

## Thin film platinum cuff electrodes for neurostimulation: in vitro approach of safe neurostimulation parameters

Sophie Mailley<sup>a</sup>, Marc Hyland<sup>a</sup>, Pascal Mailley<sup>b,\*</sup>, James A. McLaughlin<sup>a</sup>, Eric T. McAdams<sup>a</sup>

<sup>a</sup>Northern Ireland Bio-Engineering Centre, University of Ulster at Jordanstown, Shore Road, Newtownabbey, Co. Antrim, Northern Ireland, BT37 0QB, UK

<sup>b</sup>CREAB group, Laboratoire des Structures et Propriétés des Architectures Moléculaires UMR 5819 CNRS-CEA-Université Joseph Fourier Grenoble 1, DRFMC/SI3M/CREAB, CEA 17 avenue des Martyrs 38054, Grenoble cedex 9 France

Received 23 June 2003; received in revised form 21 October 2003; accepted 27 October 2003

### Abstract

Thin film technology takes more and more importance in the development of biomedical devices dedicated to functional neurostimulation. Our research about the design of implant neurostimulating electrode is oriented toward thin film cuff electrodes based on a polyimide substrate covered by a chromium/gold/Pt film. The chromium/gold sputtered film serves as adhesion layer and current collector whereas platinum acts as an electrochemical actuator. The electrode surface has been designed to obey safe stimulation criteria (i.e. chemically inert noble metal, low electrode–electrolyte impedance, high electrochemical reversibility, high corrosion stability). The electrochemical behaviour of such platinum electrodes has been assessed and compared to a foil of platinum. Extensive in vitro characterisations of the both electrode types were carried out using AFM, SEM and electrochemical techniques. The role of enhanced surface roughness enabling high double layer capacitances to be achieved was clearly highlighted. The obtained results are discussed, with particular reference to thin film electrodes stability under in vitro electrical stimulation in NaCl 0.9% (physiological serum). Therefore, these thin film devices showed reversible PtOH formation and decomposition making them potentially attractive for the fabrication of implant stimulation cuff electrodes.

© 2004 Elsevier B.V. All rights reserved.

**Keywords:** Platinum implant electrode; Cuff electrode; Neurostimulation; AC impedance

### 1. Introduction

Electrical nerve stimulation is a technique involving exogenous electrical signals to restore the functions of deficient nerves from the sensory and the motor systems [1]. In such a way, functional neuromuscular stimulation (or functional neurostimulation) deals with the stimulation of intact lower motor neurons to restore functional movement in hemiplegic, paraplegic or quadriplegic persons [2]. Different classes of electrodes have been designed for application in motor prostheses including intraneural electrodes [3], sieve electrodes [4] and cuff electrodes [5]. Owing to its biocompatibility [6], platinum is one of the most frequently implanted electrode material for clinical neurostimulation. Platinum electrodes can be referred to as “faradaic” electrodes as they couple to tissue via a faradic charge transfer process.

Following McAdams et al. [7], an interface may be well expressed other a wide frequency range in terms of an equivalent electrical circuit involving a charge transfer resistance,  $R_{ct}$  which enables faradic current to flow through the interface, in parallel with a non-faradic double layer capacitance,  $C_{dl}$ . In order to ensure safe charge transfer it is widely believed that it is best to transfer charge across the interface by means of capacitive current and to avoid faradic reactions as by-products diffuse into the surrounding tissues causing trauma. Thus, as double layer capacitance charge dominates transient responses immediately following the application of a pulse, short duration pulses are generally used in an effort to avoid faradic reactions and their by-products. However, even when pulse durations are kept relatively short, some current may flows through  $R_{ct}$  causing tissue trauma.

Biphasic pulse [8] have therefore been used to recover the by-products generated during the first half of the pulse. Noble metals/alloys, and more particularly platinum, have been generally used for implant electrodes as they present large values of  $R_{ct}$  and thus are more likely to operate under

\* Corresponding author. Tel.: +33-438784838; fax: +33-438785145.

E-mail address: [pmailley@cea.fr](mailto:pmailley@cea.fr) (P. Mailley).

