UNIVERSITI PUTRA MALAYSIA

DESIGN OF CMOS POTENTIOSTAT FOR LOW-CONCENTRATION HEAVY METAL DETECTION

MEHRAN RAEISINAFCHI

FK 2015 21

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By

MEHRAN RAEISINAFCHI

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia,
in Fulfillment of the Requirement for the Degree of Master of Science

August 2015

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DEDICATION

First and foremost I would like to thank God, my creator, for giving me the intellectual capacity to learn about His creation. I dedicate my thesis work to my loving parents, KEFAYAT and BAHMAN, whose words of encouragement and push for tenacity ring in my ears. In addition, I have a special feeling of gratitude to my loving brother(Mehdi) and sister(Sara) for supporting me entire my life. I also dedicate this grateful work to my loving wife, BITA whose motivate me to complete my research efficiently. I also would like to thanks her for love, encouragement, admiration, kindness and support.

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment
of the requirement for the degree of Master of Science

DESIGN OF CMOS POTENTIOSTAT FOR LOW CONCENTRATION HEAVY METAL DETECTION

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MEHRAN RAEISINAFCHI

August 2015

Chairman : Assoc. Prof. Roslina bt. Mohd. Sidek, PhD
Faculty : Engineering

Metal toxicity is a critical concern in both human and ecosystem health. Many heavy metals are lethal at high concentration. They can also be harmful at trace concentration since accumulating such materials in human organs lead to long-term negative health effects such as heart disease and high blood pressure. Therefore, heavy metal detection of trace concentration is very important. Electrochemical detection system consists of electrodes as transducer, potentiostat as electrical signal detector and data converter for signal processing blocks. The potentiostat detects and amplifies the current generated by the transducer, and it controls the potential of the electrodes. With the advancement of micro- and nano-technology, micro-electrochemical system provides feasible solution for sensitive detection and miniaturized platform.

Studies have shown that to detect trace concentration of heavy metals, the potentiostat should be able to detect low current typically in the range of nA to µA and a different types of heavy metals can be detected at the potential between -1V and +1V. Researchers have developed CMOS- based potentiostat for detection of limited type of heavy metals and current detection level in µA range using CMOS technology nodes of 0.18µm and above. The research is aimed to design a potentiostat that can detect nA to µA range current and -1V to +1V range of the voltage using 0.13µm CMOS technology with ±1.2 V supply voltage. By using down-scaled technology, the area consumption is expected to decrease. Dual power supply of ±1.2V are used in the design to detect the potential between -1V to +1V. To ensure the linearity of output signal, the potentiostat is designed using fully differential operational amplifier and rail-to-rail common-mode range buffer. A new circuit configuration is also proposed to read nA range of current. By using down-scaled 0.13µm CMOS technology, the physical layout is reduced to $0.041mm^2$, about 10 times smaller than design area reported particularly using 0.18µm CMOS technology. The post-layout simulation results shows that the proposed design is able to read the input current in the range of nA to µA. The linearity is R^2= 0.999 and also the maximum voltage swing obtained is 2.4 V from -1.2V to +1.2V. The Signal to Noise Ratio (SNR) of CMOS potentiostat for 1nA and 1uA sensor current is equal to 38.91 dB and 47.96 dB, respectively. The circuit developed in this

research is verified by using published experimental data for 3mgL^{-1} Cu(II) and 0.6 mM Cd(II). The results shows that the values of current peaks and potentials at which current peaks occur are close to experimental results for these types of heavy metals.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Master Sains

