Excerpt from the Proceedings of the 2011 COMSOL Conference in Bangalore

Multiphysics Modeling and Simulation of an Implantable Microelectrode for Diagnostic and Therapeutic Applications for Parkinsonism

Wassim Ferose H.*, Gokul Prasath R., Alagappan M., Anju Gupta

PSG College of Technology, Coimbatore – 641004

*email : wassimferose.h@gmail.com

Abstract: This paper deals with the design and simulation of an implantable microelectrode which can be used for the electrical stimulation of the brain and can essentially aid in the diagnosis and treatment of patients with Parkinson's disease. The electrode design consists of shanks which are arranged in a uniform pattern to facilitate accurate delivery of required current to the affected sites. The microelectrode shank was modeled and simulated using the MEMS module of COMSOL Multiphysics 4.1. The electrode designed has the dimensions of 10µm at the tip. The micron-level dimensions confine to the cellular dimensions of neuronal cells and hence help in the effective delivery of the required current. The various physical characteristics of the shank like the displacement and strain which are experienced inside the intra-cranial environment have been simulated and analyzed by placing the electrode inside the modeled brain tissues.

Keywords: Parkinson's disease, Deep Brain Stimulation, Shank, Microelectrode.

1. Introduction

The human nervous system is one of the most complex systems to understand and experiment. The brain and the spinal cord control and appropriately manage all the other parts of the human body with the help of several complex mechanisms throughout the lifetime of a human patient. Any failure in the mechanism of working in this system leads to several serious conditions such as Parkinson's disease, Alzheimer's disease, epilepsy, etc. These conditions demand critical attention, immediate diagnosis and therapy. Our study mainly focuses on diagnosis and therapy for Parkinsonism.

Parkinson's disease or Parkinsonism is a degenerative disorder of the central nervous system that results in tremors and difficulty in walking, movement, and coordination. It is characterized by progressive loss of muscle control, which leads to trembling of the limbs and head while at rest, stiffness, slowness and impaired balance. As symptoms worsen, it becomes difficult to walk, talk and perform simple tasks. The progression of Parkinson's disease and the degree of impairment vary from individual to individual. Many people with Parkinson's disease live long productive lives, whereas others become disabled at a much early stage. Premature death is usually due to complications such as fall-related injuries or pneumonia. The primary reason for occurrence of Parkinsonism is the death of dopamine generating cells in the substantia nigra, a region of the midbrain. The cause of such cell-death still remains unknown. Dopamine essentially acts as a messenger between two areas of the brain – the substantia nigra and the corpus striatum in order to produce smooth, controlled movements. Genetic and pathological studies have revealed that various dysfunctional cellular processes, inflammation and stress, can all contribute to such cell damage. In addition, abnormal clumps called Lewy bodies, which contain a protein, alpha-synuclein, are found in many brain cells of individuals affected with Parkinson's disease [1].

Though man has always found it difficult to deal with the neural disorders such as the Parkinson's; today, both our understanding of the nervous system and our ability to treat a variety of its disorders using advanced neural prostheses are making these studies productive. The combination of BioMEMS and Microelectronics has also facilitated the development of such devices. This paper discusses a model of an individual shank which can be used to build a multichannel microelectrode for treating the neural disorders like Parkinsonism. The behaviour and physical

properties of the shank are studied by immersing the electrode inside the modelled grey and white matter tissues of the brain in the intra-cranial environment.

2. Deep Brain Stimulation (DBS)

Considering the drawbacks of medications and the surgical risks, deep brain stimulation is a procedure which is comparatively more flexible and that can be upgraded in future. This procedure essentially inactivates the thalamus or globus pallidus without purposefully destroying the brain cells. Hence the risks are much less. DBS involves usage of a surgically implanted neurostimulator to deliver electrical stimulation to the targeted areas in the brain that control body movement, thus blocking the abnormal nerve signals that cause tremor and PD symptoms. The lead or the electrode is inserted through a small opening in the skull and implanted inside the brain. The tip of the electrode is positioned within the targeted brain region. This is the most important step in the DBS since it determines the area and site for stimulation. A magnetic resonance imaging or computed tomography scan is commonly used to identify and locate the exact target location from where, the electrical nerve signals defining the symptoms originate from the brain. Generally, the targets are the thalamus, subthalamic nucleus and globus pallidus.

