Voltage Field Generated by a Single Photodiode in a Volume Conductor: Simulation and Measurements

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Abstract— **One of the major challenges of neural stimulation is the mechanical stress and resulting neural trauma induced by the movement of the electrode interconnects. A potential way of eliminating interconnects is to use micro-stimulators that can be activated through optical means. To test this method, the voltage field generated by a single photodiode in a volume conductor was analyzed using finite element (FE) analysis. The voltage field was also experimentally tested using diodes with uncoated gold and electrodeposited iridium oxide film (EIROF) coated contacts pulsed with a near-infrared laser (NIR) beam. The EIROF coated microphotodiodes proved to have much larger current injection capabilities. Comparison of experimental results with the finite element model shows that the photodiode voltage is saturating at a few microamperes due to the high impedance of the contacts. However, the voltage generated is larger than 50 mV in peak at the cathodic contact. The voltage waveforms recorded directly from the contacts show that the interface needs a long time interval to discharge. This places a limit on the maximum frequency of stimulation.**

Keywords—**neural stimulation, neural interfaces, volume conductor models, electrodeposition, photodiodes.**

I. INTRODUCTION

Electrical stimulation of the nervous system is used to treat a variety of neural disorders. Devices are used in the treatment of disorders such as Parkinson's disease, bowel and bladder control in spinal cord injury, cochlear implants, and vagal stimulation in the treatment epilepsy. One of the major challenges of neural stimulation is the mechanical stress and the resulting neural trauma induced by the movement of the electrode interconnects. One method of bypassing the tethering barrier is to include telemetry electronics inside the device and control it externally using a magnetic coil and electronics. A miniature stimulator controlled by radio-frequency waves is one example of a device employing this approach [1]. The size of these devices is much larger than the neural systems being stimulated because of added telemetry and power circuitry, thereby reducing the spatial selectivity. To achieve high spatial selectivity, each individual photodiode needs to be very small and yet capable of injecting enough current to achieve stimulation. Currently, an approach combining remote activation and small size is the development of microphotodiode arrays that can be implanted in the retina to replace degenerated photoreceptors [2, 3]. Small contact size combined with the short duration pulses required in neural stimulation leads to the need for a high charge injection rate, which is dependent upon electrode material [4]. EIROF are being investigated as a possible solution. EIROF can be deposited on many metals, such as Au, Pt, and 316VM stainless steel and behaves with the same stimulation properties as activated iridium [5].

In this paper, we investigated the feasibility of using a single photodiode for neural stimulation. The voltage field generated by a single device inside a volume conductor is studied using a finite element model. The simulation results are tested experimentally by placing a photodiode in a volume conductor and measuring the field generated. The device contacts were coated with EIROF to improve the charge transfer capabilities of the interface.

II. METHODS

A. *Finite Element Model*

A photodiode with rectangular geometry and two circular contacts on top (Fig.1) was placed at the center of a volume conductor of 2x2x2 mm size and modeled using a finite element package ANSYS 6.1. The specific resistivity of the medium (ρ=300 Ωcm) simulated the gray matter [6] and that of the contacts was chosen to represent Au. The substrate was assumed to have a zero conductivity.

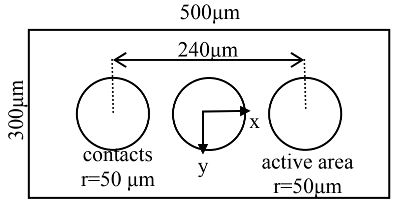


Fig 1. The top view of the photodiode. Device thickness is 120 μm. At the center of symmetry, x=0 and y=0.

B. Electrodeposition of Iridium Oxide

Iridium oxide was deposited from an $IrCl_4$ solution prepared following the method described by Yamanaka [7]. First, 0.15 g of $IrCl_4 \cdot H_2O$ was dissolved in 100 ml of deionized water and magnetically stirred for 30 minutes. Next, 1 ml of H_2O_2 (30wt %) was added to the solution and magnetically stirred for 10 minutes. Then, 0.5 g of $(COOH)_2 \cdot 2H_2O$ was added to the solution and magnetically stirred for 10 minutes. Finally, K_2CO_3 was added in small amounts until the pH of the solution reached 10.5. The solution was then allowed to stand for 48 hours to attain an Ir^{3+}/Ir^{4+} ratio equilibrium. The active area of the photodiode was then covered with a layer of Dow Corning® 732 multipurpose sealant to protect it from the deposition solution. Electrodeposition was controlled using a custom National Instruments LabVIEW program. In dark, a triangular waveform cycling between limits of 0.0 V and 0.55 V at 50mV/s sweep rate was applied for 1600 pulses to the cathodic contact of the photodiode through a 5 MΩ tungsten microelectrode with respect to a calomel reference electrode [5]. When a thin layer of iridium oxide could be seen on the cathode, a square waveform was applied at the same potential limits with a frequency of 0.5 Hz, for a maximum of 6000 pulses. Pulsing beyond this limit leads to a loss of stability and adhesion on the cathodic contact. After about 2000 pulses, a white light was simultaneously applied to the photodiode to cause deposition of the anodic contact using the photodiode current. Light application for 1200 pulses was enough to produce a thick stable coating on the anode, but was applied for a maximum of 3000 pulses with no loss of stability and adhesion.