REKA BENTUK POTENTIOSTAT CMOS UNTUK PENGESANAN LOGAM BERAT KEPEKATAN RENDAH

Oleh

MEHRAN RAEISINAFCHI

Ogos 2015

Pengerusi: Professor Madya. Roslina bt. Mohd. Sidek,
PhD Fakulty: Kejuruteraan

Ketoksikan logam adalah satu isu yang penting dalam kehidupan manusia dan kesihatan ekosistem. Banyak logam berat merbahaya pada kepekatan yang tinggi. Ia juga merbahaya pada konsentrasi rendah, oleh kerana pengumpulan bahan-bahan berkenaan dalam organ badan manusia boleh membawa kepada kesan negatif jangka panjang pada kesihatan seperti sakit jantung dan tekanan darah tinggi. Oleh itu, pengesanan logam berat pada konsentrasi rendah sangatlah penting. Sistem pengesanan elektrokimia terdiri dari elektrod sebagai transduser, potentiostat sebagai pengesan isyarat elektrik dan pengubah data untuk blok pemprosesan isyarat. Potentiostat mengesan dan menguatkan lagi arus yang dijana oleh transduser dan ia mengawal potensi elektrod. Dengan kemajuan makro dan nano-teknologi, sistem mikro-elektrokimia memberikan satu kaedah penyelesaian yang praktikal untuk pengesanan sensitif dan landasan bersaiz kecil.

Kajian telah menunjukkan bahawa untuk mengesan logam berat berkepekatan rendah, potentiostat dapat mengesan arus yang lebih rendah biasanya dalam lingkungan nA ke µA dan pelbagai logam berat boleh dikesan pada potensi antara -1V dan +1V. Penyelidik telah membangunkan potentiostat berasaskan CMOS untuk mengesan logam berat dan tahap pengesanan arus dalam jalat µA menggunakan nod teknologi CMOS dari 0.18µm dan ke atas. Kajian ini bertujuan untuk mereka bentuk potentiostat yang boleh mengesan julat arus dari nA kepada µA dan julat voltan dari -1V kepada + 1V julat voltan yang menggunakan teknologi CMOS 0.13µm dengan voltan bekalan ±1.2V. Dengan menggunakan teknologi berskala rendah, penggunaan kawasan ini dijangka akan berkurangan. Dua bekalan kuasa ± 1.2V digunakan dalam reka bentuk untuk mengesan potensi antara -1V ke +1V. Untuk memastikan kelelurusan isyarat keluaran, potentiostat direka menggunakan penguat operasian kebezaan penuh dan penimbal mod sepunga landasan ke landasan. konfigurasi litar baru juga dicadangkan untuk membaca arus dalam julat nA. Dengan menggunakan teknologi berskala rendah CMOS 0.13µm, bentangan fizikal dikurangkan kepada 0.041 mm^2, kira-kira 10 kali lebih kecil daripada kawasan reka bentuk dilaporkan terutamanya menggunakan teknologi CMOS 0.18µm. Keputusan simulasi pasca susun atur menunjukkan bahawa reka bentuk yang dicadangkan mampu untuk membaca arus masukan dalam julat nA ke µA. kelelurusan ialah $R^2 =$

0.999 dan juga voltan maksimum diperolehi ialah 2.4 V daripada -1.2V kepada +1.2V. Isyarat kepada Nisbah Bunyi (SNR) daripada CMOS potentiostat untuk 1nA dan 1uA sensor arus semasa adalah sama dengan 38.91 dB dan 47.96 dB. Litar yang dibangunkan dalam kajian ini disahkan dengan menggunakan diterbitkan data eksperimen untuk 3mgL^{-} Cu (II) dan 0.6 mM Cd (II). Keputusan menunjukkan bahawa nilai puncak arus dan potensi hampir dengan keputusan eksperimen untuk jenis logam berat tersebut.

ACKNOWLEDGEMENTS

In the Name of God, Most Gracious, Most Merciful

First and foremost I would like to thank Allah, the almighty for providing me this opportunity and granting me the capability to proceed successfully. I would like to express my deep appreciation and utmost to my supervisor Associate Professor. Dr. Roslina bt. Mohd. Sidek for her guidance, patience, encouragement and constructive notes throughout the work. Her valuable and instruction profoundly influenced the quality of this work. Sincere appreciation is extended to my co-supervisor Dr. Maryam Binti Mohd Isa for her valuable comments, generous help and encouragement. I would like also to thank all staff members of the Electrical and Electronics Engineering Department of University Putra Malaysia .My special thanks and gratitude are due to my great parents for their encouragement, morale, and financial support. I also thank my brother and sister for their support and kindness. Finally, I would like to thanks my wife for her love, patience, kindness and support she will remain in my heart all the time.

