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Novel Monolithic Silicon Probes with Flexible Parylene Cables for Neural Prostheses

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Abstract

This work presents the first parylene-insulated silicon probes, which are used for neural prostheses to record high-level cognitive neural signals. With parylene technology, our probes have several advantages compared with the current devices. First, instead of inorganic materials (e.g. SiO_2 and Si_3N_4), the electrodes and conduction traces on the probes are insulated by parylene, an easily-deposited polymer with mechanical flexibility and biocompatibility. As a result, the probes exhibit better electrical and mechanical properties. Second, flexible parylene cables are monolithically integrated with the probes, which arm the probes with very high flexibility to be easily assembled to a high density 3-D array and at the same time provide an ideal method to transmit neural signals through skull during chronic recording. The all dry fabrication process and an 8×2 probe array (64 electrodes) were demonstrated. The probes were successfully tested electrically and mechanically in rat and monkey cortex. Neural signals were properly recorded.

Keywords: Neural probes, Flexible parylene cables, Neural prostheses

1 INTRODUCTION

An important common goal, although futuristic, is to achieve cortex prostheses using implanted probes to control robotics by pure thoughts (Fig. 1). The first beneficiaries are likely to be patients with spinal-cord injuries, peripheral nerve disease, or amyotrophic lateral sclerosis [1]. To achieve this, 3-D neural probe is needed to record cortex cognitive signals. Various researchers (including the Twente, Washington, Utah and Michigan) have attempted this must-have device for decades but current 3-D neural probe is still far from being satisfactory.

Ideally, a 3-D multielectrode neural probe should have integrated electronics for high S/N and flexible cables for through-skull interconnection. Unfortunately, there are two major problems with the current devices. The first one is related to insulating/protecting materials. It's granted that probes have to use silicon when IC is necessary. The question is about insulating materials such as SiO_2 and Si_3N_4, which are all subjective to body-fluid corrosion. Worse yet, they are brittle and have reliability issues under stress. The

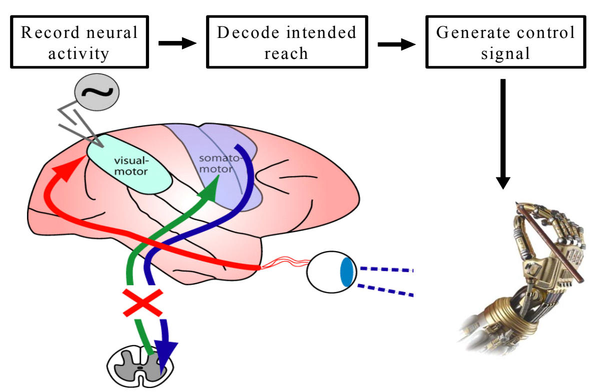

Figure 1. Schematic of the pathway of information flow for the cognitive-based neural prosthetic paradigm.

second problem is related to through-skull interconnect. Signals obtained by probes have to be cabled out of skull. Even with telemetry, a cable is still needed to link the in-cortex probes to a telemetry platform that can only be safely mounted under the skull. Cables are important. For example, the Michigan group made the famous silicon cables [2], but their cables are unfortunately subjective to fracture failure. Low yield is especially reported by the authors for longer cables. This work first presents a new method to make 3-D silicon probes enabled by parylene technology. Instead of common inorganic materials (e.g., SiO_2 and Si_3N_4), our electrodes are insulated completely by parylene, an easily-deposited polymer with mechanical flexibility and biocompatibility. More importantly, this new probe design allows integration of monolithic flexible cables by DRIE process. Better yet, the flexible cables enable high density 3-D arrays for chronic implantation. As a result, this work reports the first parylene-insulated silicon probes, the make of a 3-D probe array (64 electrodes) and the validation of the use of probes in rat and monkey cortex.

