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Neural Microprobe Device Modelling for Implant Micromotions Failure Mitigation

Abstract— **Brain micromotion is a major contributor to the failure of implantable neural interfaces. Brain micromotions and tissue damage can be effectively reduced in two ways: (i) miniaturization of the implantable device footprint and (ii) choosing flexible materials for the device substrate. To meet these requirements, in this work we perform two sets of modelling using finite element method in COMSOL Multiphysics. First, we model the performance of different materials ranging from stiff (*e.g.* Silicon) to very soft (*e.g.* PDMS) with different sizes to find the optimal dimension and material for the microprobe. For the device size optimization, the main degree of freedom is thickness, while the minimum shank width and length depend on the recording sites and the target recording point, respectively. Modelling devices with different thicknesses (50 - 200 µm) and fixed shank width (100 µm) based on different substrates, we show that the Polyimide-based microprobe exhibits a safety factor of 5 to 15 and maximum von mises stress of 248-770 MPa. Further, simulations indicate that the Polyimide-based microprobe of 50 µm thickness, exhibiting safety factor of 5 and stress of 248 MPa, provides the optimal solution in terms of size and material. Second, to analyse the device shape factor, we model different layouts based on the obtained optimal design and find that the optimal layout features von mises stress of 134.123 MPa, which is versatile and suitable to be used as microprobe especially for the brain micromotion effects mitigation purpose.**

Keywords— Brain Implantable device, Brain Micromotion, Device modelling, Miniaturization, Mechanical flexibility, Shape factor.

I. INTRODUCTION

Application of advanced technological methods to treat neurological disorders has extensively attracted the neural engineers' attentions. Recent remarkable advances in micro-fabrication and neuroscience have resulted in a great progress in development and production of miniaturized implantable devices for neuroscience research and biomedical applications. During the past decades, intracranial electrodes have been developed to study the function of the nervous system. Neural probes are the main elements in implantable microdevices used to probe and modulate brain function, as they can be used for recording brain signals as well as stimulating the brain [1]. Implantable microprobes are therefore the foundation of modern therapeutic devices designed to treat different brain disorders, such as epilepsy, Parkinson's disease, and migraine [2]. To date, different materials, shape and size have been proposed to obtain implantable neural probes with better durability and reliability while minimizing brain tissue stress; however, such features of available implantable probes are still sub-optimal.

Microwires were the first implantable electrodes, which have been used to record single-neuron activity chronically from the brain [3]. Such microprobes have also been utilized for signal recording in the rat brain [4]. Disadvantages of such a microprobe is that it has only one recording site. In multi-wire design of the probe, during implantation, the accurate location of the electrode tips relative to each other is not controllable due to the wire bending.

Advancement of micro-fabrication technology leads to the advent of micromachined electrodes. These electrodes overcome the drawbacks of microwires. For instance, silicon-based electrodes have been proposed using microfabrication techniques, with the advantages of reproducibility and the possibility of increasing the number of recording sites without increasing the probe size [5]. The main disadvantage of these types of implantable electrodes is the use of very stiff material with high Young's modulus which does not match the softness of brain tissue, which results in lower mechanical compliance of the neural implant.

Recently, the use of flexible substrates has made it possible to fabricate implantable probes which carry the advantage of matching brain softness, outclassing stiff, needle-like electrodes. For example, polymer-based flexible probes conform to the surrounding brain tissue, thereby releasing it from mechanical stress. Thus, they reduce postoperative tissue damage caused by brittle equivalents. Polyimide (PI)-based microprobes have been proposed by many groups highlighting their advantages, such as simple fabrication, biocompatibility and flexibility [6], which make them theoretically suitable for long-term implantations.

In this paper, we have designed a flexible microprobe to record the electrical activity from the rat hippocampus, in the perspective of applying the design to implantable devices for epilepsy diagnosis and treatment. Specifically, we target the CA3 region of the hippocampus, an area which exhibits a particular susceptibility to seizures [7, 8]. Fig. 1 shows the schematic representation of a flexible probe implanted in the CA3 region of the rat brain, indicating that the probe shank should have a length of about 3 mm to access this region of the hippocampus.

