

MODERN ASPECTS OF ELECTROCHEMISTRY

No. 52

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Applications of Electrochemistry and Nanotechnology in Biology and Medicine I

 Springer

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ISSN 0076-9924

ISBN 978-1-4614-0346-3

e-ISBN 978-1-4614-0347-0

DOI 10.1007/978-1-4614-0347-0

Springer New York Dordrecht Heidelberg London

Library of Congress Control Number: 2011934050

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Printed on acid-free paper

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Preface

The emergence of nanoscience and nanotechnology has led to new developments in and applications of electrochemistry. These two volumes of *Modern Aspects of Electrochemistry*, entitled: “Applications of Electrochemistry and Nanotechnology in Biology and Medicine, I and II” address both fundamental and practical aspects of several emerging key technologies. All Chapters were written by internationally renowned experts who are leaders in their area.

The chapter by A. Heiskanen and J. Emnéus provides a lucid and authoritative overview of electrochemical detection techniques for real-time monitoring of the dynamics of different cellular processes. First, biological phenomena such as the cellular redox environment, release of neurotransmitters and other signaling substances based on exocytosis, and cellular adhesion, are discussed thoroughly. Next, the capabilities of electrochemical amperometric and impedance spectroscopic techniques in monitoring cellular dynamics are highlighted, in comparison to optical and other techniques. The applications of such techniques already include biosensors and microchip-based biological systems for cell biological research, medical research and drug development. Finally, the state-of-the-art and future developments, e.g. miniaturization of planar interdigitated electrodes in order to achieve a gap/width size regime on the nanometer scale and thus considerable signal amplification, are summarized.

Electron transfer by thermally activated hopping through localized centers is an essential element for a broad variety of vital biological and technological processes. The use of electrode/self-assembled monolayer (SAM) assemblies to explore fundamental aspects of long- and short-range electron exchange between electrodes and redox active molecules, such as proteins, is reviewed comprehensively in a chapter by D.H. Waldeck and D.E. Khosh-tariya. The authors, who are pioneers in this area, nicely demonstrate that such bioelectrochemical devices with nanoscopically tunable physical properties provide a uniquely powerful system for fundamental electron transfer studies and nanotechnological applications. Studies on protein systems also reveal how the binding motif

of the protein to the electrode can be changed to manipulate its behavior, thus offering many promising opportunities for creating arrays of redox active biomolecules.

A microbial fuel cell (MFC) is a bio-electrochemical transducer that converts microbial biochemical energy directly to electrical energy. In their authoritative chapter, J. Greenman, I.A. Ieropoulos and C. Melhuish overview lucidly the principles of biofilms, biofilm electrodes, conventional fuel cells, and MFCs. Potential applications of both biofilm electrodes and MFCs are suggested, including sensing, wastewater treatment, denitrification, power packs, and robots with full energy autonomy. The symbiotic association between microbial life-forms and mechatronic systems is discussed in detail by the authors, who are internationally renowned experts in this field.

The last three chapters in Volume I deal with surface modification of implants, namely surface biofunctionalization or coating. First, R. Guslitzer-Okner and D. Mandler provide concise survey of different electrochemical processes (electrodeposition, electrophoretic deposition, microarc deposition, electropolymerization, and electrografting) to form different coatings (conducting polymers, non-conducting polymers, sol-gel inorganic-organic polymer materials, oxides, ceramics, bioglass, hydroxyapatite and other calcium phosphates) on different substrates (titanium and its alloys, stainless steels, cobalt-chrome alloys, nitinol, and magnesium alloys). The authors who are highly experienced in this field demonstrate the applicability of these coatings for medical devices such as drug eluting stents and orthopedic implants.

Different electrochemical processes to render metal implants more biofunctional and various electrochemical techniques to characterize the corrosion resistance of implants or the adsorption of biomolecules on the surface are reviewed by T. Hanawa in his authoritative chapter. Electrodeposition of calcium phosphates or polyethylene glycol (PEG), as well as anodizing and micro-arc oxidation processes to obtain TiO₂ nanotube-type oxide film on Ti substrate, or electrochemical treatment to obtain nickel-free oxide layer on nitinol alloys, are described. The effects of different surfaces on phenomena such as cell adhesion, bacterial attachment and calcification are presented.

The last chapter in Volume I, by T. Kokubo and S. Yamaguchi, lucidly summarizes the pioneering work and inventions

of these authors in the field of bone-bonding bioactive metals for orthopedic and dental implants. The metals include titanium, zirconium, niobium, tantalum and their alloys. The main surface modification technique presented in this chapter is chemical, followed by heat treatment, although other techniques such as ion implantation, micro-arc treatment, hydrothermal treatment and sputtering are also described. The bone-bonding ability of metals with modified surfaces is attributable to the formation of apatite on their surface in the body environment, which can be interpreted in terms of the electrostatic interaction of the metal surface with the calcium or phosphate ions in a body fluid. These findings open numerous opportunities for future work.

Volume II begins with a chapter by P.S. Singh, E.D. Goluch, H.A. Heering and S.G. Lemay which provides a lucid overview of the fundamentals and applications of nanoelectrochemistry in biology and medicine. First, some key concepts related to the double layer, mass transport and electrode kinetics and their dependence on the dimension and geometry of the electrode are discussed. Next, various fabrication schemes utilized in making nano-sized electrodes are reviewed, along with the inherent challenges in characterizing them accurately. Then, the “mesoscopic” regime is discussed, with emphasis on what happens when the Debye length becomes comparable to the size of the electrode and the diffusion region. Quantum-dot electrodes and charging and finite-size effects seen in such systems are also described. Then, recent advances in the electrochemistry of freely-diffusing single molecules as well as electrochemical scanning probe techniques used in the investigations of immobilized biomolecules are presented by the authors, who have pioneered several of the developments in this area. Finally, a brief survey of the applications of nanoelectrodes in biosensors and biological systems is provided.

