Effects of Fabrication Process Variation on Impedance of Neural Probe Microelectrodes

Il Hwan Cho*, Hyogeun Shin***, Hyunjoo Jenny Lee** and Il-Joo Cho***†

Abstract – Effects of fabrication process variations on impedance of microelectrodes integrated on a neural probe were examined through equivalent circuit modeling and SPICE simulation. Process variation and the corresponding range were estimated based on experimental data. The modeling results illustrate that the process variation induced by metal etching process was the dominant factor in impedance variation. We also demonstrate that the effect of process variation is frequency dependent. Another process variation that was examined in this work was the thickness variation induced by deposition process. The modeling results indicate that the effect of thickness variation on impedance is negligible. This work provides a means to predict the variations in impedance values of microelectrodes on neural probe due to different process variations.

Keywords: Neural probe, equivalent circuit modeling, fabrication process variation

1. Introduction

In recent years, there has been an active progress in neuroscience to investigate the cause of neurological diseases such as chronic pain and epilepsy. Understanding numerous neural networks in a brain is necessary for studying brain diseases and disorders. Various implantable wire electrode bundles have been used to simultaneously record neural signals at different brain regions with a goal to investigate functional connectivity among brain regions. However, these wire bundles are subject to various technical problems such as inaccurate positioning of wires, low electrode density and large brain tissue damage as reported in previous works [1]. To overcome these drawbacks, MEMS neural probes have been introduced [2]. Since MEMS neural probes have various advantages such as small size with a high electrode density and capability to accurately position each electrode in an array structure, MEMS neural probe has attracted great attentions in the past decade. Especially, accurate positioning of each electrode in an array structure is important for studying functional connectivity of brain. Furthermore, more functions have been merged into MEMS neural probes including various stimulation modalities such as optical and chemical [3]. Among MEMS neural probes, probes with optical stimulation capability has recently received much attention because genetically targeted neurons can be selectively excited or inhibited by light without stimulating neighboring neuron networks [4].

Previously reported MEMS neural probe for optical stimulation suffered from few limitations, such as thick probe shank and inaccurate positioning of manually attached optical fiber. In the previous work, we achieved a thin neural probe integrated with an optical waveguide but offered only two stimulation sites due to relatively high optical loss [5]. The low-loss optical waveguide, the key advantage of this process, utilizes a thick glass as the cladding layer based on glass reflow process to reduce optical transmission loss.

However, there was impedance variation within the microelectrodes on the neural probe. The impedance variations were observed on not only the neural probe with optical waveguide but also various other types of neural probes with MEMS structures [6]. Most of the previous works were focused on reducing electrical impedance of the electrodes to increase the possibility of recording proximal neural signals [7]. However, the electrical impedance of microelectrode affects the SNR (signal to noise ratio) and the amplitude of recorded signals [8]. Therefore, fabricating microelectrode arrays with uniform and stable impedance value is also important in sorting and analyzing neural signals but often overlooked. In this paper, we investigate the causes of impedance variations and analyze the variations using equivalent circuit modeling and SPICE simulation.

2. Structure and Equivalent Circuit Model

Fig. 1(a) shows the conceptual diagram and SEM image of the neural probe integrated with an optical waveguide.
Iridium microelectrode array for recording signals from individual neurons and a waveguide for transmitting light are integrated in a single shank. The material for electrode is iridium and the sizes of each component are shown in Fig. 1(b). The neural probe consists of 16 microelectrodes and each electrode is connected to an external node through gold metal line. As shown in Fig. 2, size of metal microelectrodes is $14 \times 14 \mu m^2$ and the thickness is 1500 Å. A 4000-Å-thick silicon dioxide layer is deposited using chemical vapor deposition (CVD) for passivation layer. Material and dimensions of each layers used to form microelectrodes and signal lines are illustrated in Fig. 2. When the fabricated neural probe is used to record neural signals, metal microelectrodes are immersed in an electrolyte (a conducting medium); then, electrochemical reactions occur at the interface between the solid microelectrodes and the electrolyte.

The equivalent circuit model of the microelectrode on the neural probe consists of passive components that represent various physical phenomena involved in electrochemical reactions. Passive components in the model include interfacial capacitance ($C_I$), charge transfer resistance ($R_t$), diffusion-related Warburg elements ($R_w$ and $C_w$), and the solution resistance ($R_s$) [7].

