

Testing of Thin-Film Electrode Arrays for Cochlear Implants of the Future

J. R. Parker*, Y. Y. Duan*, J. Patrick*, H. B. Harrison**, O. Reinhold*, G. M. Clark*

*CRC for Cochlear Implant Speech and Hearing Research, VIC.

** School of Microelectronic Engineering Griffith University, QLD

*Defence Science and Technology Organisation, SA.

Abstract—The Nucleus cochlear implant has been shown to give substantial communication benefit to the severe to profoundly deaf. Future cochlear implants will incorporate an advanced multi-channel electrode array, which will enable better sound-coding strategies to be implemented. This new electrode array will be fabricated using state-of-the-art micromachining technology.

Any long-term implanted device such as a cochlear implant must undergo rigorous testing to ensure biological safety. In this paper four tests for the micromachined array are discussed. The tests are based on electrochemical methods, and include open circuit potential, galvanostatic biphasic pulse, 4-electrode shorting tests, and electrochemical impedance spectroscopy. This paper demonstrates that these test techniques are effective and informative in the development of thin-film electrode arrays. They can be used to verify the fabrication steps, electrode quality, and the suitability for the biological environment.

I. INTRODUCTION

The Nucleus cochlear implant is a biomedical device used to provide communication benefit to patients with a severe to profound sensorineural hearing loss. The current commercial device uses an array of 22 platinum electrodes to stimulate the nerves in the cochlea. This is the maximum number of electrodes that can be currently implemented due to the method of fabrication and channel interaction limits. To significantly increase the number of stimulating sites, which would be an advantage for complex signal processing strategies, a different means of manufacture is required, *micromachining*. Thin-film micromachined electrode arrays were developed for this experiment and are shown in Figure 1. A thin-film cochlear array would be micromachined using a similar process.

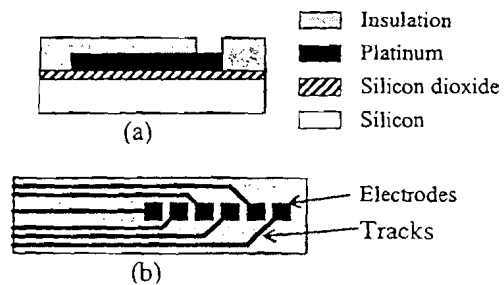


Figure 1: Micromachined thin-film electrode array. (a) Cross-section; (b) Top view.

Silicon dioxide is first grown to insulate the electrodes from the silicon. Photoresist is deposited and patterned in the negative of the required pattern. A thin layer of chromium is evaporated onto the surface to promote adhesion, before the platinum electrodes are sputtered on and patterned using lift-off. The final step is to deposit and pattern the top insulator.

An electrode array will form an electrochemical cell when placed in contact with a biological environment or saline solution. The interface of a platinum electrode in saline solution at resting potential can be approximately represented by either of the equivalent circuits shown in Figure 2. [1,4]

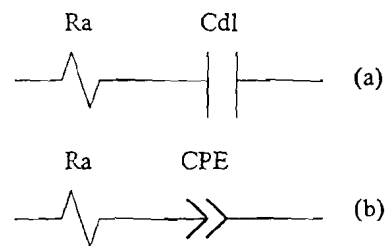


Figure 2: Equivalent circuit of platinum/saline electrochemical cell. (a) Using a standard capacitor; (b) Using a constant phase element.

The capacitor, C_{dl} , represents the electrochemical double layer, the interface between the electrode surface and the solution. In the physical system this is not a true capacitor because it does not give a full 90° phase shift. This effect is usually accounted for by the use of a *constant phase element* in place of the capacitor, shown in Figure 2(b). C_{dl} and CPE are related to the true surface area of the electrode, which is larger than the

geometric surface area on a microscopic scale. The resistor, R_a , is called the *access resistance*. It is the total series resistance due to the solution and track resistance of the working electrode, and also depends on the electrode geometric area.

Faults such as pinholes in insulation or discontinuities in electrical connections can occur during thin-film fabrication. These faults are difficult or impossible to detect using conventional electrical tests, but become evident during electrochemical testing. This paper presents the development of an effective electrochemical test method which will show the quality of the fabrication process, and the integrity of the electrode arrays.

II. EXPERIMENTAL METHOD

A. Test Electrode Array

The electrodes to be tested are micromachined thin-film electrode arrays as shown in Figure 1. They have six square platinum electrodes, $674\mu\text{m}$ side length. The average length of the arrays is 30mm.