I certify that a Thesis Examination Committee has met on 7 August 2015 to conduct the final examination of Mehran Raeisinafchi on his thesis entitled "Design of CMOS Potentiostat for Low-Concentration Heavy Metal Detection" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Master of Science.

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(Chairman)

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Faculty of Engineering
Universiti Putra Malaysia
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(Internal Examiner)

Norhayati binti Soin, PhD
Associate Professor
University of Malaya
Malaysia
(External Examiner)

ZULKARNAIN ZAINAL, PhD
Professor and Deputy Dean
School of Graduate Studies
Universiti Putra Malaysia

Date: 12 January 2016

This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Master of Science. The members of the Supervisory Committee were as follows:

Roslina bt. Mohd. Sidek, PhD
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Maryam Binti Mohd Isa, PhD
Senior Lecturer
Faculty of Engineering
Universiti Putra Malaysia
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Supervisory
Committee: Roslina bt. Mohd. Sidek, PhD

Signature: ______________________
Name of
Member of
Supervisory
Committee: Maryam Binti Mohd Isa, PhD

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LIST OF ABBREVIATIONS

A_V	Differential Gain
A_{cm}	Common Mode Gain
C_C	Double Layer capacitance associated with the Counter Electrode
C_W	Double Layer capacitance associated with the Working Electrode
I_f	Faradic Current
R_C	Faradic Resistance
V_{ref}	Reference Voltage
ADC	Analog to Digital Converter
ASV	Anodic stripping Voltammetry
Cd	Cadmium
CE	Counter Electrode
CMOS	Complementary Metal Oxide Semiconductor
CMRR	Common Mode Rejection Ratio
Cu	Copper
CV	Cyclic Voltammetry
DAC	Digital to Analog Converter
DPASV	Differential Pulse Anodic Stripping Voltammetry
DPV	Differential Pulse Voltammetry
FD	Fully Differential
Hg	Mercury
ITRS	International Technology Roadmap for Semiconductor
Ni	Nickel
OP	Operational Amplifier
Pb	Lead
RE	Reference Electrode
SE	Single Ended
TIA	Trance Impedance Amplifier
Vb	Bias Voltage
VCMFB	Common Mode Feedback Voltage
VDD	Positive supply voltage
Vo	Output Voltage
VSS	Negative supply voltage
WE	Working electrode
$Vcell$	Cell Voltage

CHAPTER 1

INTRODUCTION

1.1 CMOS Technology for Monitoring System

Developments in Complementary Metal Oxide Semiconductor (CMOS) processing technologies and biomedical sensors have led to the realization of monitoring devices such as implantable biosensors for monitoring patients for example to reduce the risk of poison [1, 2]. The integration of transistor with CMOS technology enables development of miniaturized systems with higher throughput, lower cost and reliable performances. Figure 1.1 illustrates the overview of CMOS technology in patients monitoring. Hence, several physiological phenomena are monitored by body sensors. Then the data sent to a personal server through the internet. As the data is stored in a medical server, long term and short term patient term patient treatment can be optimized based on the medical history.