During the last decade, nanowire-based electronic devices emerged as a powerful and universal platform for ultra-sensitive, rapid, direct electrical detection and quantification of biological and chemical species in solution. In their authoritative chapter, M. Kwiat and F. Patolsky describe examples where these novel electrical devices can be used for sensing of proteins, DNA, viruses and cells, down to the ultimate level of a single molecule. Additionally, nanowire-based field-effect sensor devices are discussed as promising building blocks for nanoscale bioelectronic interfaces

with living cells and tissues, since they have the potential to form strongly coupled interfaces with cell membranes. The examples described in this chapter demonstrate nicely the potential of these novel devices to significantly impact disease diagnosis, drug discovery and neurosciences, as well as to serve as powerful new tools for research in many areas of biology and medicine.

The Human Genome Project has altered the mindset and approach in biomedical research and medicine. Currently, a wide selection of DNA microarrays offers researchers a high throughput method for simultaneously evaluating large numbers of genes. It is anticipated that electrochemical detection-based DNA arrays will provide many advantages over radioisotope- or fluorophore-based detection systems. Due to the high spatial resolution of the scanning electrochemical microscope (SECM), this technology has been suggested as a readout method for locally immobilized, micrometer-sized biological recognition elements, including a variety of DNA arrays with different formats and detection modes. In his concise review, K. Nakano explains the underlying electrochemistry facets of SECM and examines how it can facilitate DNA array analysis. Some recent achievements of Nakano and his colleagues in SECM imaging of DNA microdots that respond toward the target DNA through hybridization are presented.

Biological membranes are the most important electrified interfaces in living systems. They consist of a lipid bilayer incorporating integral proteins. In view of the complexity and diversity of the functions performed by the different integral proteins, it has been found convenient to incorporate single integral proteins or smaller lipophilic biomolecules into experimental models of biological membranes (i.e. biomimetic membranes), so as to isolate and investigate their functions. Biomimetic membranes are common in pharmaceuticals, as well as for the investigation of phase stability, protein-membrane interactions, and membrane-membrane processes. They are also relevant to the design of membrane-based biosensors and devices, and to analytical platforms for assaying membrane-based processes. The last two chapters in Volume II are dedicated to these systems. In their thorough chapter, R. Guidelli and L. Becucci review the principles and types of biomimetic membranes, the advantages and disadvantages of these systems, their applications, their fabrication

methodologies, and their investigation by electrochemical techniques – mainly electrochemical impedance spectroscopy (EIS). This definitive chapter was written by two authors who are among the leaders in the field of bioelectrochemistry worldwide.

Ion channels represent a class of membrane spanning protein pores that mediate the flux of ions in a variety of cell types. They reside virtually in all the cell membranes in mammals, insects and fungi, and are essential for life, serving as key components in inter- and intracellular communication. The last chapter in Volume II, by E.K. Schmitt and C. Steinem, provides a lucid overview of the potential of pore-suspending membranes for electrical monitoring of ion channel and transporter activities. The authors, who are internationally acclaimed experts in this area, have developed two different methods to prepare pore-suspending membranes, which both exhibit a high long-term stability, while they are accessible from both aqueous sides. The first system, nowadays known as nano black lipid membrane (nano-BLM), allows for ion channel recordings on the single channel level. The second system – pore-suspending membranes obtained from fusing unilamellar vesicles on a functionalized porous alumina substrate – makes it possible to generate membranes with high protein content. The electrochemical analysis of these systems is described thoroughly in this chapter, and is largely based on EIS.

I believe that the two volumes will be of interest to electrochemists, chemists, materials, biomedical and electrochemical engineers, surface scientists, biologists and medical doctors. I hope that they become reference source for scientists, engineers, graduate students, college and university professors, and research professionals working both in academia and industry.

I wish to thank Professor Eliezer Gileadi who was the driving force making me edit these two volumes. I dedicate this project to my wife Billie and our two daughters, Ofri and Shahaf, for their infinite love and support.

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Modern Aspects of Electrochemistry

Topics in Number 50 include:

- Investigation of alloy cathode Electrocatalysts
- A model Hamiltonian that incorporates the solvent effect to gas-phase density functional theory (DFT) calculations
- DFT-based theoretical analysis of ORR mechanisms
- Structure of the polymer electrolyte membranes (PEM)
- ORR investigated through a DFT-Green function analysis of small clusters
- Electrocatalytic oxidation and hydrogenation of chemisorbed aromatic compounds on palladium Electrodes
- New models that connect the continuum descriptions with atomistic Monte Carlo simulations
- ORR reaction in acid revisited through DFT studies that address the complexity of Pt-based alloys in electrocatalytic processes
- Use of surface science methods and electrochemical techniques to elucidate reaction mechanisms in electrocatalytic processes
- In-situ synchrotron spectroscopy to analyze electrocatalysts dispersed on nanomaterials

Topics in Number 51 include:

- Temperature effects on platinum single-crystal and aqueous solution interphases
- Surface thermodynamics of the metal and solution interface
- XAS investigations of PEM fuel cells
- Palladium-Based electrocatalysts required for alcohol oxidation in direct alcohol fuel cells
- Structure and Reactivity of transition metal chalcogenides used for molecular oxygen reduction reactions
- Proton conductivity and electrocatalysis in high temperature PEM fuel cells