Some electrodes were deliberately given errors during fabrication to ascertain the ability of the tests to detect them. The errors included short and open circuits, missing top insulator, and missing internal oxide insulator.

B. Electrochemical Cell

The electrochemical cell consists of three electrodes in phosphate buffered saline solution, as shown in Figure 3.

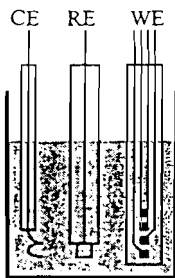


Figure 3: Electrochemical cell. CE = Counter electrode; RE = Reference electrode; WE = Working electrode.

The working electrode is one of the six electrodes on the thin-film array. The surface area of each electrode is 0.0045cm^2 , the same as the cochlear band electrodes. The reference electrode is a standard calomel reference electrode. The counter electrode is a piece of platinum wire, with a much greater surface area than the working electrode.

Phosphate buffered saline solution was made using SIGMA Phosphate Buffered Saline Tablets with distilled water which gave a solution consisting of

0.01M phosphate buffer, 0.0027M potassium chloride, and 0.137M sodium chloride at pH 7.4. All experiments were carried out at room temperature, and the cell was exposed to air.

C. Test Instruments

The galvanostatic biphasic pulse tests used a stimulator made in-house, capable of producing constant-current, charge-balanced biphasic pulses. The stimulator was controlled using the *BPP* software, also developed in-house. Measurements were taken using a Tektronix *TEKSCOPE* THS710 oscilloscope. The scope was a portable, battery-powered model, chosen to prevent the introduction of a ground in the system.

The open-circuit potential and electrochemical impedance spectroscopy (EIS) tests used a Solartron SI1287 Electrochemical Interface and a SI1260 Impedance/Gain-Phase Analyzer. These instruments were controlled using the ZPlot and ZView software by Scribner Associates.

III. RESULTS AND DISCUSSION

A. Open-Circuit Potential Test

When an electrode array is immersed into saline solution it will attain an open-circuit potential (or resting potential) with respect to the reference electrode. This potential will depend mostly on the electrode material and the solution composition. It is measured prior to any experimentation as it can give an instant indication of electrode or track connection failures. Table 1 shows some of the open-circuit potential (E_c) measurements for thin-film electrodes in good condition, and with various faults.

Electrode	Condition	E_c (mV)	Comment
A-2	good	272	
Cochlear	good	300-350	
B-5	shorted	225	
B-6	together	225	
A-3	open-circuit	unable to measure	fluctuating
C-1	no internal oxide	-94	very stable
C-3	oxide	-94	

Table 1: Examples of open-circuit potential measurements.

Of all the electrodes tested, the good electrodes gave an open-circuit potential ranging from 200-350mV. Any platinum electrode will give an open-circuit potential which falls into this range, as demonstrated by the cochlear band electrode. Other researchers also report open-circuit potential values for platinum within this range [2].

The test indicates possible shorting of electrodes on arrays B and C by giving E_c values which are the

same or similar. The electrodes on array C are all shorted together through the silicon due to the absence of the internal insulating oxide. This shorting also causes a large increase in surface area, which makes the reading more stable. The potential is not within the characteristic range for platinum due to the mixing of the open-circuit potentials of silicon and platinum. The test immediately shows the open-circuits in array A by giving a wildly fluctuating reading.

This data demonstrates that the open-circuit potential test is a very easy but highly useful method. It can give important information instantly, relating to the electrode material characteristics and connection and insulation quality.

B. Biphasic Pulse Test

A symmetric, charge-balanced, biphasic current pulse was applied between the working electrode and counter electrode. The potential of the working electrode was measured with respect to the reference electrode. The circuit representation is shown in Figure 4.

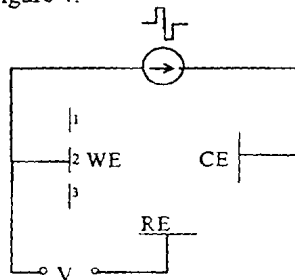


Figure 4: Biphasic pulse test.

As the cochlear implant stimulates using a biphasic pulse, the pulse must be charge-balanced and below a certain charge density to prevent any possible electrochemical reactions occurring.

The input and output waveforms for this test are shown in Figure 5. The input is a square biphasic pulse, 1mA in amplitude, and 200µs per phase pulse width.