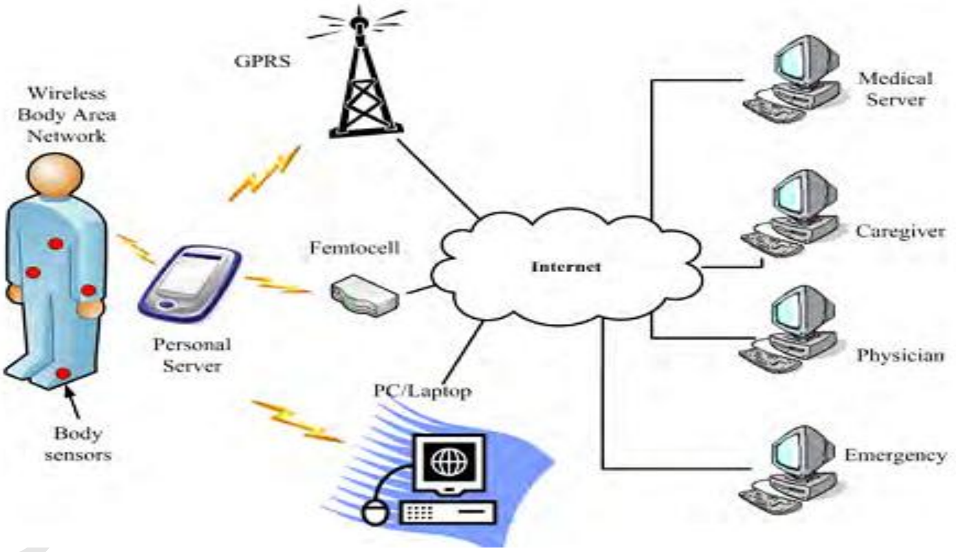

Figure 1.1 Overview of Patient Monitoring System based on CMOS Technology[2]

Economic and functional needs stimulate a progressive increase of the number of transistors integrated on a single chip. Until now the electronic technologies have been able to satisfy these needs through dimension scaling and reliability improvement of electronic components. Figure 1.2 shows the International Technology Roadmap for Semiconductor (ITRS) [3]. According to ITRS, Scaling (which is also known as more Moore) refers to not only the continued shrinking of transistors but also includes non-geometrical process techniques such as study of new materials that affect the electrical performance of the chip, as well as design technologies that enable high performance, high reliability, low cost, and high design productivity. Functional diversification (which is also known as more than Moore) aims to provide additional value, in particular non-digital functionalities (Analog/RF communication), to be migrated from the system board level into package-level (system-in-package, SiP) or chip-level (System-on-Chip, SoC) [4].

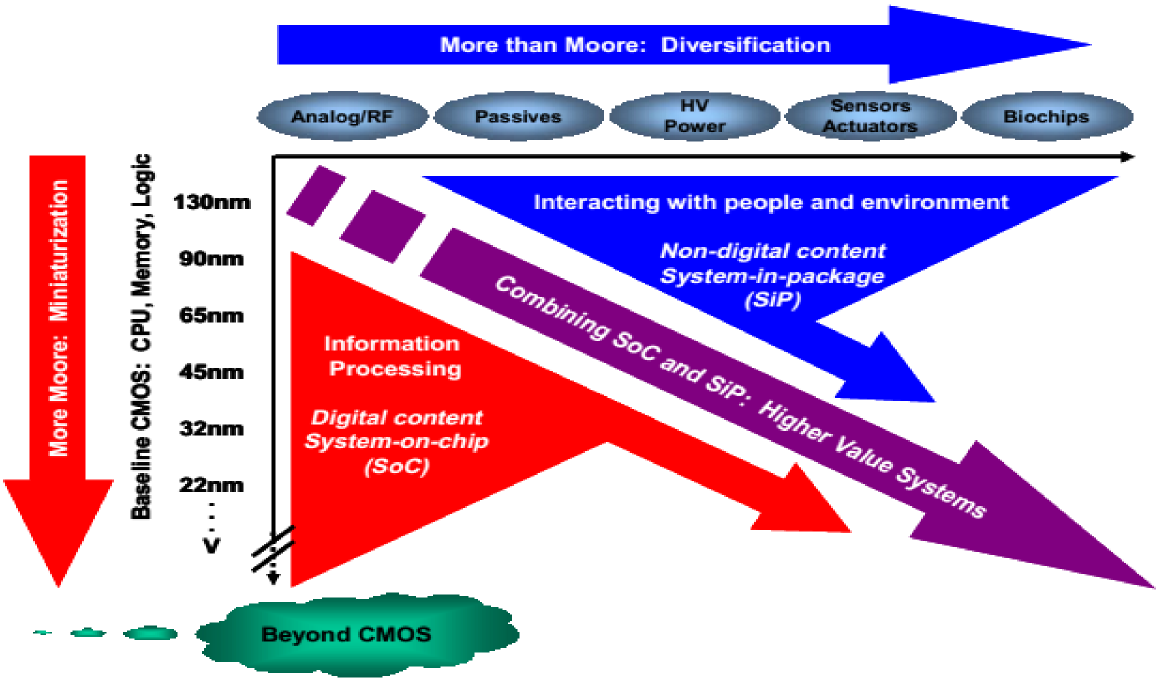

Figure 1.2 International Technology Roadmap for Semiconductor (ITRS)[3]