Unlike the previously adopted surgical methods for Parkinsonism treatment, DBS provides a significant advantage by not damaging healthy brain tissue or nerve cells. Instead, the procedure just blocks electrical signals from targeted areas in the brain. Thus, if newer, more promising treatments develop in the future, the DBS procedure can be reversed and upgraded. Also, the amount of electrical stimulation and other parameters can be manually or automatically programmed according to the patient's response without requirement of further surgeries.

3. Technology and Design Aspects

During neuronal activity, the cell membranes of the neurons depolarize as the result of inputs received from other cells and this results in the production of ionic current. The microelectrodes are used primarily to record the voltages produced by these currents. The neural spike potentials represent the electrical half of an electrochemical system.

Microelectrodes for neural applications have been used since a long time primarily for achieving single unit activity in neural tissues [2, 3]. Various types of microelectrodes such as metal microelectrodes, glass microelectrodes and tantalum on sapphire microelectrode arrays have been used [4-6]. The recording area of a metal microelectrode is confined to a small site at the electrode tip by a thin layer of insulation. With the advancements in MEMS technology and microelectronics; micromachining of silicon is now possible offering lots of advantages over other methods. Properties such as greater precision, geometric matching with neural circuit, less volume displacement during implantation and integration of circuits directly on the probes have made the micromachining of silicon probes superior [7, 8].

The probe structures consist of a selectively etched substrate, with conducting leads insulated above and below by inorganic dielectrics. The recording and the stimulating sites are formed by an area of exposed metal. Techniques such as diffused boron etch-stops, reactive ion etching (RIE) and silicon-on-insulator wafer technology can be used for probes to be realized reproducibly with high yield using single-sided processing of wafers having normal thickness [9]. Gold or platinum are used to form the recording sites, although anodically formed iridium oxide is increasingly used because of the charge delivery to the tissues being 20 times more than platinum or gold at the same voltage for stimulating sites [10, 11].

4. Use of COMSOL Multiphysics

COMSOL Multiphysics 4.1 was primarily used for the three most important parts of our work:

i) Design of the Microelectrode
ii) Modeling of the Brain tissues
iii) Simulation of electrode-tissue interaction within the intracranial environment.

A micron-level geometry is built to form the electrode design. Appropriate materials are selected and assigned for the various structures such as the substrate, insulation layer, sites for current delivery and the connecting leads.

The brain tissues are primarily split into grey and the white matter. The corresponding physical properties are assigned to the tissues. The dimensions are chosen as to be suitable for implantation of the electrode.

Then the microelectrode is impinged into the brain tissue in a manner that the sites are completely enclosed within the grey matter. Solid mechanics physics is employed for simulation and analysis. The top surface of the designed electrode and the brain tissues are provided with fixed constraints. Boundary loading conditions are given by selecting the boundaries which are under the influence of grey and white tissues. An Intracranial pressure of 10mmhg is simulated and given as the boundary load.

5. Electrode Design

The shape and dimensions of the electrode are well defined to suit the implant requirements for the brain tissues. In this design, we have considered the substrate to be made up of Silicon because of its wide acceptance, biocompatibility and the most importantly, its ability to incorporate electronic circuits. A thin layer of Silicon dioxide has been considered as the dielectric material which is placed upon the substrate [12]. The sites are the most important structures since they deliver the electric current to the tissues. Here a 4 site shank has been designed. The site is made up of iridium over titanium because of the favorable conductivity properties offered by them. Finally the conducting wires are made up of gold placed upon titanium. These help in transferring the current from the external electronic circuitry to the sites for appropriate delivery and stimulation. The modeled shank has a height of 1500µm, width of 200µm and the thickness is varied from 10µm to 100µm for the purpose of analysis. Figure 1-3 show the different views of the microelectrode that has been modeled using COMSOL Multiphysics 4.1.

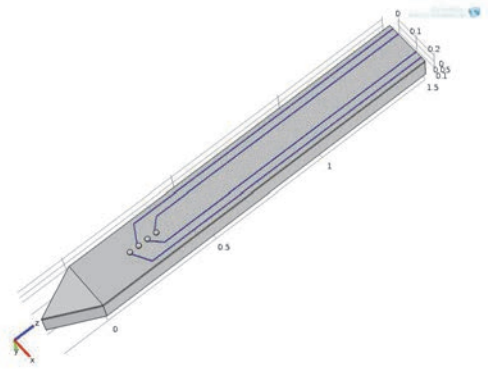

Figure 1. View I showing the entire microelectrode.