Since process variation affects the dimension of metal line in neural probe, metal line resistance ($R_L$) from metal electrode interface to external node is added to the equivalent circuit model. In this work, we introduced a new equivalent circuit component, $R_L$, which is in series connection with the traditional electrode equivalent model. Therefore, all of analysis in this work included variation of metal-line resistance, which results in more accurate prediction of electrode impedance than those of previous works. Each of passive components was extracted by equation or finite element simulation as expressed below.

Each element used in the model was obtained as follows to calculate the impedance of microelectrodes. Total interfacial capacitance $C_I$ is series combination of the Helmholtz capacitance ($C_H$) and the Gouy-Chapman capacitance ($C_G$) as shown in (1).

$$\frac{1}{C_I} = \frac{1}{C_H} + \frac{1}{C_G}$$

Helmholtz capacitance is determined by the total area of the interface ($A$), the dielectric permittivity of electrolyte ($\varepsilon_\varepsilon'$), and the distance of the OHP (Outer Helmholtz Plane) from the metal electrode ($d_{OHP}$) as shown in (2). Also, Gouy-Chapman capacitance is determined by two terms. The first term ($\varepsilon_\varepsilon'/L_D$) is simply the capacitance per unit area of two plates separated by a distance $L_D$ while the second term implies that the effects of mobile charges are compensated by the hyperbolic cosine. Here, $z$ is the valence of the ion, $V_o$ is the potential at the electrode and $V_T$ is the thermal voltage ($kT/q$).

$$C_H = \frac{\varepsilon_\varepsilon'A}{d_{OHP}}, \quad C_G = \frac{\varepsilon_\varepsilon'A}{L_D} \cosh\left(\frac{zV_o}{2V_T}\right)$$

The transfer resistance $R_t$ is expressed with exchange current density ($J_0$) and electrode area ($A$). In the transfer
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resistance, electrode material affects the amount of current that flows in response to an applied voltage (3).

\[ R_s = \frac{V_i}{J_0 A} \]  

(3)

Solution resistance \( (R_s) \) considers the effects of the spreading of current from the localized electrode to a distant counter electrode in the electrolyte. Since neural probe in this work uses rectangular electrode, \( R_s \) is calculated with length \( l \) and width \( w \).

\[ R_s = \frac{\rho \ln \left( \frac{4l}{w} \right)}{\pi l} \]  

(4)

The Warburg impedance is theoretically determined by the following equations shown in (5). This equation is based on the assumption that the electrode is operated near equilibrium and the diffusion is dominated by a single ion species.

\[ R_w = \frac{10^3 V_i}{2q n^0 \sqrt{\pi f D}} \]  

(5)

\[ C_w = \frac{1}{2\pi R_w} \]  

(6)

where \( f \) is the frequency in Hertz, \( n^0 \) is the bulk number concentration of ions in the electrolyte (ions/liter), \( D \) is the diffusion coefficient (cm²/sec) of the ion, and \( z \) is the valence of the ion.

The impedance of diffusion-related Warburg elements is summarized below:

\[ Z_w = \left[ \frac{1}{R_w} + j2\pi C_w \right]^{-1} \]  

(7)

Since the \( R_L \) contains only resistance factor, it is independent from frequency variation and can be easily extracted by the finite element simulation as shown in Fig. 4. Although \( R_L \) is smaller than other parameters, \( R_L \) should be included to examine fabrication process variation of the neural probe. Influence of fabrication process variations on impedance will be explained in next section.

3. Results and Discussion

Based on the equivalent circuit model and parameters described in Table 1, total impedance change due to the variation in fabrication process was estimated by using spice simulation. Also, the impedance change was compared with the experimental results.

We examined the fabricated neural probes with SEM images to estimate the variations of electrodes (Fig. 5). The most noticeable variation in microelectrode characteristics in neural probe was the structure dimension such as size of microelectrodes and width and thickness of metal lines. From the SEM image in Fig. 5, process variations induced by patterning of metal layers exhibit 5% error in the worst case. Those variations were measured over the whole area of the processed wafer. However, the surface area of metal electrode exhibited no meaningful variation.

Previous work demonstrated that the impedance of metal electrode is affected by effective surface area that is determined by surface roughness of deposited metal layer.

