Chemical-Free Metal PDMS Thermal Bonding in Flexible Bio-Potential Electrode Fabrication

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ABSTRACT

The flexible bio-potential electrode is gaining signifiacnt interest in wearable or implantable biosensors. Among many soft materials, polydimethylsiloxane (PDMS) is widely studied because of its good biocompatibility and elasticity. However, due to the nature of poor adhesion between an electrode material and PDMS, use of PDMS in the flexible electrode fabrication is limited. Recently, we had discovered a new approach which can create a strong adhesion between PDMS and metal. It enables the fabrication of a PDMS based flexible bio-potential electrodes for wearable or implantable sensors. As a proof of concept, a PDMS based flexible Ag/AgCl electrode was fabricated and characterized.

Keywords: Dry biopotential electrode, bio-potential measrurement, polymethylesiloxane, Ag/AgCl electrode

1 INTRODUCTION

The traditional electrode type of the bio-potential measurement is called the wet electrode because it uses electrolyte gel between the electrode and the skin of patient. The most popular material of the electrode is silver chloride (Ag/AgCl). However, the wet electrode can cause skin irritation, thus, the dry electrode is studied as an alternative. Unlike the wet electrode, the dry electrode does not cause skin irritation, and it is beneficial in terms of the installation speed and the eligibility of fabricating wearable or implantable biosensors.

One of the key of the dry electrode is flexibility of the electrode. This can reduce the air-gap between electrode and the skin which is the main source of the noise. The air-gap is a common issue in bio-potential monitoring, and it is usually filled with electrolyte gel. The removal of the electrolyte gel creates the air-gap, and the collected data contains significant noise due to the increased impedance. The flexible electrode can deform along the skin and minimize the air-gap, furthermore, the air-gap is filled with sweat which act as natural electrolyte gel.

There are various soft materials studied for the flexible electrode fabrication, and among these materials, PDMS is gaining interest significantly due to its physical properties such as biocompatibility and elasticity. The elasticity of PDMS is similar to that of human organs, as a result, it causes less damage on the tissue, and the electrode can be operating longer [1-2].

Although, PDMS is widely studied in the flexible electrode fabrication, use of PDMS in the fabrication is challenged due to the poor adhesion between PDMS and electrode. Therefore, extra processes like chemical treatment were required to overcome the poor adhesion.

Recently, we had discovered a chemical-free method for enhancing the adhesion between metal and PDMS [3]. This method is named as Chemical-Free Metal PDMS Thermal Bonding (CFMPTB). It can be used in the fabrication of a Ag/AgCl electrode. In this paper, a flexible Ag/AgCl electrode was fabricated and characterized to prove the eligibility of CFMPTB in the fabrication of a flexible bio-potential electrode.

2 METHOD AND EXPERIMENT

2.1 Chemical-Free Metal PDMS Thermal Bonding (CFMPTB)

CFMPTB is modified version of the PDMS curing process, and it a thermally induced process that enhances the adhesion between metal and PDMS by creating Metal-Oxide-Silicon bonds [4]. The standard PDMS curing condition cannot create these bonds, however, these bonds can be created by modifying the condition.

The three main factors of the PDMS curing condition are the PDMS mixing ratio, the baking temperature and the baking time. The standard PDMS curing condition is baking PDMS (weight mixing ratio 10:1 = polymer base: curing agent) at 65–95℃ for at least 30 minutes, but up to as much as, at longest, 48 hours (longer baking is required if the baking temperature is lower). No bonding between PDMS and metal was observed from the standard PDMS curing process. Nevertheless, when the condition was baking PDMS (weight mixing ratio 5:1, increased curing agent) at a higher baking temperature for longer time, strong adhesion between PDMS and metal was observed. It does not require any extra technique like chemical treatment for generating a strong adhesion between metal and PDMS [3].

CFMPTB allows the fabrication of a flexible electrode by transferring metal layer onto a PDMS.

