Figure 3. Example showing how 10 electrodes can share 4 conductors. By cutting six of the connections, 4 different site distances (a, 2a, 4a or 8a) can be implemented.

should be kept as small as possible to minimise tissue damage. The number of conductors, in turn, limits the number of possible electrode sites. To have different electrode distributions selectively connected to the same conductors is thus a way to make efficient use of the available space. Figure 3 illustrates how this would be possible, starting from a common configuration of electrode sites and conductors and ”programming” different patterns of connected sites.

A standard mask set is inflexible for redesigns and varying demand for different designs, therefore we prefer some kind of adjustable technique that allows for programmable designs. A possible technique to be considered is to use programmable fuses that can be blown by a high current [6], laser cutting or ultra-sonic cutting of conductors. Another similar approach is laser destruction of link insulators. A slightly different method is the selective opening of windows in the passivation layer on top of the electrode sites. This opening will make the electrode site active.

We found the electrode window approach a straightforward and cost efficient way to proceed. A sample CAD-design of an “electrode window programmable” probe shaft is shown in figure 4, and demonstrates three different electrode distributions on one shaft with 16 electrodes sharing eight conductors, *i.e.* eight opened sites.

Selective opening of windows can of course be accomplished by custom made stepper masks. To avoid this rather inflexible method we used a programmable direct write lithography (DWL) machine to define the electrode window mask layer instead. The general drawback of DWL is its low throughput, as it works in a scanning mode. Our application seems, however, ideally suited for DWL, as only one mask layer needs to be written and the complexity of the pattern is limited. The other mask layers will still be defined by conventional, *e.g.* stepper, lithography equipment.

Additional design possibilities due to the DWL lithography technique are *e.g.* to alter the size of the electrode window and to program each shaft, within the same probe, in its own pattern.

FABRICATION PROCESS

We have previously presented a fabrication process for neural probes based on double-sided Deep Reactive Ion Etching (DRIE) of Silicon-on-Insulator (SOI) substrates and shown the manufacture of 32-site [3] as well as 64-site recording probes [7]. For cost reasons we used our first generation of 64-site probes, to show a proof of concept of the on-demand fabrication principles described above. The conductor pattern on these probes provides individual connections to each site. During the process flow shown in figure 5, we routed some wafers into a side-track at step (e). The resist-coated wafers were exposed in Heidelberg Instruments DWL 2.0 followed by development and reactive ion etching (RIE) of the Si_3N_4.

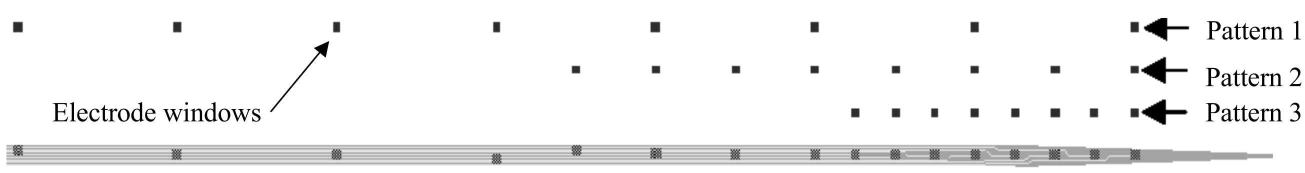

Figure 4. CAD design of a probe shaft with 16 sites. The shaft can be programmed to three different site c/c distances (50, 100 or 200 µm), see squares above the shaft.

This resulted in differently spaced and sized electrode windows in the passivation Si_3N_4 layer.

The DWL equipment uses standard CAD files (GDSII) as raw input data. The light source is a HeCd laser (λ = 442 nm, E ~ 70 mW). An acousto-optic modulator (AOM) splits the laser beam into 30 parallel beams. Each beam is modulated on/off according to the data pattern and an acousto-optic deflector (AOD) scans the beams 200 µm in the x-direction, at the same time as the wafer is moved in the y-direction. An interferometer controls the wafer position relative the laser beam, see figure 6.