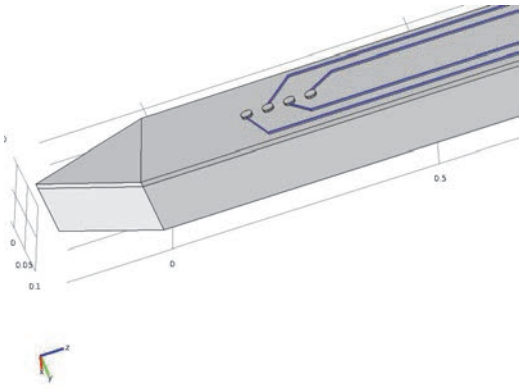

Figure 2. View II of the designed microelectrode showing the placement of SiO_2 dielectric upon the Si substrate.

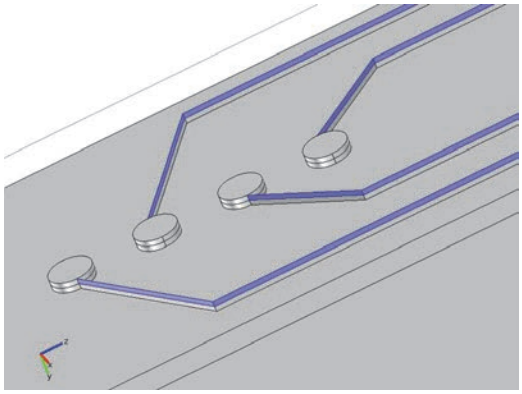

Figure 3. View III of the designed microelectrode showing the current delivering sites and the connecting leads made up of gold on titanium.

6. Electrode Placement

The patient is administered with a local or general anaesthesia and a stereotactic MRI scan or a CT scan is then performed to identify the deep brain stimulation target.

Coordinates are determined for the electrode placement and a safe trajectory down to the target is identified. A 14mm hole is then made in the frontal cranial bone at 2-3cm lateral of the midline and anterior to the coronal suture. The dura (covering of the brain) is opened and a tiny area of the brain is exposed. The probe is then passed down toward the deep brain structures. The microelectrode is then inserted into the brain toward the thalamus and subthalamic region. The electrode placement is done with utmost care to ensure the placement in appropriate location. Often the room will be dark during this time period and the patient will be kept comfortable to evaluate the brain. The time for microelectrode recording can take several hours. Once the appropriate area is identified, test stimulation is performed in order to check that the electrode is in a safe location such that it does not disturb brain function. When the safe area is identified, the electrode will be left in place and clipped to the skull bone fastening device.

Thus we have considered two blocks, one representing the grey matter and the other representing the white matter of the brain. The blocks are given the properties of the grey and white matter and the designed electrode is suitably immersed inside such that the electrode sites are in contact with the grey matter, considered to be a part of the globus pallidus or subthalamus [13]. The thickness of the modeled grey matter is 0.5mm and that of white matter is considered as 0.3mm. The simulation of the electrode behavior and its interaction with the tissue is performed and analyzed. Figure 4 shows the placement of electrode inside the tissue.

Table 1. Numerical values for essential Physical parameters of Grey matter and White matter of the brain

Parameter	Grey Matter	White Matter
Density (kg/m^3)	0.01	0.01
Elastic Modulus (Pa)	29474	45453
Young's Modulus (Pa)	2500	2000
Poisson's Ratio	0.45	0.45

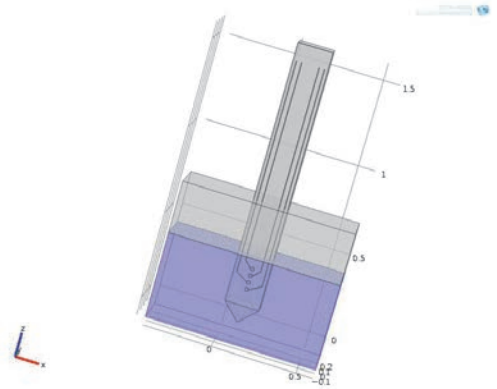

Figure 4. Electrode placement inside the model grey matter (shown in blue) and white matter (shown in grey).