$C_{dl}$  control. However such electrodes give rise to large overall interface impedances. To overcome such a disadvantage, implant electrode surface can be roughened giving rise to low interface impedance couple to large double layer capacitance [9]. As a way of consequence, rough electrode surfaces provides an extended number of electroactive sites which may favour the reversibility of low potential faradic transfer reactions and the uniform distribution of charge transfer. Thereby, if the faradic transfer is well controlled, it becomes possible to avoid electrode reactions having higher potentials, which tend to cause tissue damage due to hazardous reactions such as oxygen or hydrogen generation associated with water hydrolysis.

Following the aforementioned prerequisites, we report here the design of thin film platinum cuff electrodes fabricated by platinum electrodeposition onto roughened sputtered chromium–gold thin films coated on polyimide substrate. The advantages of these electrodes deal with their flexibility, which avoids tissue trauma due to mechanically rigid structures, and with their enhanced electroactive surface area consecutive to the roughening treatment of the gold layer [9]. The morphology and the electrochemical behaviour of these thin film cuff electrodes were assessed and compared to classically used platinum foil.

## 2. Experimental

All in vitro electrochemical characterisations were made in 0.1 M pH 6.8 phosphate-buffered saline prepared with  $\text{Na}_2\text{HPO}_4$ ,  $\text{NaH}_2\text{PO}_4$  and NaCl (0.9%) (Analar Prolabo) as a model of biological media. All chemicals were of the highest purity available and were used without further purification.

The platinum stimulation electrodes were made either with a platinum foil, 0.25 mm thick (Aldrich) or with a thin film platinum electrode. The latter was prepared by electrodeposition of platinum onto a thin film of gold (100 nm thick) sputtered on top of a flexible polyimide foil (50  $\mu\text{m}$  thick) previously coated with a sputtered chromium (10 nm thick) layer. Prior to Pt electroplating, the thin film gold substrate was roughened as described previously [9] and then washed with ethanol and electrochemically pre-treated (0.8 V/SCE, 120 s). Platinum electrodeposition was performed by electrolysis of an hexachloroplatinic acid (sigma) 10 mM phosphate buffer 0.1 M solution (pH = 7.9) at a potential of  $-0.4$  V/SCE during 600 s. A Plexiglas device was used to define the working electrode surface ( $S = 0.156 \text{ cm}^2$ ). All the electrochemical experiments were carried out with a platinum counter electrode and a calomel-saturated electrode as the reference using a PGSTAT 20 Autolab potentiostat (Ecochemie). The effective surface areas of the electrodes were determined by chronoamperometric oxidation of hexacyanoferrate II 2.5 mM (Aldrich) in aqueous KCl 1 M. Impedance spectra were measured over a frequency range of 10000–0.1 Hz with a potential amplitude of 5 mV rms by maintaining the electrode at the dc potential bias of oxygen desorption (0V/

SCE). Stimulation signals were carried out using a cathodic first square wave current with a pulse amplitude of 0.5 mA and pulse widths ranging from 0.5 to 0.001 s.

Structural and morphological characterisations of the electrode surfaces were performed using a Hitachi S-3200N low vacuum scanning electron microscope and a Burleigh ARIS-3300 SPM used in contact mode. A statistical analysis programme (Burleigh PSPM software) was used to determine the surface roughness  $R_a$  and the fractal dimension for  $1 \times 1 \mu\text{m}^2$  scanned surfaces.

## 3. Results and discussion

Surface topography is of the first importance for implant neurostimulation electrodes. Thereby, the surface morphology of thin film electrodes were imaged by AFM (Fig. 1) and SEM (not shown) and compared to a platinum foil as standard electrode material.

As expected, thin film electrode (Fig. 1B) shows a dramatic enhancement of surface roughness compared to the platinum foil that exhibits a smooth topography (Fig. 1A). As a matter of fact, thin film electrode is characterised by a six-fold increase in the  $R_a$  parameter over the platinum foil electrodes studied and a higher fractal dimension (Table 1). AFM analysis of the surface of both the conductive sublayer (Cr/Au) used to electroplate platinum and the final electroplated platinum surface illustrates that the roughness and the fractal dimension of the platinum is close to that of the conductive sublayer. This result indicates that electrodeposition of the active layer produces uniform coverage and conserves the sublayer roughness without mechanical distortion. Consequently, the surface morphology created by sputter deposition of the gold enables the roughness of the final electrode surface to be optimally tailored. However, in an electrochemical point of view, this highly developed surface has to promote enhanced electrocatalytical properties to be considered as a reliable interface for neurostimulation. This was assessed through the oxidative chronoamperometry of hexacyanoferrate. As shown in Table 1, thin film electrode presents an electroactive surface area up to four times higher than its geometric area (Table 1). This illustrates the generation of an extended number of electroactive sites coupled to good cohesion and intrinsic conduction of the electrode material.