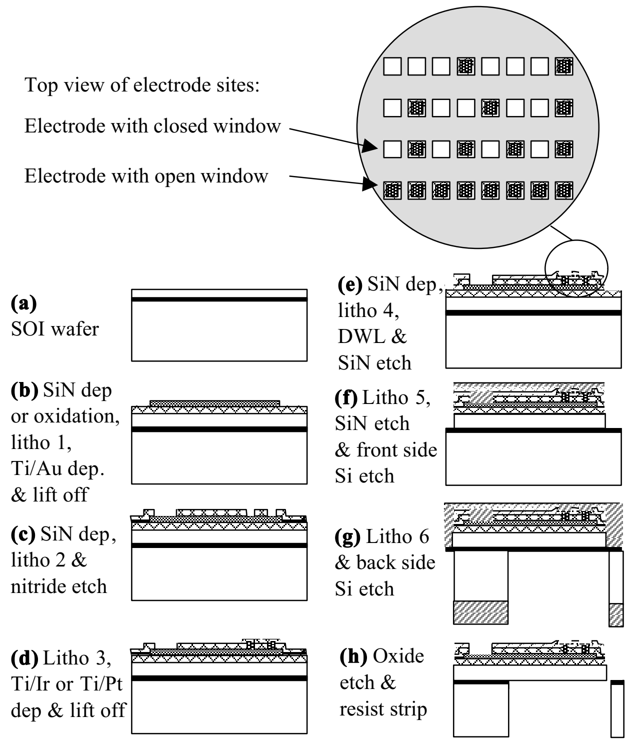

Figure 5. Schematic cross-section of the neural probe fabrication process (not to scale). In step (e) windows are selectively exposed with DWL and opened in a reactive ion etch.

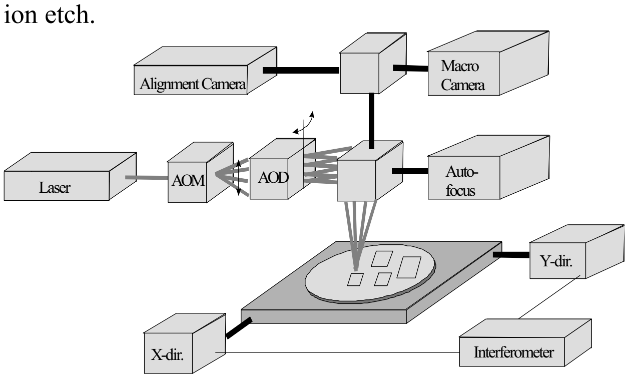

Figure 6.Schematic picture of the DWL principle.

If a large number of wafers will be exposed in the DWL, the process time can be minimised if all contact pads on the base plate (see figure 1, top, (d)) are exposed by conventional lithography equipment and only the electrode sites are exposed in the DWL equipment.

RESULTS

Figures 7 and 8 show scanning electron microscope (SEM) pictures of a neural probe where the electrode distance is varied by selective opening of windows in the top Si_3N_4 layer using DWL, and RIE. Figure 9 demonstrates the result from selective opening of windows with different sizes. In this picture the underlying platinum electrode, recognised by its outline, is 22 µm × 22 µm.

As figures 7 – 9 show, the alignment between stepper lithography and DWL worked well. Including some DWL alignment marks in the stepper CAD design is a good idea in order to minimise process difficulties.

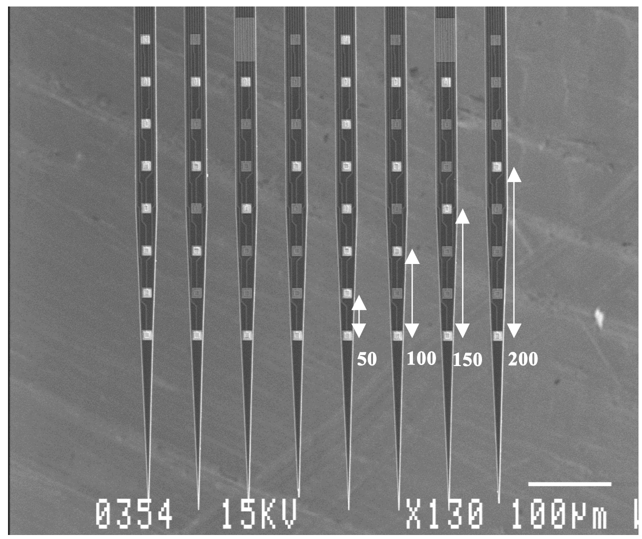

Figure 7. SEM picture of selectively opened electrode windows in Si_3N_4 layer on probe shafts. The site distance varies from 50 µm to 200 µm. Bright squares are opened windows.