The brain micromotions inside the skull dictate two key factors that should be considered in the probe design, i.e., (1)

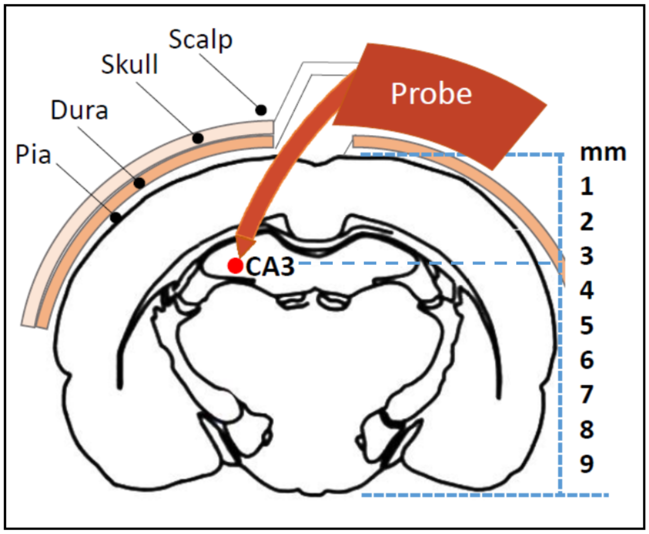

Fig. 1. Conceptual model of the flexible neural probe in the rat brain.

flexibility and (2) miniaturization. This paper investigates the mechanical behaviour of neural microprobes based on flexible materials [9-11] as compared against the behaviour of microprobes made of non-flexible material. We use the finite element method in COMSOL Multiphysics to model and optimize the microprobe considering specific design requirements for application to the target brain area and the required mechanical stiffness for successful insertion of the probe to overcome its mechanical failure due to buckling and fracture. By analysing the safety factor and von mises stress, we obtain the optimal probe design from the mechanical behaviour standpoint so to reduce the effects of brain micromotion on the probe. First, we model and compare the mechanical behaviour of microprobes of different size and materials ranging from very soft to very stiff and rigid. Next, to analyse the device shape factor, we model different device layouts based on the obtained optimal size and material to identify the optimal layout with lowest von mises stress.

Among tested devices, the optimal mechanical features and the lowest von mises stress (134.123 MPa) were found in PI-based microprobes with thickness of 50 μm. It should also be noted that the PI-based microprobe, in addition to the advantage of brain micromotion mitigation, also exhibits a higher compatibility with brain tissue as opposed to stiff material.

II. MODEL DEVELOPMENT

The modelled device consists of a 2 × 1 mm^2 rectangle, with a shank length of 3 mm and width of 100 μm, carrying 4 recording sites; the substrate thickness is varied from 50 μm to 200 μm, to investigate the influence of thickness on the microprobe stress. Tested materials include Polydimethylsiloxane (PDMS), PI, Silicon (Si) as the probe substrate and gold (Au) for the metallization layer, the properties of which are summarized in Table I. It should be noted that the Young's modulus of the brain tissue is in the range of 5-30 KPa.

TABLE I. Neural probes material properties.

Material	Young's Modulus [GPa]	Poisson's ratio	Density [kg/m^3]
PI	3.1	0.37	1300
PDMS	0.87×10^{-3}	0.49	965
Si	200	0.28	2330
Au	77	0.42	19320