In neurostimulation applications, faradic transfer reactions occurring onto platinum surfaces involve Pt surface oxidation and oxygen desorption. Thus, cyclic voltammetry has been utilised to visualise the electrochemical behaviour of both interfaces in model saline media (PBS). Such a media, even if dramatically different from biological fluids, models here physiological serum exempt from biomolecules and allows us to identify rationally pure electrochemical phenomena. Fig. 2 shows the cyclic voltammograms recorded for each type of platinum electrode. Electrochemical oxidation of platinum and oxygen desorption/reduction occurs respective-

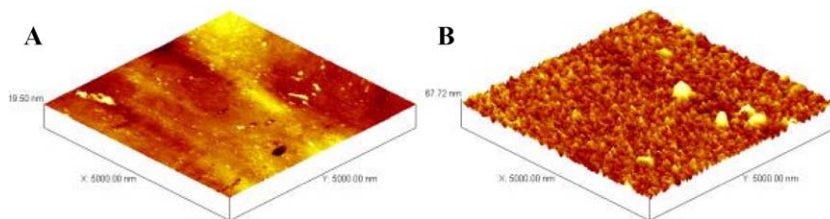
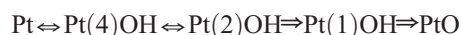


Fig. 1. AFM pictures of platinum foil (A) and thin film Pt electrode (B) surface morphologies.

ly at potentials of 0.2 and 0 V/SCE. Contrary to the pure oxidative oxygen-adsorption currently described [10], electrochemical analysis [11,12] shows that there is in fact a three-step sequence to obtain PtOH followed by a fourth step to give PtO:



The fourth reaction step which leads to PtO is a non-reversible reaction and the formation of PtOH is reversible only up to step 2. In fact, according to Angerstein-Kozłowska et al. [11], some reorganisation of the successive platinum hydroxide layers formed on the electrode surface can occur before irreversible PtO formation following steps 2 and 3. The successive steps correspond to different organisations of platinum with various coordinance 1/4 in Pt(4)OH, 1/2 in Pt(2)OH and 1 in Pt(1)OH. With the coordinance 1/2 and 1 being more strongly bound on the surface, the dissolution of PtOH in reduction after this reorganisation stage is difficult. Thereby, the reversibility of the stimulating electrode is effectively dependent upon the reversibility of the two first steps.

Fig. 2 displays the obtained voltammograms for platinum foil (A) and thin film platinum (B) electrodes. The potentiodynamic behaviour of the electroplated interface presents a large capacitive component, as displayed by the distortion of the obtained voltammogram (Fig. 2B), compared to platinum foil (Fig. 2A). Such comportment is directly related to the extended surface area of the electrodeposited interface. Nevertheless, the adsorption step and the first reorganisation step are seen on Fig. 2B to be particularly prevalent on the rough platinum electrode where a continuous current increase is obtained. The platinum foil electrode, due to the low adsorption of hydroxide, rapidly form

irreversible PtO as evidenced by a broad flat region for potentials above 0.25 V/SCE (Fig. 2A).

To complete the interpretation of the cyclic voltammograms recorded on these platinum electrodes, for a potential in excess of 1 V/SCE (not shown), chloride and oxygen formation from electrolyte oxidation hydrolysis occur successively. For a potential lower than  $-0.3$  V/SCE, successive hydrogen adsorption steps appear and, finally, hydrogen formations from the water reduction are visible at potentials lower than  $-0.6$  V/SCE.