2 DEVICES DESIGN

The geometric design of the probes is shown in Fig. 2. The front part is floating silicon probes, which is connected with silicon coupling part via a 20mm long flexible parylene cable. Wire bonding is used to electronically connect the silicon coupling part to a small PC Board. Fig. 3 shows two layout designs for the floating silicon probes: long shank probes and short shank probes, aiming different neuron layers in monkey cortex. For the long shank probes, eight shanks (6mm and 8mm long alternately, 500µm spacing) with four gold electrode sites each (20µm × 20µm in 300µm spacing) are in front of a thicker plate, resulting in a 32-site 2-D probe array. Reference electrodes are on the two side 4mm long shanks. The short shank probes have four shanks (1mm and 1.5mm long alternately, 500µm spacing) with four gold electrode sites each (20µm × 20µm in 200µm spacing), therefore, a 16 site 2-D probe array is made. Two side 4mm long shanks are designed for the reference electrodes and the anchors. In this new design, multi-site electrodes are sandwiched by insulating/protecting parylene.

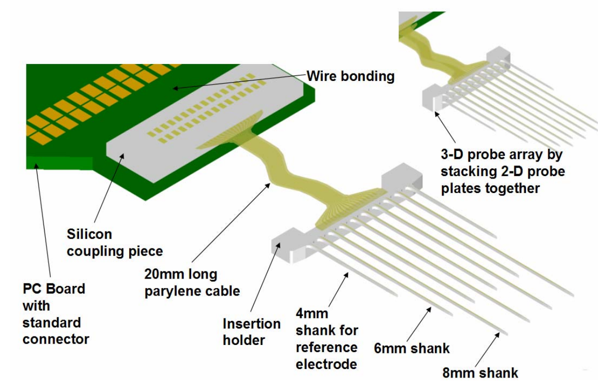

Figure 2. Geometric design of the probes.

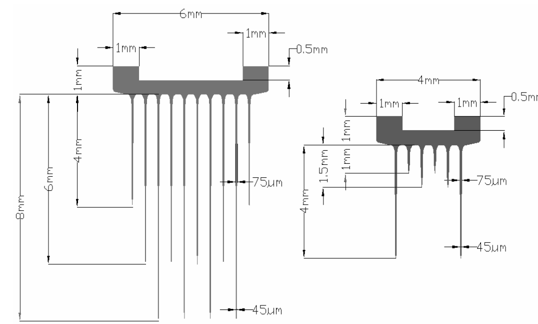

Figure 3. Layout design of the floating silicon probes.

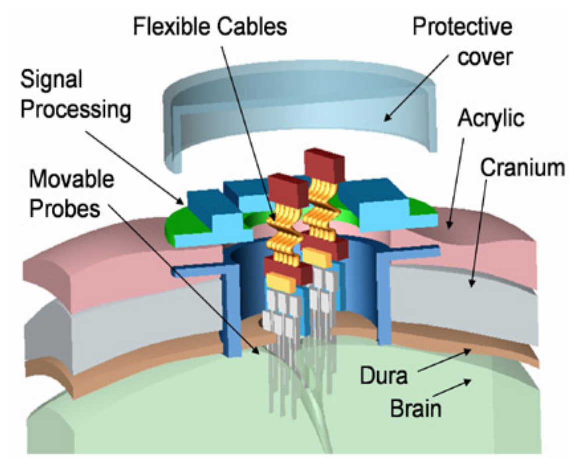

Figure 4. Schematic of cortical implantation using parylene cables.

The target shaft thickness is 100 µm; the shaft width is 75 µm at the bottom and 45 µm at the outmost section. The lateral taper angle of the chisel-shaped tip is designed to 5°. The width of the trace lines at the outmost shaft section is 2 µm. 3-D arrays are made by stacking 2-D probes together. The concept of through-skull use of the parylene cables are shown in Fig. 4.

