The Impact of Variations in Membrane Capacitance on the Detected Neural-Electronic Signal

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Abstract - **There have been various theoretical and experimental studies presented in the literature that focus on interfacing neurons with discrete electronic devices such as transistors. The demonstrated lack of reproducible fidelity of the nerve cell action potential at the device junction would make it impractical to implement these devices in any neural prosthetic application where reliable detection of the action potential was a pre-requisite. In this study, the impact of typical variations in membrane capacitance on the detected neural signal is investigated.**

Keywords – **Neural-electronics, membrane capacitance**

I. INTRODUCTION

Specific nerve cell excitation using a semiconductor based electronic device has been demonstrated by Fromherz and Stett [1]. It has also been demonstrated experimentally by Weis and Fromherz, as well as Vassanelli and Fromherz, that a detectable signal can be conducted from a neuron *in vitro* to a silicon transistor [2;3]. Direct interface and subsequent signal conduction between individual neurons and single transistors would, if practically achievable in an *in vivo* environment, have the potential of providing a solution to many of the localization issues associated with conventional non-specific field based functional electrical stimulation sensory nerve signal detection approaches.

While some characteristics of the interface region are open to design manipulation, other characteristics, such as the membrane capacitance, are not subject to design modification. Typical variations in these characteristics can have a significant impact on the detected signal at the junction. This simulation study investigates the fidelity of the detected nerve signal for different values of membrane capacitance.

II. METHODOLOGY

An idealized cylindrical geometry was assumed for the neuron. This geometry was chosen as a simplified approximation of the Retzius cell used in neuron-transistor interface experiments presented by Weis and Fromherz [2].

Although the fundamental physical parameters used in determining the equivalent circuit component values shown in Fig. 1., are specified in a per unit area format, defining the geometric parameters of the neuronal radius a_j and length L allow the circuit component values to be specified in absolute units. The physical parameters related to the

membrane and the transistor are shown in Table 1., along with the definition of the circuit components.

TABLE I
List of the variables and physical as well as geometric parameters that were used in the equivalent circuit model.

a_j	Interface and nerve cell radius	10 (μm)
d_j	Nerve cell transistor seal distance	10 (nm)
L	Length of the nerve cell	40 (μm)
A_Ψ	Free membrane region area	$\pi a_j^2 + 2\pi a_j L$ (cm²)
A_P	Interfaced membrane region area	πa_j^2 (cm²)
T	Temperature	6.3 (°C)
t_i	Simulation time step	(s)
k	Number of time steps	3000
ρ_J	Extracellular environment resistivity	(Ωcm)
c_{JG}	Gate oxide capacitance per unit area	0.3 (μF/cm²)
c_{Na}^o	Extracellular sodium ion concentration	0.491 (mol/L)
c_{Na}^i	Intracellular sodium ion concentration	0.05 (mol/L)
c_K^o	Extracellular potassium ion concentration	0.02011 (mol/L)
c_K^i	Intracellular potassium ion concentration	0.400 (mol/L)
G_{Na}^M	Maximum sodium conductance per unit area	0.120 (S/cm²)
G_K^M	Maximum potassium conductance per unit area	0.036(S/cm²)
m	Hodgkin Huxley first order kinetic variable [4]	
h	Hodgkin Huxley first order kinetic variable [4]	
n	Hodgkin Huxley first order kinetic variable [4]	
Ψ_{Na}	Free membrane region sodium conductance	(S)
Ψ_K	Free membrane region potassium conductance	(S)
P_{Na}	Interfaced membrane region sodium conductance	(S)
P_K	Interfaced membrane region potassium conductance	(S)
R_J	Interface junction seal resistance [2]	$\rho_J/(5\pi d_j)$ (Ω)
c_M	Membrane capacitance per unit area	(F/cm²)
C_Ψ	Free membrane region capacitance	(F)
C_P	Interfaced membrane region capacitance	(F)
C_{JG}	Gate oxide capacitance	$c_{JG}\pi a_j^2$ (F)
V_{Na}	Sodium ionic (Nernst) potential	(V)
V_K	Potassium ionic (Nernst) potential	(V)
V_I	Intracellular potential	(V)
V_J	Interface junction potential	(V)
V_M	Interface region transmembrane potential	(V)
I	Injected stimulus current	(A)