After identification of the interfacial reactions, impedance was used to characterise the electrical comportment of both platinum interfaces, since the obtained spectra are directly linked both to the electrode morphology and the redox reactions, which take place at the interface. In this study, AC impedance characterisation was performed at a bias potential of 0 V/SCE corresponding to oxygen desorption potential (Fig. 3). The obtained results were modelled using the equivalent circuit of Fig. 3 where  $R_{el}$ ,  $R_{ct}$  and  $Z_{CPA}$  represent, respectively, the electrolyte resistance, the charge transfer resistance and the constant phase angle impedance.

$R_{el}$  was found to have a similar value for both samples.  $R_{ct}$  represents the charge transfer resistance associated with the electrochemical oxygen reduction occurring at the electrode surface.  $R_{ct}$  calculated for the thin film electrode cannot be considered as accurate due to the lack of impedance points at sufficiently low frequencies but is in the same

Table 1

Morphological characteristics obtained by AFM, electroactive surface measured by chronoamperometry and impedance parameters defined by the fitting of impedance locus of platinum electrode (Fig. 2) using the equivalent circuit shown in Fig. 2 insert

Electrode	Pt foil	Thin film Pt
Roughness $1 \times 1 \mu\text{m}^2$	0.89	6.88
Fractal dimension	2.87	2.93
Electroactive surface ( $\text{cm}^2$ )	0.06	0.8
Electroactive vs. geometric surface	30%	408%
$R_{ct}$ (k $\Omega$ )	33	44
$C_{eff}$ ( $\mu\text{F}$ )	1.1	9.6
$\alpha$	0.88	0.82

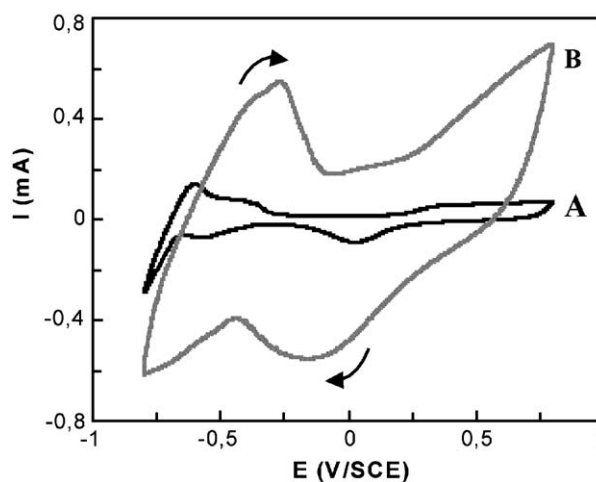


Fig. 2. Cyclic voltammetry of platinum foil (A, dark line) and thin film Pt (B, grey line) electrodes in PBS at a scan rate of  $200 \text{ mV/s}^{-1}$ .

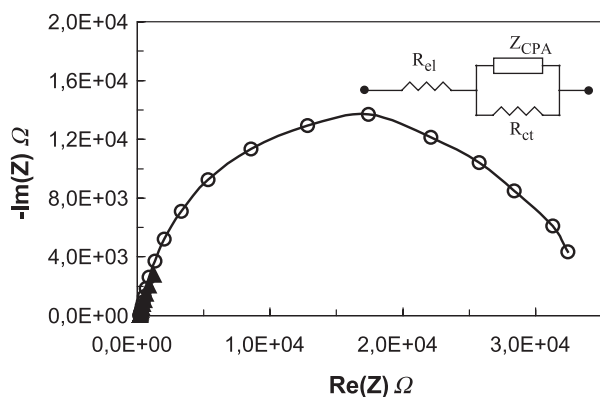


Fig. 3. AC impedance spectra of platinum foil (O) and thin film Pt (▲) electrodes and equivalent circuit used for interface modelling.

order of magnitude than such observed for platinum foil (Table 1).

The “constant phase angle” impedance,  $Z_{CPA}$ , shunts  $R_{ct}$  and can be expressed by:

$$Z_{CPA} = (j\omega C_{eff})^{-\alpha}$$

In the literature various alternative and equally valid expressions for  $Z_{CPA}$  have been reviewed. We have used here  $C_{eff}$  in an effort to derive a simple capacitance value from the experiment while still noting the non-ideal behaviour of the “capacitance”. This latter behaviour is generally thought to arise ( $\alpha \neq 1$ ), from the presence of electrode interface inhomogeneities and more particularly surface roughness [13,14]. The higher  $\alpha$  value recorded for the platinum foil, representative of a smoother surface, than such obtained for the thin film electrode is in good agreement with the evolution of the fractal dimension calculated by AFM (Table 1). Moreover, as expected, the magnitude of  $C_{eff}$  for the thin film electrode is larger, again indicating a rougher surface. This higher “capacitance”  $C_{eff}$  reflects a decrease in the electrode–electrolyte impedance.