In environmental application CMOS technology is used for monitoring and measuring electrochemical analaytes. Figure 1.3 illustrates the block diagram of the electrochemical instrumentation system [5]. This electrochemical instrument includes electrochemical sensor, data conversion, microcontroller and potentiostat. Basically, a potentiostat has two main functions, controlling the potential difference between working electrode (WE) and reference electrode (RE) and measuring the current flowing between working electrode and counter electrode. The signal is generated by the microcontroller in digital form and is then converted to analogue form using a digital to analogue converter (D/A) [6]. It is applied to the counter electrode (CE) and reference electrode (RE) via a potentiostat which acts to control the applied potential. The signal output, in the form of a current, is obtained from working electrode (WE).

In the data acquisition process, the current is digitized by an analog to digital converter (A/D) under the control of the microcontroller. These binary numbers are then stored in the microcontroller memory for storage and further processing.

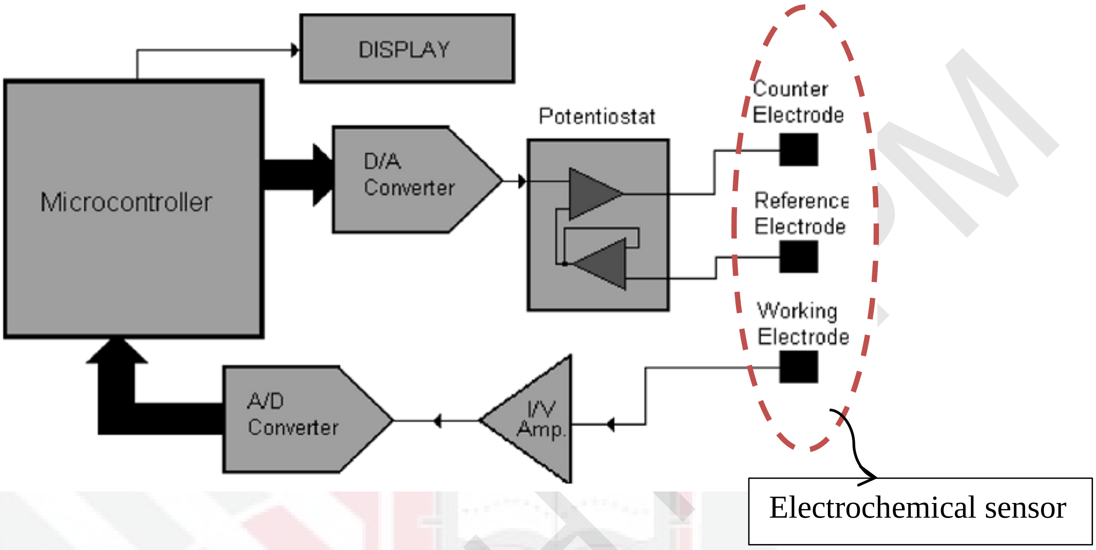

Figure 1.3 Block Diagram of the Electrochemical Instrumentation System[5]

1.2 Heavy Metal

Metal toxicity is a critical concern in both human and ecosystem health. Many heavy metals are lethal at high concentrations. They can also be harmful at trace concentration since accumulating such materials in human organs lead to long-term negative health effects such as heart disease and high blood pressure [7-9]. Heavy metals are namely mercury, lead, cadmium, nickel. Danger of heavy metals is their ability for bioaccumulation. Some heavy metals may also play a role in the development of various cancers. Environmental pollution from industry is the main source of high amount of heavy metals in the environment. In fact, after the penetration of these metals into the body, they accumulate in tissues such as fat, muscle, bones and joints and cause many diseases and bring various other aggravating problems to human [10, 11]. As is shown in the following Figure 1.4, the accumulation of heavy metals in the human body is often associated with some complications as in the following: Getting cold feet, immunodeficiency, skin rashes, digestive problems, fatigue, heart disease, high blood pressure, irritability, allergy, forgetfulness and dizziness.