7. Results and Discussion

The designed microelectrode is placed inside the modeled brain tissues and the electrode-tissue interaction is simulated. The major properties such as total displacement, surface deformation and volumetric strain are observed and analyzed. The electrode exhibits deformation near the tip regions as shown in figure 5. However, the deformation does not affect the conducting sites. Also the volumetric strain has been simulated and observed. Similar simulations are performed by varying the thickness of the electrode from 10μm to 100μm and the responses are plotted as shown in figure 7 and figure 8.

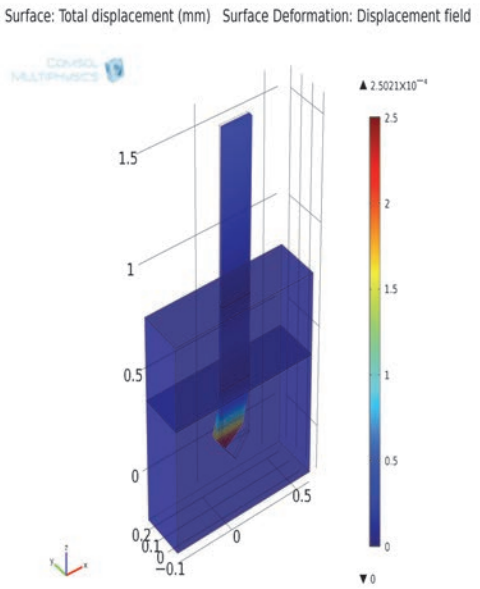

Figure 5. Total Displacement in mm of the electrode when implanted inside the tissues

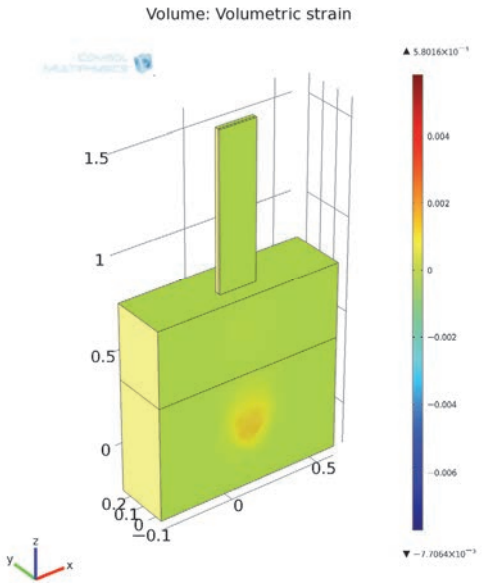

Figure 6. Total Volumetric strain of the electrode when implanted inside the tissues

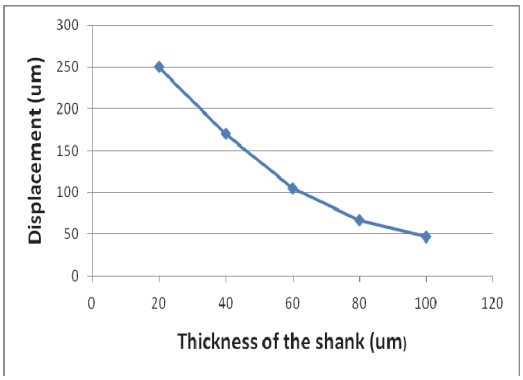

Figure 7. Plot of Thickness of the shank Vs Total Displacement

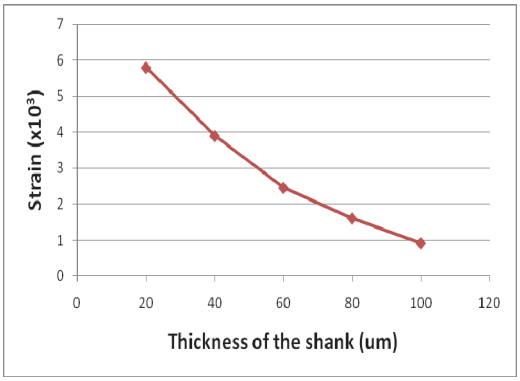

Figure 8. Plot of Thickness of the shank Vs Strain

The plots clearly show that the thickness of the shank is inversely proportional to both displacement and strain. Thus shanks of very low thickness are deformed more, making it prone to damage. Also, shanks of large thickness cannot be preferred because they do not concentrate on individual neurons and tend to affect nearby neurons which is again unfavorable. Hence optimum values should be chosen for the electrode dimensions in order to facilitate the best possible stimulation performance and least deformation.