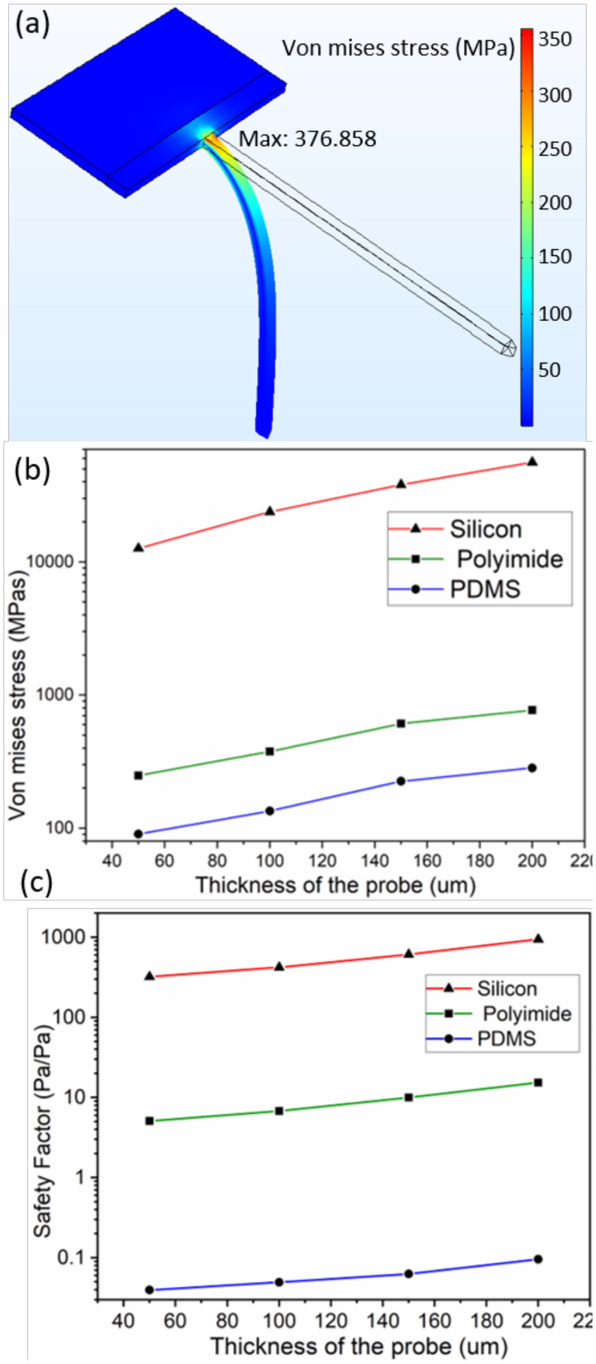

Fig. 2. Probe model developed in COMSOL. (a) Results for von mises stress of the probe in implantation condition. Shank width and thickness: 100 μm; shank length: 3 mm. (b) Safety factor and (c) von mises stress for microprobes of different materials and thicknesses.

III. RESULTS AND DISCUSSION

A. *Modelling approch results*

We have applied the finite element method in COMSOL Multiphysics to perform 3D modelling of the microprobe in 90° bend implantation condition, gradually applying perpendicular force to the shank (Fig. 2(a)). The values of von mises stress have been calculated at the tip maximum displacement of 3.2 mm. As shown in Fig. 2(b), by increasing the thickness of the substrate the stress value considerably arises, for instance obtained value for the 150 µm thick device is almost double comparing to the 50 µm device. It is also evident that the stress value for the Si-based device is very high comparing to the one made by PI or PDMS; for example, obtained value for the Si-based 50 µm device is 64 times higher than the same device made by PI. This is because of the Si very high Young's modulus. Comparing to other material, the PDMS-based probe shows lowest stress value, but obtained safety factors for the all PDMS-based devices are very low and are not reliable (much lower than the accepted minimum value of 5 [12]). To investigate the device mechanical behaviour during implantation, we have calculated its safety factors for different materials and thicknesses (Fig. 2(c)). The safety factor for axial loading is calculated by comparing yield stress strength and von mises stress, using:

$$Safety\ factor = \frac{yield\ stress}{von\ mises\ stress} \tag{1}$$

More details on the yield stress for different material can be found in [13]. For example, yield stress value for the PI is 40 MPa. The obtained simulation results show the PI-based probe has better safety factor values for different thicknesses comparing to the one made by PDMS.

B. *Shape factor simulation results*

We have modelled different microprobe geometrical shapes and layouts and compared the resulting von mises stress value and safety factor to investigate how the shape influences the microprobe mechanical behaviour, aiming to find the optimal shape parameters. We have performed two sets of analysis; (i) von mises stress and safety factor analysis for the probe substrate only (ii) von mises stress analysis for the probe with all wires, contacts and circle pads.

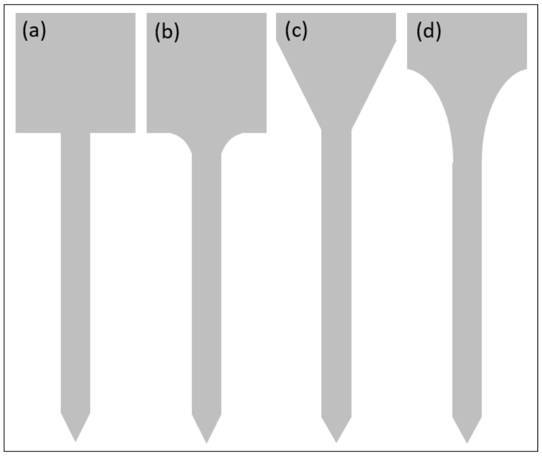

Fig. 3. Different substrate layout designs label as **(a)**, **(b)**, **(c)**, and **(d)** to investigate the shape factor influence on the device mechanical behavior.