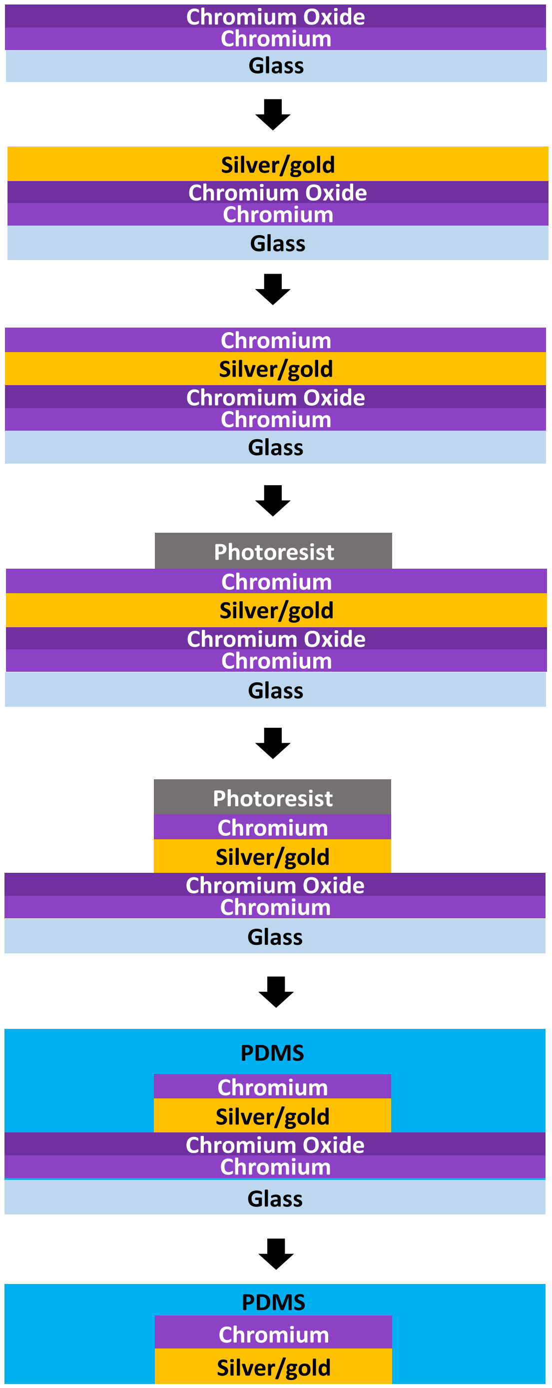

Figure 1: Illustration of CFMPTB. Initially, metal layers were deposited on a glass substrate, firstly a chromium layer (with a thin chromium oxide layer growth) then a 1.5 µm-thick. A pattern of the silver was fabricated by conventional photolithography and wet etching. Uncured PDMS was then poured on the metal surface. The curing conditions such as the PDMS mixing ratio, the baking temperature and the baking time was varied based on the optimal adhesion parameters. After the PDMS was cured, the PDMS was peeled off.

2.2 Fabrication of a Ag/AgCl Electrode

The fabrication process of a Ag/AgCl electrode is illustrated in Figure 1. Initially, on a clean glass substrate, a 10 nm-thick chromium was deposited using the BOC Edwards Auto 500 E-beam metal deposition system (Edwards, Burgess Hill, UK) and a thin chromium oxide layer was grown by baking in the air at 180℃ for 20 minutes. Then, a 1.5 µm-thick silver was deposited onto the chromium oxide layer using the BOC Edwards Auto 500 thermal metal deposition system (Edwards, Burgess Hill, UK). The reason of using the thermal metal deposition system is for a higher metal deposition rate. The metal deposition process can be replaced by electroplating. The pressure was set to 7.5×10^{-7} Torr, and the deposition rate was set to 3 Å/s for silver and 0.5 Å/s for the chromium layer. Then, a pattern of Ag layer (Figure 2) was fabricated by photolithography and wet etching. After fabrication of the pattern, the Ag layer was transferred onto a ~800 µm-thick PDMS substrate.