C. *Volume Conductor Measurements*

Volume conductor measurements of both coated and uncoated photodiodes (Do007, GaAs PIN, GCS Technologies, CA) with the geometry shown in Fig. 1 were conducted in 4% (weight/volume) agar gels filling a petri dish 4 mm from the bottom. The photodiode was then placed beneath the surface of the gel, and the petri dish was filled with 2mm of normal saline diluted five times to simulate the specific resistivity of the CNS gray matter[6]. A tungsten electrode and a large Pt reference (6mm x 1mm) was used to record the voltage field generated by the diode, in response to a laser beam at 850nm, pulsing at 1 Hz (PW= 0.5 ms). The laser source (DLS-500-830FS-50, StockerYale, Canada) and acquisition of the signals into the computer were controlled by a custom LabVIEW program (National Instruments, TX). The voltage field was recorded with the electrode immediately above the contact and then in 20µm increments in the vertical direction (z). A train of pulses was also applied to the coated photodiode (f= 330 Hz, PW= 0.5 ms, duration= 10ms) to study the multi-pulse response.

III. RESULTS

A. *Finite Element Modeling*

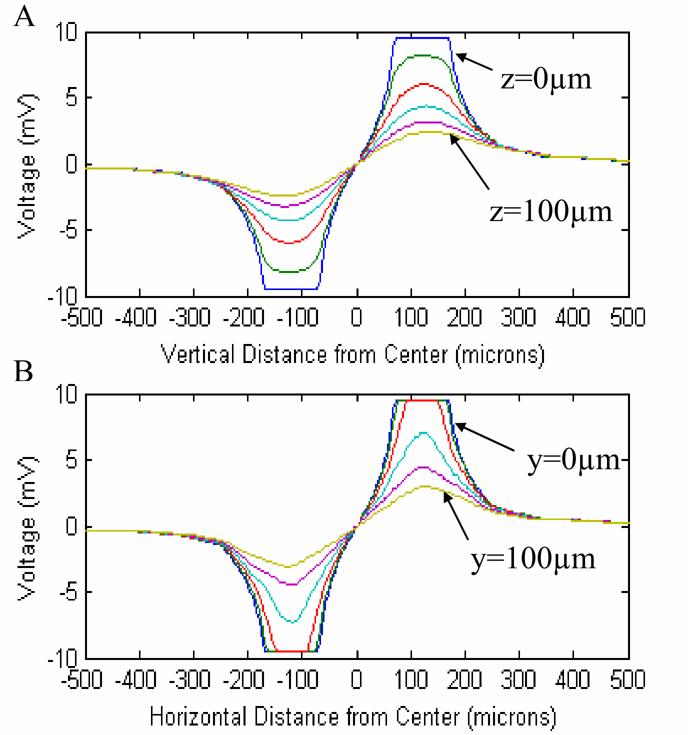


Fig. 2. The voltage field simulated using finite element analysis. … The potential A) for incremental distances above the surface (z) and along a line in the x direction B) for incremental values of y. X=0 corresponds to the center of the active area in both plots.

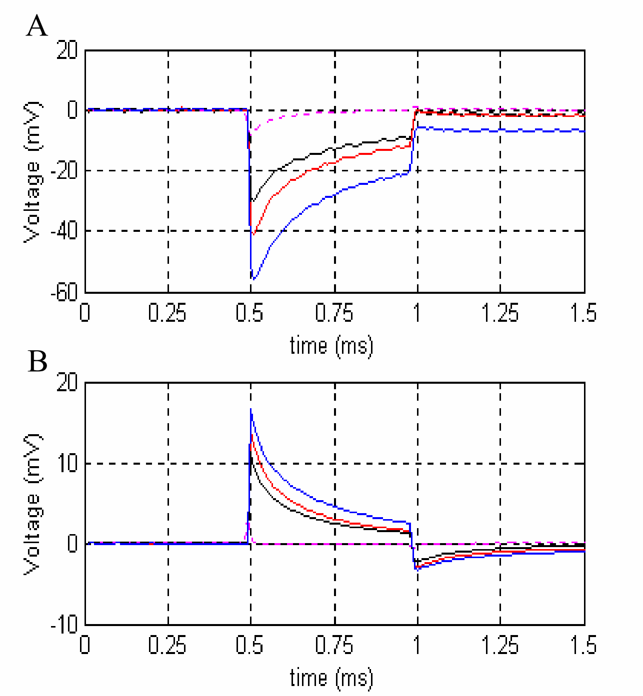
The voltage field generated by a constant current injected into the medium through one of the contacts of the photodiode and returning to the other is studied. Fig.2A shows the voltage field along the x axis for a current intensity of 1 µA at various elevations from the device surface (z=0, 20, 40, 60, 80, and 100 µm). Fig. 2B shows the voltage along the x axis at the diode surface (z=0) for increments of 20 µm along the y axis (see Fig. 1). The differential voltage between the two terminals of the diode is about 20 mV, and it decreases by distance both vertically and horizontally. The decay in the horizontal direction begins after 50 µm, which corresponds to the contact diameter.