Surface characterisations and impedance measurements highlighted the improvements in terms of interface quality bringing by thin film electrodes while potentiodynamic characterisation provides the fundamental basis to an understanding of the phenomenon recorded during electrical stimulation, but there still remains a need for concise interpretation of potentiometric responses under galvanic stimulation. Over a large variety of stimulation signals reported in the literature [14–16], most of the signals used in clinical applications consist on a series of monophasic or biphasic direct current pulses. In this work, we choose to apply biphasic ‘square wave’ current pulses to the electrodes. These signals are often used in an effort to reverse electrochemical processes and thus minimise the release of reaction by-products into the tissues. This principle was first proposed by Lilly et al. [8] and discussed more recently by Donaldson and Donaldson [15]. A cathodic pulse is generally applied first to facilitate stimulation. In our experiments, a current pulse amplitude of 0.5 mA (i.e. 3.2 mA/cm<sup>2</sup>) was

used, being representative of the clinical values employed in neurostimulation using cuff electrodes. The phase pulse duration was varied from 1 ms to 0.5 s (from 250 to 0.5  $\mu$ C by phase) in order to determine the safe working range.

From Fig. 4 (insert), at long pulse durations, it is seen that electroplated platinum is relatively reversible, with recorded potential consistent with Pt surface evolution, while Pt foil electrode exhibits pronounced unsymmetrical behaviour. Thus, the potential response of platinum foil shows clearly two potential steps whatever was the pulse phase. This distortion of the potentiodynamic response is clearly associated with the existence of two successive charge transfer phenomena occurring at low potential, presumably linked to Pt reactions and at high potentials that imply electrolyte oxido-reduction. This “irreversible” reaction has been obtained on an electrode with a small electroactive surface and at long pulse duration. Thus, due to the low number of adsorption sites, the electrochemical system may progress to quasi non-reversible platinum hydroxide species such as Pt(2)OH or Pt(1)OH, and then the reduction process proceeds rapidly to water hydrolysis, which could possibly give rise to toxic effects.

As seen for the aforementioned example, the evolution of the potential recorded at the end of the pulse offers a qualitative evaluation of the charge transfer reversibility through the potential labelling of the involved reactions. Thereby, the evolution of the potential recorded at the end of the pulse was plotted against the pulse duration employed (Fig. 4). For long pulse durations, the platinum foil electrode exhibits a high potential (up to 1 V/SCE) in oxidation and a low potential (less than  $-0.8$  V/SCE) in reduction. These high potential values could be taken as indicating possible oxygen evolution during oxidation and similarly hydrogen evolution in reduction. These evolutions occur when the step duration is much longer than 0.025 s. For short pulse

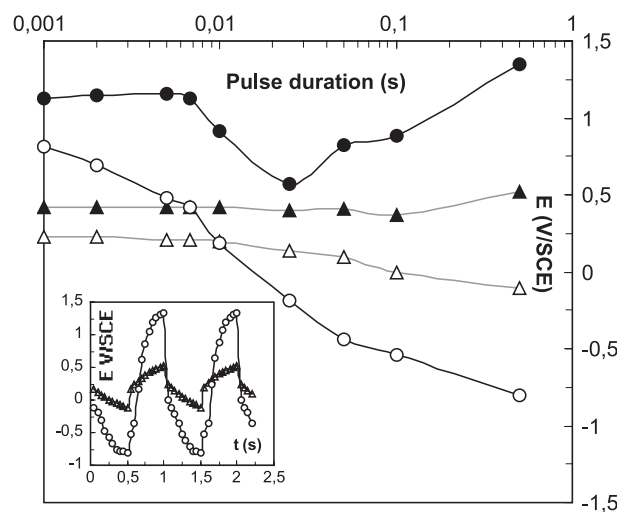


Fig. 4. Potential responses at pulse phase end recorded for Pt foil (O) and thin film Pt (▲) electrodes under galvanic square wave stimulation (DC amplitude 0.5 mA) for pulse durations of 1 ms to 0.5 s and potentiodynamic responses (insert) for a series of 0.5 s pulses.