Table 1. Parameter values of passive device model for neural probe in electrolyte

<table>
<thead>
<tr>
<th>Parameter (dimension)</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( d_{OHM} ) (m)</td>
<td>( 5 \times 10^{-10} )</td>
</tr>
<tr>
<td>( V_T ) (V)</td>
<td>0.0259</td>
</tr>
<tr>
<td>( q ) (C)</td>
<td>( 1.6 \times 10^{-19} )</td>
</tr>
<tr>
<td>( Z )</td>
<td>2</td>
</tr>
<tr>
<td>( J_0 ) (A/m²)</td>
<td>( 8.5 \times 10^{-4} )</td>
</tr>
<tr>
<td>( \epsilon )</td>
<td>78</td>
</tr>
<tr>
<td>( \epsilon_{r} ) (F/m)</td>
<td>( 8.85 \times 10^{-12} )</td>
</tr>
<tr>
<td>( n^0 )</td>
<td>( 9.3 \times 10^{22} )</td>
</tr>
<tr>
<td>( D ) (m²/s)</td>
<td>( 1.99 \times 10^{-9} )</td>
</tr>
</tbody>
</table>
However, in this paper, we ignored the variation of effective surface area because neural probes in the same wafer have almost same surface roughness value.

The effects of variations due to patterning process on electrical impedance of neural probe are shown in Fig. 6. This patterning-process includes dry etching of Cr/Au layer for signal lines and Ir layer for electrodes. Dry etching process is the main process step that results in non-uniformity in dimensions of signal lines and electrodes. These variations are extracted by the proposed equivalent circuit model and parameters in Table 1. As shown in Fig. 6(a), the impedance of neural probe in low frequency region matches well with the experimental data from our previous work, which shows the impedance variation of ±15% at 1 kHz [9]. Impedance variation decreases as frequency increases up to 4 kHz. Fig. 6(b) shows the percentage of impedance variation when the dimension of the microelectrodes changes by ±5%. The impedance variation decreases as frequency increases and shows zero value at 4 kHz. The electrochemical impedance of microelectrodes at 1 kHz is important because most of the neural signals have frequency of 1 kHz. 5% of process variation by etching of metal layer induces about 9% of impedance variation at 1 kHz.

These variations match with the measurement results from our previous work [10]. From this result, estimation of impedance variation by metal etching process is predictable and these variations can be further optimized. Fig. 7 shows the impedance variation by thickness variation of deposited metal for electrodes. As shown in Fig. 7, the thickness variation shows no effect on the impedance over different frequency range.

In the equivalent circuit model of the neural probe shown in Fig. 3, metal deposition process that affects the value of RL has negligible effect on the impedance of electrodes on the neural probe.

**Fig. 6.** (a) Impedance variation of neural probe with 5% etching process variation; (b) Impedance variation percentage of neural probe with 5% etching process variation.

![Image](http://www.jeet.or.kr)

**Fig. 7.** Impedance variation of neural probe due to 5% variation in deposited metal thickness.

In this work, impedance variation of microelectrodes on neural probe was investigated with an improved equivalent circuit model. The proposed equivalent circuit model considers process variations from fabrication process of the neural probe. The amount of fabrication process variations was extracted from experiments and these variations were applied to the input parameters for simulation which was used to estimate the impedance. Deposition and etching of metal layers during the overall fabrication process were closely examined to investigate their effects on the overall impedance variation. From the simulation results with the proposed equivalent circuit model, the impedance variation of 9% at 1 kHz is well matched with experimental data. However, the thickness variation of deposited metal has negligible effect on the microelectrode impedance. Expectation and estimation of impedance variation of microelectrodes in neural probe were calculated with the suggested equivalent circuit model. The proposed equivalent circuit model and the estimation of impedance variation from process will be used in the design optimization of various human interface devices as well as neural probe.

**4. Conclusions**

In this work, impedance variation of microelectrodes on neural probe was investigated with an improved equivalent circuit model. The proposed equivalent circuit model considers process variations from fabrication process of the neural probe. The amount of fabrication process variations was extracted from experiments and these variations were applied to the input parameters for simulation which was used to estimate the impedance. Deposition and etching of metal layers during the overall fabrication process were closely examined to investigate their effects on the overall impedance variation. From the simulation results with the proposed equivalent circuit model, the impedance variation of 9% at 1 kHz is well matched with experimental data. However, the thickness variation of deposited metal has negligible effect on the microelectrode impedance. Expectation and estimation of impedance variation of microelectrodes in neural probe were calculated with the suggested equivalent circuit model. The proposed equivalent circuit model and the estimation of impedance variation from process will be used in the design optimization of various human interface devices as well as neural probe.
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