3 FABRICATION PROCESS

The silicon probe and parylene cable fabrication process flow is shown in Fig. 5, which is based on DRIE double side

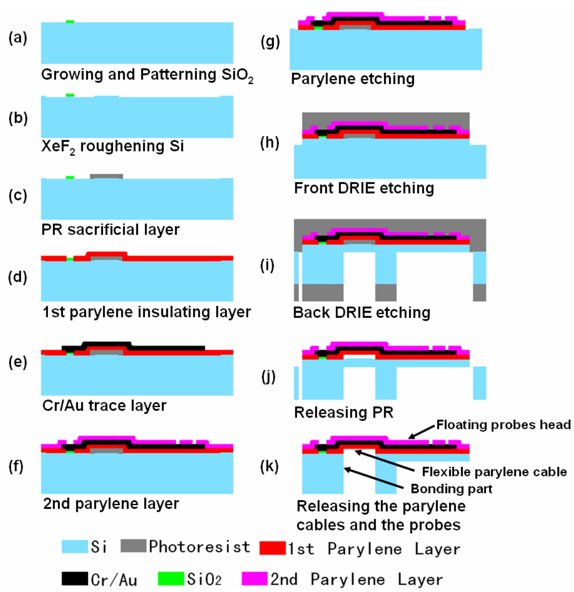

Figure 5. Fabrication process flow.

etching technology. Lift-off parylene skin technique is used to fabricate the flexible cables. Instead of silicon-on-insulator (SOI) wafers [3], double-side-polished (DSP) wafers are used, which are less expensive. (a) 3000 Å SiO_2 is thermally grown and then patterned for insulation of wire bonding pads. (b) XeF_2 etching is performed on the probes top silicon surface to enhance the adhesion property between silicon and parylene. (c) A photoresist sacrificial layer is patterned on the place where the parylene cables will be. (d) An 8 μm parylene C insulating layer is conformably deposited. (e) Cr/Au (~100 Å/2000 Å) is e-beam evaporated and patterned by lift-off to form the conduction traces. (f) A second parylene C layer (~2 μm) is deposited as a protective layer; the electrode sites and bonding pads are opened by plasma etching. (g) The parylene layers are patterned along the probe shape by plasma etching. (h) Front side DRIE (deep reactive ion etching) (~100 μm deep) is performed to define the probe shape into silicon. (i) Back side DRIE defines the probe thickness, and releases the probes. During backside DRIE etching, the probes are protected by baked photoresist. By depositing protection photoresist on the backside of the finished probes die by die, the probe thickness can be well controlled in 5μm range on whole wafer. (j) Release all the mask and sacrificial photoresist. (k) Break the thin silicon film underneath the parylene cables to release them; break the connection parts between the wafer and the probe plates to release the whole devices.