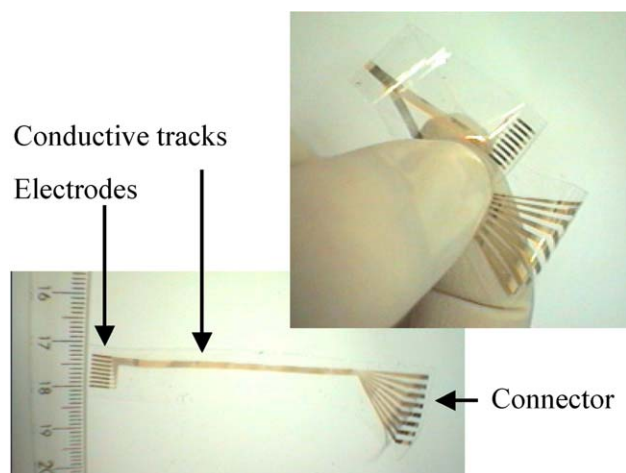


Fig. 5. Photographies of multipolar thin film electrodes dedicated to functional nerve stimulation.

duration, platinum foil electrodes have exhibited an unsteady behaviour in oxidation over a series of pulses, with a progressive increase in potential to a large positive value. This comportment may be related to the chemisorption of chloride ions [16]. Chlorine adsorption blocks the electro-oxidation sites of platinum favouring the formation of irreversible surface oxides and further oxidation reactions such as oxygen or chloride evolution [17]. Moreover, short pulse duration in reduction led to an inefficient stripping of chloride ions thus amplifying the role of electrolyte ion during Pt oxidation.

In the cases of the thin film platinum electrodes, potential values close to 0 V/SCE in reduction and 0.4 V/SCE in oxidation could be associated with reversible Pt(4)OH formation. Moreover, the recorded potentials are stable over the complete range of pulse durations, indicating that only Pt(4)OH adsorption occurs without the successive reorganisation of hydroxide adsorption on the electrode surface. Thus, owing to the large roughness of thin film platinum electrodes, and to the large number of available adsorption sites, a safe electrode interface has been designed which facilitates the reversible formation of Pt(4)OH in ideal electrolytes.

Finally, the obtained materials were applied to the design of multipolar cuff electrodes (Fig. 5) for functional nerve stimulation of paralysed persons. Electrode fabrication involved the photolithography of the chromium–gold film. Conductive tracks were then protected by a dielectric coating prior to the electrodes functionalisation. Then the electrodes were roughened as described previously and finally recovered by the electrodeposited platinum layer. The obtained electrodes present a high flexibility coupled to good adhesion of the metallic layers as illustrated in Fig. 5. The size of the electrodes were fixed to encircle nerves of the lower motor system with an adjusted diameter avoiding both electrode movements and tissue trauma due to mechanical stress. At now, these electrodes are tested *in vivo* onto rabbit, used as

animal model, at the University of Aalborg within the framework of the TMR project NEUROS.

#### 4. Conclusion

This work has evidenced the advantages of new roughened thin-film platinum cuff electrodes compared to classically used platinum foil interfaces in neurostimulation applications. These electrodes exhibit good mechanical behaviour in flexion and adhesion that would avoid tissue trauma due to electrode rigidity or to a lack of integrity. Moreover, the roughening process of the underlying Cr–Au coating enables the design of highly fractal electrodes in terms of electroactive surface area and thus allows the control of the interface electrochemical behaviour. Our electrode material has then exhibited reversible charge transfer under square wave biphasic signals over a wide range of pulse periods (up to 0.5 s). However, this work is a first insight onto the characterisation and the comprehension of the electrochemical behaviour of these new electrodes and thus depicts only their electrochemical limitations in simplistic model media. Further works are currently on the way to assess these new materials in more complex electrolytes (proteic PBS and cephalic fluids) to approach their behaviour as long-term implant electrodes.