B. *Volume Conductor Measurements*

The voltage field generated in the agar gel above the cathode of the uncoated and EIROF coated devices are shown in Fig. 3. The response of the uncoated photodiode is largely capacitive (the initial peak in dash lines) and it decays quickly down to the baseline, indicating a very small faradic current. In the EIROF coated photodiode, a much larger capacitive peak with a slower decay develops. The elevated voltage level at the end of the pulse indicates a substantial faradic component. A similar behavior is observed for the anodic contact except for lower amplitudes. The signal amplitudes decrease for both contacts with increasing distances from the surface.

In Fig. 4, a train of 4 pulses is applied to the EIROF coated photodiode and the field potentials are recorded both directly from the cathode by touching with the tip of the recordings electrode and immediately above the surface (z=0). The cathode voltage peaks at around 450 mV. The

Fig. 3. Volume conductor measurements. The waveforms recorded



above the center of the cathode at z=0, 20, and 40 µm. with the EIROF coated diode (solid traces) and with the uncoated diode (dash line) just above the surface (z=0) of A)cathode, B) anode.

waveform between the pulses indicates an incomplete discharging of the interface. The total time constant is about 17.3 ms. In the recordings just above the surface (Fig. 4B), the peak of the first pulse is similar to what was observed in the single pulse stimulation. However, the voltage peak decreases with each successive pulse.

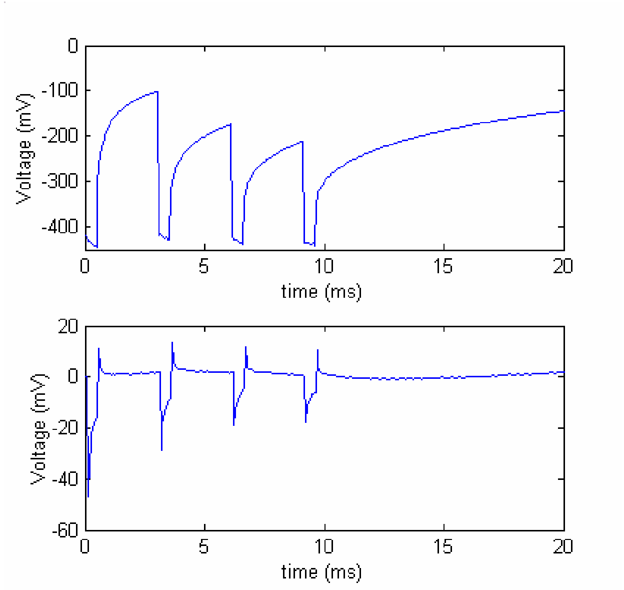


Fig. 4. Pulse train measurements. The waveform recorded with the EIROF coated cathodic contact when the recording electrode was, A) touching the contact and B) just above the contact.

IV. DISCUSSION

Comparing the results of FE analysis and the volume conductor measurements, one concludes that the photodiode must be saturating at a few microamperes due to the high impedance of the contacts even with EIROF deposited devices. However, the differential voltage generated between the two contacts seems sufficiently large to activate nearby nerve cells. The voltage is directly proportional to the specific resistivity of the medium which is assumed to be 300 Ωcm in this study. Haueisen et al. reports resistivity values as high as 450 Ωcm for the gray matter and an average value of 700 Ωcm for the white matter [6]. The device geometry should be optimized for a maximum voltage field with a minimum device size. Minimizing the device size will improve the spatial selectivity of the neural stimulation.

The fact that the interface needs such long time intervals to discharge is worthwhile to mention. This places a conservative limit on the maximum frequency of stimulation. A potential solution to this problem may be to incorporate a parallel resistance into the device that reduces the time constant, although this would also shunt some of the stimulation current.

V. CONCLUSION

The FE analysis suggests that several microamperes of diode current should be able to stimulate neural tissue within a small volume around the device. The voltage field decays rapidly in both vertical and horizontal directions from the center of the device. The photodiodes with bare gold contacts generated only short transient voltages in the volume conductor when activated under a powerful IR laser beam that was sufficient to saturate the diode voltage. Electrodeposition of the contacts with iridium oxide films improved the current injection capability of the device substantially both over the cathodic and anodic contacts. The build up charge at the contact-saline interface needs several tens of milliseconds to discharge completely with the coated devices. In case of a high frequency pulse train, the interface cannot discharge sufficiently between the pulses and thus the current amplitude injected into the volume decays continuously with each additional pulse.

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