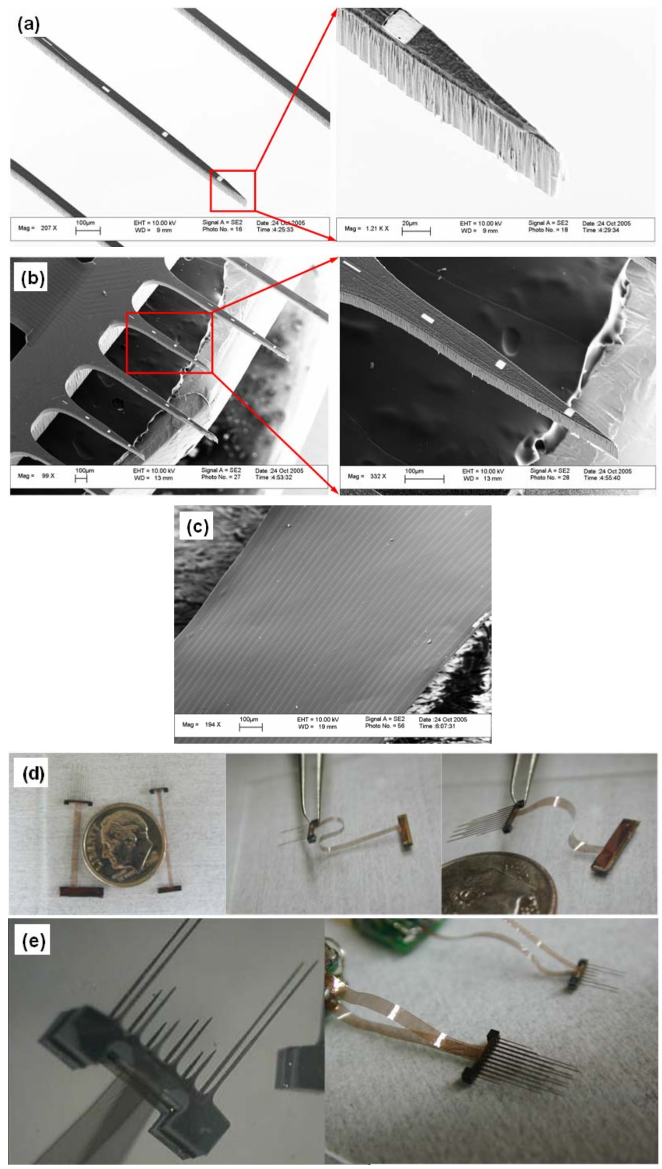

Figure 6. Pictures of the fabricated probes. (a) SEM pictures of the long shank probes; (b) SEM pictures of the short shank probes; (c) SEM picture of the parylene cable; (d) optical pictures of the 2-D probe arrays with parylene cables; (e) optical pictures of the 3-D probe arrays (4×2 with 32 electrodes and 8×2 with 64 electrodes) stacked by two 2-D probes plates.

4 EXPERIMENTAL RESULTS

Probes fabrication results are shown in Figure 6. The probes were successfully tested electrically and mechanically in rat and monkey cortex. Electrode impedance is perfectly ~ 700 KΩ at 1 kHz. The probes can be easily inserted into to rat cortex without buckling or cracking and are even strong enough to penetrate monkey's pia (Fig. 7). The 3-D probe arrays (4×2 with 32 electrodes and 8×2 with 64 electrodes) with parylene cables are shown in Fig. 6e. The cables are 20 mm long, with parallel Cr/Au trace lines between two parylene layers (Fig. 6c). Chronic recording was performed in monkey cortex (Fig.7). Neural signals were properly recorded from rat cortex (Fig. 8).

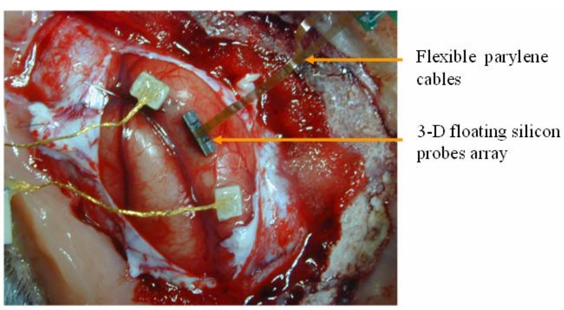

Figure 7. Chronic implantation in monkey cortex using the new silicon probes array with flexible parylene cables.

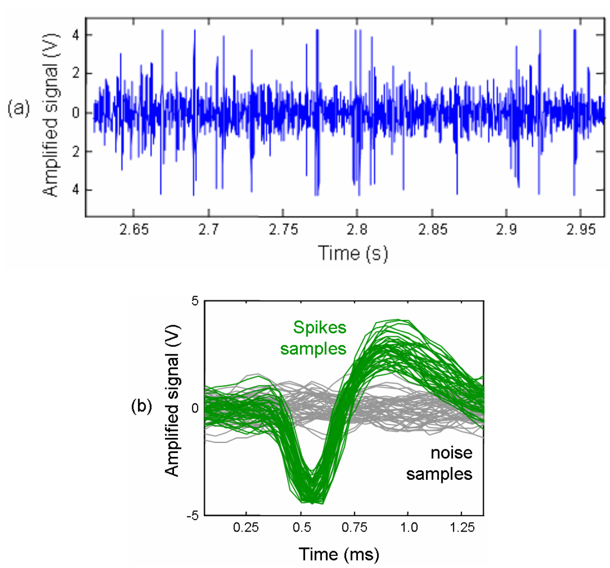

Figure 8. (a) Sample filtered neural data recorded from one channel of the neural probe in rat cortex; (b) sample action potential waveforms.

5 CONCLUTION

In conclusion, the new parylene-embedded probes are developed and validated by animal tests, the 3-D probes are made, and the chronic use of the 3-D array in rats and monkeys is underway. The parylene-cabled probes provide the improvement for the ease of fabrication, use and assembly.

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