Next, it was submerged into a bleach (Clorox, Oakland, CA) bath, which is a simple method of growing a silver chloride layer. Bleach is a powerful oxidizing chemical solution with excessive chlorine ions (Cl^-) that reacts with silver and grows a silver chloride layer.

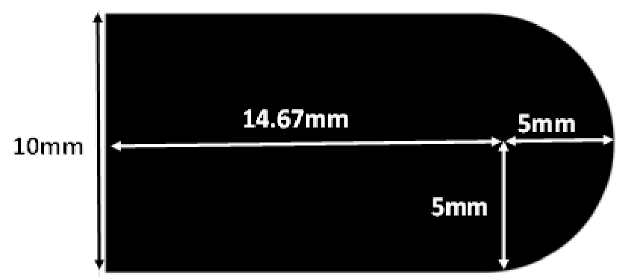

Figure 2: A simple design for a mold to create a silver pattern. The mold was composed of a rectangular pattern size of 10 mm × 14.67 mm with a semi-circular pattern with radius of 5 mm.

2.3 Characterization of a Ag/AgCl Electrode

The fabricated flexible Ag/AgCl electrodes were characterized by the equipment set-up as shown in Fig 3. A pair of flexible Ag/AgCl were attached on a 3D printed object and merged into a saline solution. Then a signal was applied using function generator and the signal was measured for calculating the impedance of the flexible Ag/AgCl electrode at different frequency, from 10Hz to 1kHz. The frequency range of the bio-potential is within this frequency range therefore, the impedance of the electrode in this range is important. Ideally, the impedance of the electrode must be < 1kΩ.

The impedance of the flexible Ag/AgCl electrode was measured at different frequencies, ranging from 10–1000 Hz using the equipment in Figure 3a). As shown in Figure

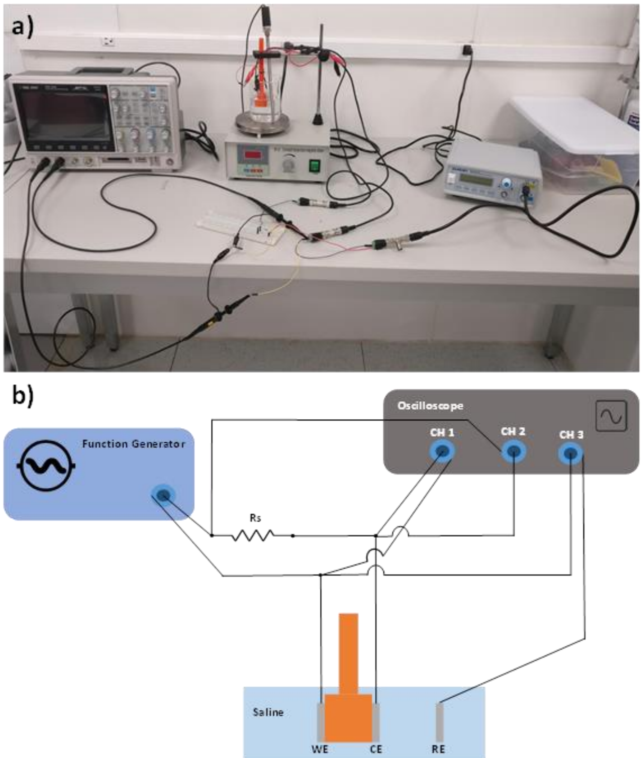

Figure 3: The experimental set-up for measuring impedance of the flexible Ag/AgCl electrode. a) Photograph of the equipment set-up. The electrode is attached on a stage (orange rod) and submerged into a salt bath. The impedance of the electrode was measured using the function generator (right) and oscilloscope (left). b) Schematic diagram of the connections. The WE and CE are uniformly spaced by the 3D printed object.

3b), there are three Ag/AgCl electrodes used in the impedance measurement: the working electrode (WE), the counter electrode (CE), and the reference electrode (RE). A pair of the flexible Ag/AgCl electrode was used as the WE and the CE, and a commercially available Ag/AgCl electrode was used as the RE.