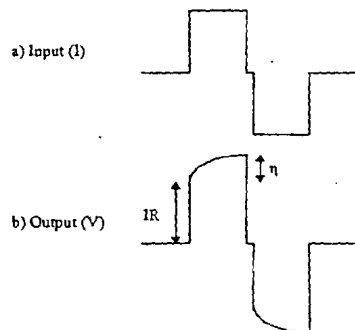


Figure 5: Input and Output waveforms in the biphasic pulse test.

Relating the output to the circuit in Figure 2(a), the IR drop is due to the access resistance, and the overpotential (η) is due to the double layer capacitance. The pulse-width must be chosen so that Cdl has a prominent effect in the output. If the pulse-width is too short, the stray capacitance of the cables will dominate, giving erroneous output readings. If the pulse-width is too long, polarization of the electrodes may cause faradaic reactions, which we wish to avoid. Table 2 shows data from the biphasic pulse test on electrodes with different faults.

Electrode	Condition	IR(mV)	η (mV)
A-5	good	400	120
A-4 A-6	open-circuit	all go to rails	0 - square wave
B-1	no top insulation	200	70
B-2	insulation	140	50
D-1	No	100	40
D-2	internal	100	40
D-3	insulation	90	35

Table 2: Data from the Biphasic Pulse Test.

The IR drop reflects the quality of the platinum track, and is related to the geometric surface area of the electrode. With no top insulation, the exposed track of array B causes the geometric area to approximately double, roughly halving the IR value. The IR value is lower for the array with no internal insulation because all the electrodes are effectively shorted together (through a resistive pathway).

The overpotential is related to the real surface area. On arrays D and B where there is shorting or the tracks are not insulated, the increase in surface area causes η to decrease.

The open-circuit electrodes (A-4 and A-6) did not give a transient charging on their output waveforms. The measured potential was a square wave at the compliance voltage limit of the stimulator.

In summary, this test is useful for indicating possible fabrication errors which result in apparent changes of surface area.

C. 4-Electrode Test for Shorting

The four-electrode technique is usually used for the study of electrolyte properties because no potentials are induced at the potential recording electrode if no current is drawn by a high impedance measurement instrument. We borrow the concept but use it as a shorting test, based on the same principle. It involves stimulating an electrode with a galvanostatic charge-balanced biphasic pulse as in the previous section, but measuring the potential of

the neighbouring unstimulated electrodes. This concept is shown in Figure 6.

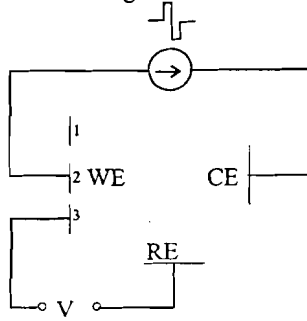


Figure 6: Test for shorting.

If the potential recording electrode is shorted with the stimulated electrode, its transient potential response will show a polarised characteristic with rising potential as indicated in Figure 5(b). Otherwise the output should be just a square wave as in Figure 5(a).

This test was demonstrated using electrodes 1 and 5 of array A which are in good condition, electrodes 5 and 6 of array B which are shorted together, and array D, which has no internal insulation. As expected, the electrodes in good condition gave a square wave output for this test, indicating no shorting, and all the rest gave an output similar to Figure 5(b), due to the presence of shorting. These results are presented in Table 3.

A(good)	B(shorted)	D(no internal insulator)		
1-5	5-6	1-2	2-3	3-4
OK	short	short	short	short

Table 3: Results of 4-electrode shorting test. Electrode numbers are listed in pairs with the convention: (stimulated electrode)-(measured electrode).

The novel use of this test enables the detection of shorts in a thin-film electrode that are not easily measured by normal electronic techniques. These usually arise from fabrication errors.

D. Electrochemical Impedance Spectroscopy

Electrochemical Impedance Spectroscopy (EIS) is a method of measuring the impedance of a system across the frequency spectrum [5]. It is a highly useful technique for studying the electrochemical interface at different polarisation potentials. The tests presented here were all done at resting potential.

The potential of the working electrode (vs RE) was made to fluctuate as a 10mV sine wave by applying current between the working and counter electrodes [6]. The corresponding impedance was calculated and the measurement was conducted between 100kHz and 0.01Hz. Figure 7 shows the Bode plots for three electrode arrays.