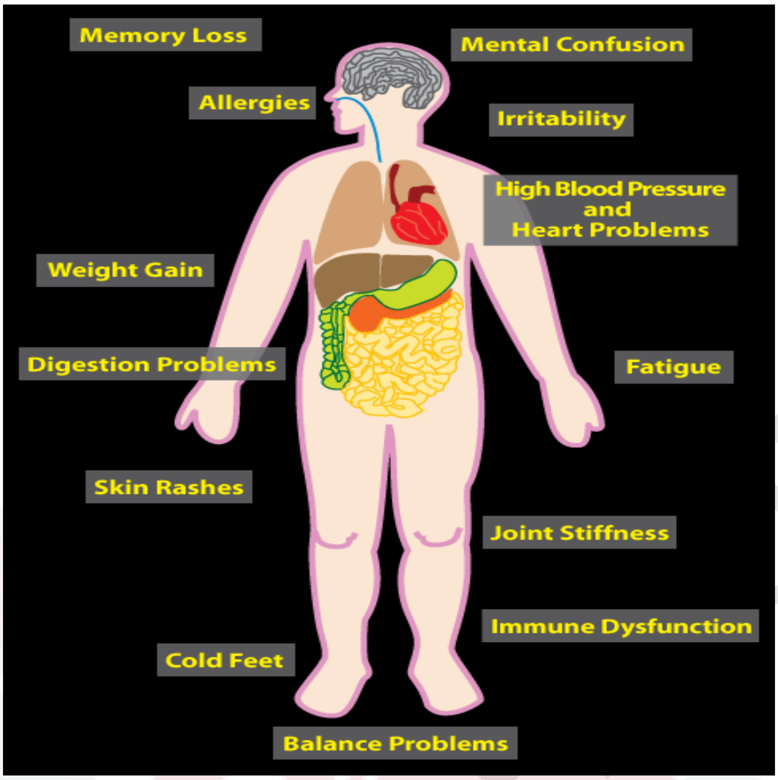

Figure 1.4 Human problems Caused by Accumulation Heavy Metals in Body

1.3 Problem Statement

Researchers have developed potentiostat based on CMOS technology but for the detection of limited type of heavy metals and current detection level in µA range [18, 46]. In order to detect trace concentration of heavy metals, the potentiostat should be able to detect lower current typically in the range of nA to µA. Therefore, previous CMOS potentiostat due to detection current in µA range cannot be used for low concentration heavy metal detection. Scaled down CMOS technology which tends to operate at lower current may be useful for detecting low concentration of heavy metals. Down-scaling trend of CMOS technology has significantly improved the performance of digital system. However, the decreasing supply voltage imposes challenges to analog design. In addition, the requirement for analog-digital integration required by study fully on-chip electrochemical sensor system demands for feasibility of adopting smaller node CMOS technology.

1.4 Research Objective

This research investigates the design and performance of CMOS potentiostat that can detect heavy metals at low concentration using 130nm CMOS technology with low supply voltages of ±1.2V. The CMOS potentiostat is aimed to support voltage range from -1V to +1V in order to detect different types of heavy metals. It is also aimed to sense current in nA range for low concentration detection. Therefore, the CMOS potentiostat is aimed to detect Cu(II) and Cd(II).

1.5 Research Scope

The research focuses on the design and simulation phases of 0.13µm CMOS technology. The design has been verified through post-layout simulation and is ready for next step which is chip fabrication. Therefore, chip fabrication and experimental measurement are excluded for scope of this thesis.

1.6 Thesis Organization

Chapter 1 specified the research area explains the motivation of this research. Next, the problem statement and also research objective are introduced prior to our brief explanation of the whole system. In chapter 2, the literature review which helps to understand the rated aspect of the thesis is explained. It includes the overview of electrochemistry. Then, the electrochemical analysis techniques are presented. In this chapter the potentiostat is introduced. Potentiostat topologies and their performance are also presented. In chapter 3, the methodology of this research is presented. In this chapter, design procedure, simulation setup and physical layout of this research is explained. The simulation result is discussed in chapter 4. Chapter 5 presents the conclusion of this work.

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