#### Acknowledgements

This work has been supported by Neuros research project from the European Community.

#### References

- [1] W.M. Grill, J.T. Mortimer, Stimulus waveforms for selective neural stimulation, *IEEE Eng. Med. Biol.* (1995) 375–385.
- [2] R.B. Stein, P.H. Peckam, D.B. Popovic, *Neural Prostheses: Replacing Motor Function After Disease or Disability*, Oxford Univ. Press, New York, 1992.
- [3] W.L.C. Rutten, H.J. Van Wier, J.H.M. Put, Sensitivity and selectivity of intraneural stimulation using a silicon electrode array, *IEEE Trans. Biomed. Eng.* 38 (1991) 192–198.
- [4] A. Blau, C. Ziegler, M. Heyer, F. Endres, G. Schwitzgebel, T. Matthies, T. Steiglitz, J.-U. Meyer, W. Göpel, Characterisation and optimisation of microelectrode arrays for *in vivo* nerve signal recording and stimulation, *Biosens. Bioelectron.* 12 (1997) 883–892.
- [5] C. Veraart, W.M. Grill, J.T. Mortimer, Selective control of muscle activation with a multipolar nerve cuff electrode, *IEEE Trans. Biomed. Eng.* 40 (1993) 640–653.
- [6] D. Williams (Ed.), *Biocompatibility of Implant Materials*, Sector Publ., London, England, 1976.
- [7] E.T. McAdams, J.A. Mc Laughlin, D.S. Holder, *Neurosensors: a review of some fundamental electrode parameters*, Satellite symposium on neuroscience and technology, 14th Annual international conference of the IEEE Engineering in Medicine and Biology Society, Lyon, France, 1992, pp. 226–234.
- [8] J.C. Lilly, J.R. Hughes, E.C. Alvord Jr., T.W. Galkin, Brief non-inju-

- rious electric waveforms for stimulation of the brain, *Science* 121 (1955) 468–469.
- [9] M. Hyland, J.A. McLaughlin, D.M. Zhou, E.T. McAdams, Surface modification of thin film gold electrodes for improved in vivo performance, *Analyst* 121 (1996) 705–709.
- [10] L.S. Robblee, T.L. Rose, Electrochemical guidelines for selection of protocols and electrode materials for neural stimulation, *Neural Protheses: Fundamental Studies*, vol. 2. Prentice-Hall, Englewood Cliffs, NJ, 1990, p. 26.
- [11] H. Angerstein-Kozłowska, B.E. Conway, W.B.A. Sharp, Real condition of electrochemically oxidized platinum surfaces: I. Resolution of component processes, *J. Electroanal. Chem. Interfacial Electrochem.* 43 (1973) 9–36.
- [12] B.V. Tilak, B.E. Conway, H. Angerstein-Kozłowska, Real condition of oxidized platinum electrodes: III. Kinetic theory of formation and reduction of surface oxides, *J. Electroanal. Chem. Interfacial Electrochem.* 48 (1973) 1–23.
- [13] R. De levie, in: P. Delahay, C.W. Tobias (Eds.), *Advances in Electrochemistry and Electrochemical Engineering*, vol. 6. Interscience, New York, 1967, p. 329.
- [14] E.T. McAdams, Effect of surface topography on the electrode–electrolyte interface impedance part 3, *Surf. Topogr.* 3 (1989) 3–24.
- [15] N. de Donaldson, P.E.K. Donaldson, When are actively balanced biphasic (Lilly) stimulating pulses necessary in a neurological prosthesis?: 1. Historical background, Pt resting potential, Q studies, *Med. Biol. Eng. Comput.* (1986 January) 41–49.
- [16] M.F. Mrosek, M.J. Weaver, Periodic trends in monoatomic chemisorbate bonding on platinum-group and other noble-metal electrodes as probed by surface-enhanced Raman spectroscopy, *J. Am. Chem. Soc.* 122 (2000) 150–155.
- [17] B.E. Conway, J. Mozota, Chloride ion effects on the reversible and irreversible surface oxidation processes at platinum electrodes, and on the growth of monolayer oxide films at platinum, *J. Chem. Soc., Faraday Trans. I* 78 (1982) 1717–1732.