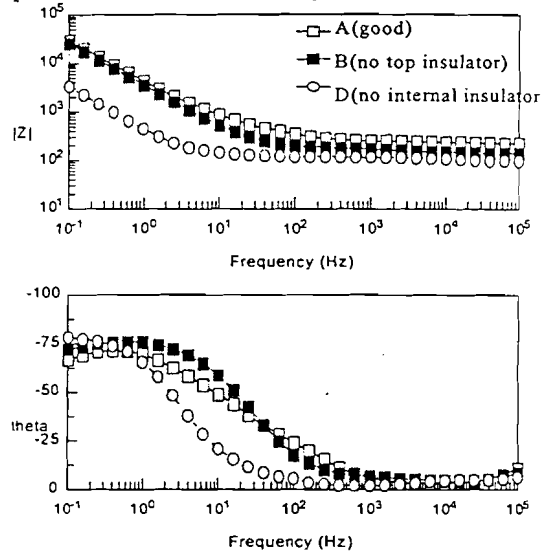


Figure 7: Bode plot of EIS results.

By inspecting the magnitude plot, and using the circuit in Figure 2, it can be seen that the impedance at the highest frequencies is dominated by the access resistance. This is also in agreement with the fact that R_a is dependent on geometric surface area and therefore is highest for the good electrode, lower for the electrode with exposed track, and lower still for the electrode with no internal insulation. At low frequencies the impedance and phase are dominated by the double layer characteristics. It can be seen that the phase does not reach 90° like a true capacitor, but shows the properties of a distributed capacitor, or constant phase element.

The value of the CPE has two parts: CPE_T and CPE_p . If the impedance of a normal capacitor is denoted

$$Z_c = \frac{1}{j\omega C} \quad (1)$$

then the impedance of a constant phase element is denoted as

$$Z_{CPE} = \frac{1}{CPE_T (j\omega)^{CPE_p}} \quad (2)$$

where CPE_p is a value generally between -1 and 1, and CPE_T is the effective capacitance if CPE_p is equal to 1[3]. If CPE_p is equal to 0.5, then there are other processes occurring at the double layer such as diffusion, and CPE_T no longer represents a capacitance. It does however, still relate to the true

surface area of the electrode. Different constant-phase-elements can generally only be compared if their CPE_p values are similar. The fit results for the three electrodes are given in Table 4.

Electrode	Condition	Ra	CPE_T	CPE_p
A	Good	247	5.5E-5	0.76
B	No top insulator	162	6E-5	0.85
D	No internal insulator	115	4.7E-4	0.88

Table 4: Circuit fitting results for three electrodes.

As discussed, the access resistance of electrode B is lower than A due to the larger geometric area. It is felt that the CPE_p values differ too much to allow comparison of CPE_T for these two electrodes.

For electrode D, the access resistance again shows the larger geometric surface area. The CPE_T value is also larger than for B, indicating the increased true surface area.

In conclusion, EIS is a sensitive technique which can provide useful information about the electrode-solution interface. As it uses a very small signal it causes minimal disturbance to the system and can be used for very delicate tests. It can also provide information about the quality and integrity of the electrode.

IV. CONCLUSION

Four methods of electrochemical testing were explored and found to be effective in testing thin-film electrode quality. They were shown to give information about insulating coating quality and electrical connectivity, that conventional electrical measurements could not. These techniques ensure the test to be carried out is either at close equilibrium conditions like the open-circuit potential test or EIS, or uses a transient method such as the galvanostatic biphasic pulse test and the 4-electrode test for shorting. The tests were found highly suitable for platinum electrodes in saline solution, as they minimise polarisation of the system, while obtaining the maximum information. The results of all the tests together can be used to verify the integrity of the thin-film electrode and the quality of the fabrication.

V. ACKNOWLEDGEMENTS

The authors would like to thank Griffith University for the use of the Microelectronics fabrication laboratory.

VI. REFERENCES

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Author/s:

Parker, J. R.; Duan, Y. Y.; Patrick, J.; Harrison, H. B.; Reinhold, O.; Clark, Graeme M.

Title:

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Date:

1999

Citation:

Parker, J. R., Duan, Y. Y., Patrick, J., Harrison, H. B., Reinhold, O., & Clark, G. M. (1999). Testing of thin-film electrode arrays for cochlear implants of the future. In Biomedical Research in the 3rd Millennium. Proceedings of the Inaugural Conference of the Victorian chapter of the IEEE Engineering in Medicine and Biology Society, Caulfield, Victoria.

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