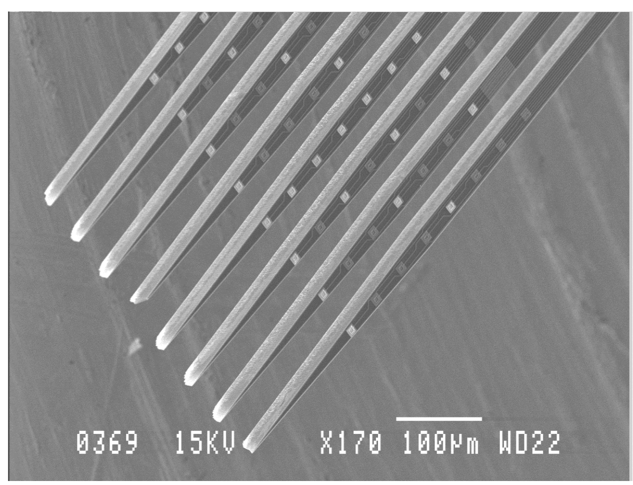

Figure 8. SEM picture of the same probe shafts and electrode sites as in fig. 7, but from a side view.

The Pt microelectrode impedance was characterised, in 0.9 % saline solution, by 3-point-measurements with an HP 4284A Precision LRC Meter, a Pt counter electrode and a Ag/AgCl reference electrode.

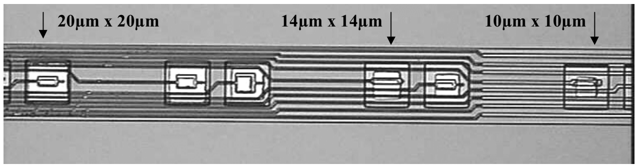

Figure 9. Photomicrograph of selectively opened electrode windows with varying size, side 20, 18, 16, 14, 12 and 10 µm from left to right.

The results show ~15 times higher impedance at 1 kHz for closed compared to opened 10 µm × 10 µm windows, see figure 10, which is considered sufficient for signal discrimination. If desired, using a thicker Si_3N_4 passivation layer than the 4600 Å used in this experiment can further increase the closed window impedance. As a reference, the impedance from a contact pad not connected to any electrode site was also measured, see dotted line in figure 10.

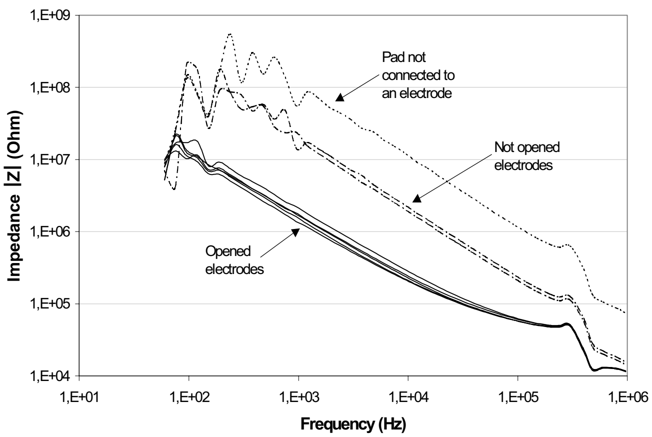

Figure 10. Impedance magnitude at different frequencies for closed and opened 10 µm ×10 µm Pt electrodes.