Probe substrate analysis. We have modelled several probe layouts and tested their mechanical properties. The proposed layouts are presented in Fig. 3. In general, the bases are designed with big size to accommodate interconnect pads for easy connections, while the shank of the probe is considered to reside within the 3 mm inside the brain. The mechanical performance of the probe is affected by three main parameters: layout, material and geometry [14]. According to the performed analysis reported in the previous section and to the simulation results illustrated in Fig. 2, we chose PI as substrate material for the probe, since it has shown a lower stress value in the working bend condition with respect to the one made by Si, and also higher safety factor comparing to the PDMS-based probe. Further, we have selected the thinnest device within the acceptable safety factor in order to miniaturize the probe footprint as much as possible so as to mitigate the brain micromotion effects as well as to minimize the tissue stress. In the simulations reported in sections II-B

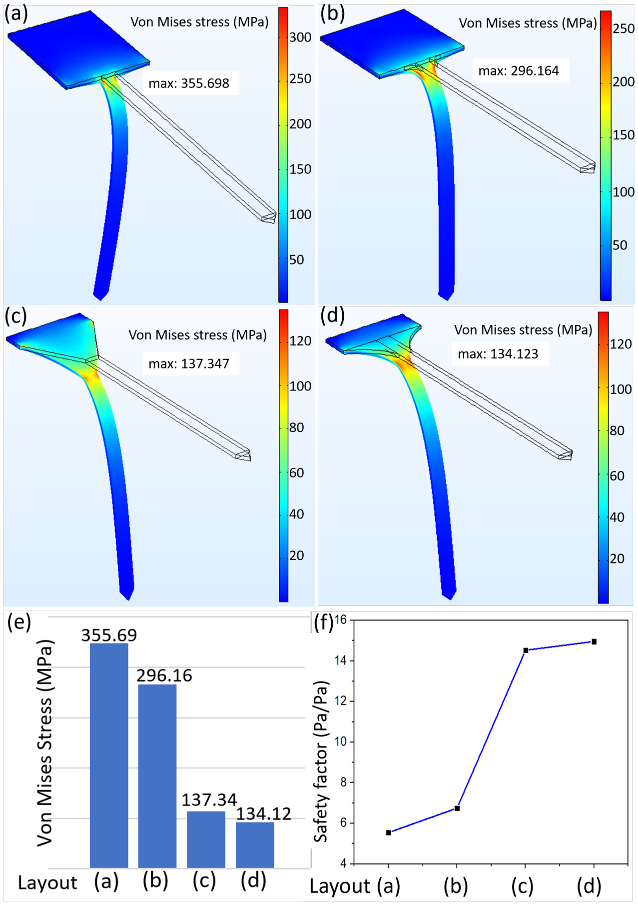

Fig. 4. Simulation results: von mises stress values for the different layouts a - d of device substrate in bend working condition, (e) Layout d has the lowest stress value of 134.12 MPa among the different proposed layouts, (f) Obtained safety factors for different PI based 50 µm thick layouts; layouts a and d have scored minimum and maximum safety factors of 5.55 and 14.96, respectively.

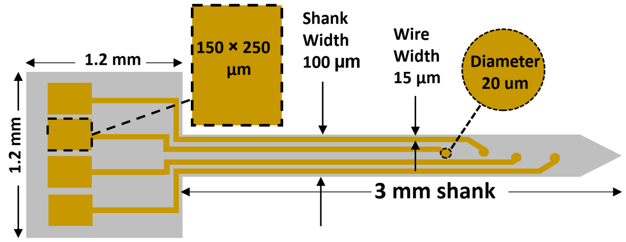

Fig. 5. Schematic representation of modelled neural probe layout A, including PI based substrate and recording sites including connections, pads and wires made by gold.

and III-C, the PI-based 50 µm-thick probe with different layouts have been modelled in bend working condition. A perpendicular force has been gradually applied to the shank area (see Fig. 4(a)-(d)) and the values of von mises stress have been calculated when the tip maximum displacement reaches to 3.5 mm. It can be seen from Fig. 4 that the stress value can be considerably reduced by choosing different layouts for the probe substrate. For example, the maximum von mises stress of 355.698 MPa has been obtained for layout (a), while the obtained value for the layout (c) is much lower, i.e. 134.123 MPa. Fig. 4(f) shows the safety factors calculated for different layouts using (1). Layout (d) has scored the highest safety factor of 14.96 and satisfies the mechanical requirements for the device.