The non-linear equivalent circuit that incorporates the non-linear properties of the membrane is shown in Fig. 1. Based on the Weis, Fromherz hypothesis, this model was developed by dividing the membrane into a region that is interfaced with the electronic device, represented by the P labeled circuit components, and a free region of the membrane, represented by the Ψ labeled circuit components as per (1).

$$\Psi_{Na} = A_\Psi G_{Na}^M m^3 h$$
$$\Psi_K = A_\Psi G_K^M n^4 \qquad (1)$$
$$P_{Na} = A_P G_{Na}^M m^3 h$$
$$P_K = A_P G_K^M n^4$$
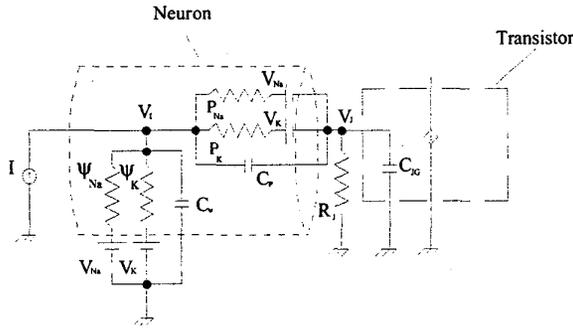
Fig. 1. Non-linear equivalent circuit model of the neuron-transistor configuration. The equivalent circuit component values are calculated using the physical parameters and formulas shown in Table 1.

The coupled ordinary differential equations (2) implemented in the solver routine were written in terms of the intracellular potential V_I and the transmembrane potential V_M across the region of the membrane interfaced with the transistor gate.

$$\Psi_{Na}(V_{Na} - V_I) + \Psi_K(V_K - V_I) - C_\Psi \frac{dV_I}{dt} + I$$

$$+ P_{Na}(V_{Na} - V_M) + P_K(V_K - V_M) - C_P \frac{dV_M}{dt} = 0$$

$$P_{Na}(V_M - V_{Na}) + P_K(V_M - V_K) + C_P \frac{dV_M}{dt} - \frac{V_I}{R_J} \qquad (2)$$

$$+ \frac{V_M}{R_J} - C_{JG} \frac{dV_I}{dt} + C_{JG} \frac{dV_M}{dt} = 0$$

A relationship can be defined between the intracellular, junction and transmembrane potentials as per (3).

$$V_M = V_I - V_J \qquad (3)$$

A Runge-Kutta ordinary differential equation solver was used to calculate the response of this circuit to a brief 10 μs stimulus current pulse.

The square root of the sum of the squared differences between the intracellular potential V_I and the junction potential V_J was used to quantify the reliability of the reproduction of the nerve cell action potential at the junction, as per (4), where t_i is the time step and k is the number of time steps.

$$\delta = \sqrt{\sum_{i=0}^{k-1} [V_I(t_i) - V_J(t_i)]^2} \qquad (4)$$

III. RESULTS

The effect of variations in membrane capacitance on the reliability with which the nerve cell action potential was reproduced at the junction was also studied and quantified

as per (4) for a physiologically relevant range of membrane capacitance values. A significant improvement in the reliability with which the action potential was reproduced at the junction was observed for larger values of membrane capacitance as per Fig. 2.
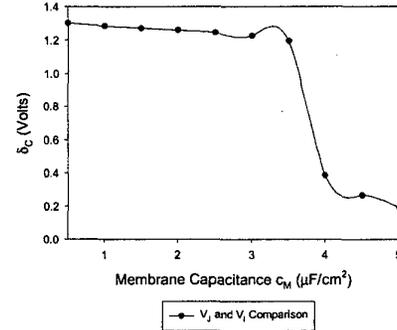
Fig. 2. Norm of the difference between the intracellular potential V_I and the junction potential V_J as a function of membrane capacitance. This curve quantifies the reliability with which the intracellular action potential is reproduced at the junction. A stimulus of 40nC/cm^2 and an extracellular resistivity of 25 kΩcm were used.

IV. DISCUSSION

The intracellular action potential waveform is reproduced at the junction without significant distortion when no action potential is initiated in the region of the membrane interfaced with the device. Larger values of membrane capacitance result in smaller initial changes in potential across the cell membrane. Small values of membrane capacitance yield larger initial changes in transmembrane potential that can be sufficient to generate an action potential in the region of the membrane interfaced with the device. For intermediate values of membrane capacitance, an action potential can still be generated in the interface region of the membrane as a result of the action potential generated in the free region of the membrane.

REFERENCES

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