A pair of flexible Ag/AgCl electrodes were attached on a 3D printed structure for keeping the distance between each electrode constant (like a capacitor). Then, the electrodes were fully merged into a saline solution (NaCl 0.9%) bath, and they were connected to a function generator, Kuman Dual Channel DDS signal generator (Kuman, Shenzhen, China) and an oscilloscope, Siglent SDS2204 (Siglent, Solon, Ohio, USA). The CE was connected to the function generator via 10 Ω resistor (sensing resistor Rs), and the function generator supplied sinusoidal voltage through the pair of the electrode 10 Vpp at frequency from 10 Hz to 1 kHz. To calculate the impedance of each flexible Ag/AgCl, the voltage measured in channel 1 was divided by the current flowing through Rs ($Z = V/I$). Since the electrodes were connected in series through the saline solution, half of the calculated impedance is the impedance of each electrode. In this measurement, the phase was ignored and only the magnitude of the impedance was measured.

3 RESULT AND DISCUSSION

The impedance of five pairs of the electrodes were measured and the results are shown in the Figure 4. The results show that the impedance of the electrodes is higher than it is desired to be (<1 kΩ). According to the results, the impedances of the electrodes generally are <~40 kΩ at >90 Hz. The impedance of three pairs of the electrodes are <~50 kΩ at 10 – 1000 Hz frequency range but other pairs have relatively high impedance at <200 Hz. Some electrodes have high impedance (>~40 kΩ) at <200 Hz that decreased rapidly below 40 kΩ at 200 Hz. Additionally, the results show that some electrodes have low impedance (~20 kΩ) at the frequency range of the bio-signal (~100 Hz) which can be used in the bio-signal measurement.

The result generally shows that impedance of the electrode is high and not stable at the frequency range of the bio-signals (the impedance fluctuates in Figure 4). This was mainly caused by the crack on the surface of the electrode and the instability of the interconnection between the electrode and the equipment. For the practical bio-signal measurement, the flexible electrodes must be improved.

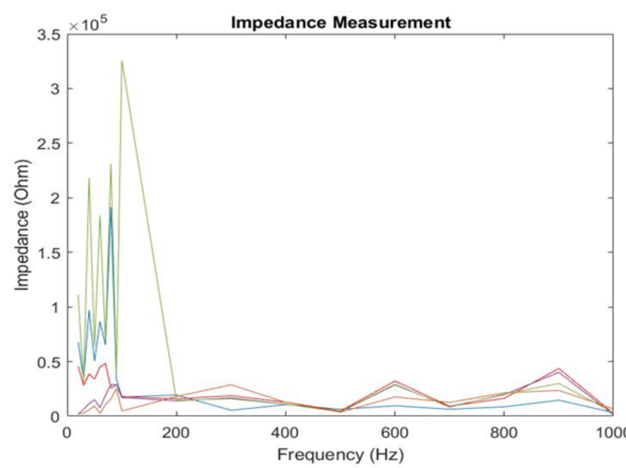

Figure 4: The measurement of impedance of silver chloride electrode. The impedance of a Ag/AgCl electrode, was measured from 10-1000Hz frequency. There are 5 different impedance measurement. The results generally show that the impedance is <~40 kΩ at <90 Hz and some electrodes have >~40 kΩ at >90 Hz. The impedance of some electrodes are ~20 kΩ at ~100 Hz that is the frequency range of the bio-signal.

4 CONCLUSION

In conclusion, with some improvement, CFMPTB is able create a good flexible electrode for practical bio-potential measurement.

The impedance of the flexible Ag/AgCl electrode must be stable and low (< 1 kΩ) at the frequency range of bio-signal, 10 Hz – 1 kHz. However, the results show that the impedance is very high < 20k that is caused by the crack on the electrodes. It can be overcome by optimizing the fabrication process for minimizing formation of the cracks. Additionally, an extra study on the interconnection will be required for collecting a high quality signal.

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