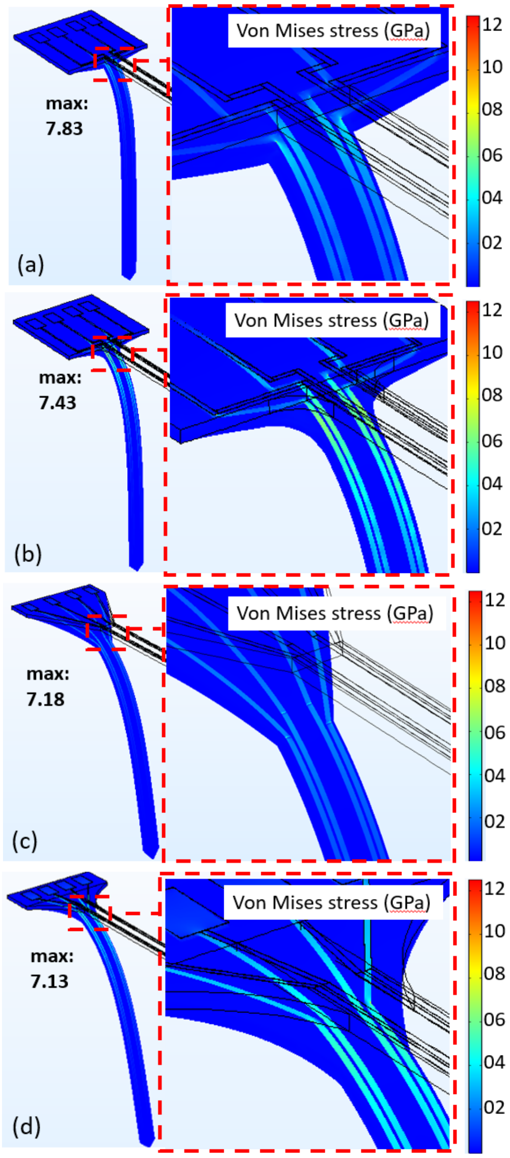

Fig. 6. Simulation results: von mises stress values for the different microprobe layouts (a)-(d) in bend working condition. PI-based substrate and recording sites including connections, pads and wires made by gold.

C. Mechanical analysis with wiring and connections.

We have also carried out stress analysis for the various flexible probes layouts, including all contact pads, wiring and recording contacts. Fig. 5 depicts layout (a), with 1.2 × 1.2 mm^2 base, four 250 × 150 µm electrode pads and four round recording contacts of 20 µm diameter at the tip. As for the metallization layer, we have chosen Au for the wiring and electrode pads because of its biocompatibility; the Au thickness is 5 µm. When the all components (substrate with wires, contacts, and recording pads) of the probe are modelled, simulation results (Fig. 6. (a)-(d)) show that maximum von mises stress appears in gold wire. The point with maximum stress is located in the junction of the base and shank. This is because the Young's modulus of gold is much higher than that of the PI substrate. Among the different developed layouts for the neural probe, obtained von misses stress value for the layout (d) is minimum and can be considered as an optimal layout.

IV. CONCLUSION

In this paper, we have explored and analysed various neural microprobe designs to satisfy the requirements for an optimal implantable device from the mechanical behaviour standpoint. Specifically, we have focused on the development of a neural probe for mitigation of brain micromotions effect. Brain micromotions effects can be effectively reduced in two ways: (i) miniaturization of the implantable device footprint (ii) the use of flexible and soft material for the device substrate. The analysis of device safety factor and von mises stress for different microprobe of different size, materials and layouts have shown that the 50 µm-thick PI-based device with safety factor of 5 and maximum von mises stress of about 248 MPa (layout d) is an optimal probe design from the mechanical and biocompatibility standpoints. Although the probe made by very soft material (*e.g.* PDMS) shows lowest von mises stress value, simulation results have shown that its safety factor is low and therefore PDMS is not a reliable material for an implantable microprobe, especially during insertion into the tissue. The developed model demonstrates that a microprobe design with reliable safety factor and suitable mechanical compliance enables mitigation of the brain micromotions effects on the microprobe implant.

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