7. Conclusion

We have designed an implantable microelectrode using COMSOL Multiphysics 4.1 and successfully analyzed its physical properties by immersing it inside a brain tissue model. The simulation shows appreciable results in terms of low displacement and strain experienced by the electrode in the intra-cranial environment. Thus such a design and material can be suitable for implantation in terms of its strength. Our future work involves the analysis of the electrical and heat conduction properties of the electrode and the effect of current delivery on the tissues. Also we aim to develop an optimized design of the microelectrode and a model of the non-homogeneous brain tissue with differential properties.

8. References

1. Patricia Limousin , Paul K Rack , Pierre Pollak , AbdelHamid Benazzouz , Claire Ardouin ,Dominique Hoffmann and Alim –Louis Benabid, "Electrical Stimulation Of The Subthalamic Nucleus in Advanced Parkinson's Disease", *The New England Journal of Medicine*, **Volume 339**, **Number 16**.

2. J. E. Rose and V. B. Mountcastle, "Activation of single neurons in the tactile thalamic region of the cat in response to a transient peripheral stimulus," *Bull. The Johns Hopkins Hospital*, **Vol. 94**, pp. 238-282, (1954).

3. Norman A. Blum, Bliss G. Carkhuff, Harry K. Charles, Jr., Richard L. Edwards, and Richard A. Meyer, "Multisite Microprobes for Neural Recordings", *IEEE Transactions on Biomedical Engineering*, **Vol. 38**, **No. 1** , (January 1991).

4. David A. Robinson, "The Electrical Properties of Metal Microelectrodes", *Proceedings of the IEEE*, **Vol. 56**, **No. 6**, (June 1968).

5. Otto F. Schanne, Marc Lavallee, Raynald Laprade and Simon Gagne, "Electrical Properties of Glass Microelectrodes", *The Procoeedings IEEE*, **Vol. 56**, **No. 6**, (June 1968).

6. Gerald A. May, Shihab A. Shamma and Robert L. White, "A Tantalum-on-Sapphire Microelectrode Array", *IEEE Transactions on Electron Devices*, **Vol. Ed-26**, **No. 12**, (December 1979)

7. K. D. Wise, D. J. Anderson, J. F. Hetke, D. R. Kipke, and K. Najafi, "Wireless implantable microsystems: Electronic interface to the nervous system", *Proc. IEEE (Special Issue on Biomedical Applications for MEMS and Microfluidics)*, pp. 76–97, (Jan. 2004).

8. K. E. Petersen, "Silicon as a mechanical material," *Proc. IEEE*, **Vol. 70**, pp. 420–457, (May 1982).

9. K. Najafi, K. D. Wise, and T. Mochizuki, "A high-yield IC-compatible multichannel recording array", *IEEE Trans. Electron Devices*, **Vol. ED-32**, pp. 1206–1211, (Jul. 1985).

10. Kensall D. Wise, Amir M. Sodagar, Ying Yao, Mayurachat Ning Gulari, Gayatri E. Perlin, and Khalil Najafi, "Microelectrodes, Microelectronics, and Implantable Neural Microsystems", *Proceedings of the IEEE* **Vol. 96**, **No. 7**, (July 2008).

11. S. J. Tanghe, K. Najafi, and K. D. Wise, "A planar IrO multichannel stimulating electrode for use in neural prostheses", *Sens. Actuators*, **Vol. B1**, pp. 464–467, (Jan. 1990).

12. K. Najafi and K. D. Wise, "An implantable multielectrode array with on-chip signal processing", *IEEE J. Solid-State Circuits*, **Vol. SC-21**, pp. 1035–1045, (Dec. 1986).

13. David A. Robinson, "The Electrical Properties of Metal Microelectrodes", *Proceedings of the IEEE*, **Vol. 56**, **No. 6**, (June 1968).