Figure 11 shows the magnitude of the measured impedance for different window areas. A reference line, representing a closed window over a 10 µm × 10 µm Pt electrode is also included in the plot. Differently sized electrode window areas could provide a possibility to vary and tailor the trade-off between the signal-to-noise ratio and the spatial selectivity of the microelectrodes.

CONCLUSIONS

In this paper a concept for on-demand manufacture of semi-custom neural probes is presented. The concept is based on direct write lithography to selectively open windows in the insulating Si_3N_4 layer on top of the Pt electrode sites. We show how a large parameter space for neural probes can be covered and manufactured on-demand, without having to redesign the entire lithographic probe mask set. The approach presented here is based on the use of the standardisation of some probe parameters, such as c/c distance between electrode sites and c/c distance between probe shafts, in combination with a technique for programmable electrode sites.

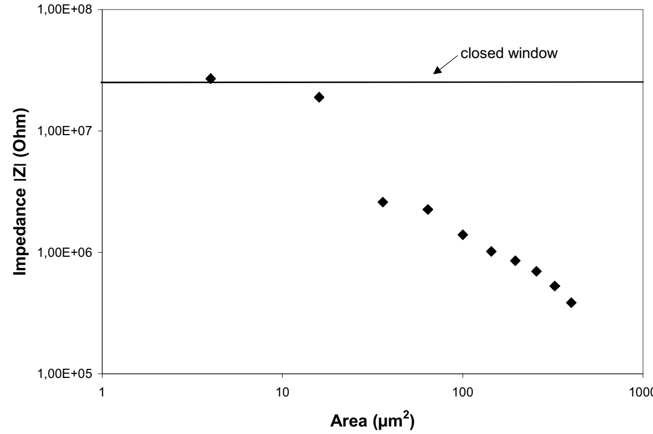

Figure 11. Electrode impedance magnitude at 1 kHz as function of window area, compared to a closed window.

The concept is demonstrated on neural probes in the manufacture of microelectrodes with differently spaced and sized electrode windows.

Acknowledgements

The authors wish to thank Sara Ahlberg, Sirpa Persson and Helena Strömberg for their skilled help with the device fabrication. We also thank Per Ericsson for help with the DWL software and Ken Yoshida, Aalborg University, for valuable advice on impedance measurements. The European Commission under contract no. IST-1999-10073 supported this work.

References

[1] D. T. Kewley, M. D. Hills, D. A. Borkholder, I. E. Opris, N. I. Maluf, C. W. Storment, J. M. Bower and G. T. A. Kovacs, “Plasma-etched neural probes”, *Sensors and Actuators*, A **58**, 27-35 (1997).

[2] K. Najafi and K. D. Wise, “An implantable multielectrode array with on-chip signal processing”, *IEEE J. Solid-State Circuits*, **21**, 1035-44 (1986).

[3] P. Norlin, M. Kindlundh, A. Mouroux, K. Yoshida and U. G. Hofmann, “A 32-site neural recording probe fabricated by DRIE of SOI substrates”, *J. Micromech. Microeng*., **12**, 414-19 (2002).

[4] “Passive Multichannel Recording and Stimulating Electrode Arrays – A Catalog of Available Designs”, 1999, webpage http://www.engin.umich.edu/center/cnct/

[5] P. K. Campbell, K. E. Jones, R. J. Huber, K. W. Horch and R. A. Normann, “A silicon-based, three-dimensional neural interface: manufacturing processes for an intracortical electrode array”, *IEEE Trans. Biomed. Eng.* **38**, 758-68 (1991).

[6] M. D. Gingerich, J. F. Hetke, D. J. Anderson, and K. D. Wise, “A 256-Site 3D CMOS Microelectrode Array for Multipoint Stimulation and Recording in the Central Nervous System”, *Proc. 11th Int. Conf. on Solid-State Sensors and Actuators (TRANSDUCERS’01)*, Munich, Germany, 2001, p. 416-19.

[7] U. G. Hofmann, A. Folkers, F. Mösch, D. Höhl, M. Kindlundh and P. Norlin, “A 64(128)-channel multisite neuronal recording system”, *Biomedizinische Technik*, **47 (E1)**, 194-97 (2002).