

DEVELOPMENT OF FLEXIBLE PIEZOELECTRIC
ENERGY HARVESTER FOR WEARABLE DEVICE

BY

MUHAMMAD IRSYAD BIN SUHAIMI

A thesis submitted in fulfilment of the requirement for the
degree of Master of Science (Electronics Engineering)

Kulliyyah of Engineering
International Islamic University Malaysia

DECEMBER 2020

ABSTRACT

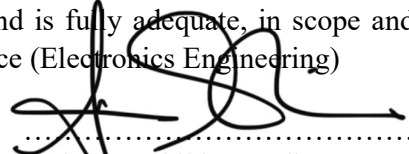
Recent advancements in sensing technology and wireless communications have accelerated the development of the Internet of Things (IoT) and wearable sensors. An emerging trend self-powered wearable devices, which eliminates the necessity of the user to carry bulky batteries. In this work, the development of a flexible piezoelectric energy harvester that is capable of harvesting energy from low-frequency vibration is presented. It was designed with a cantilever structure of PET/AZO/Ag layers in d_{33} mode which can generate large output voltages with small displacements. Aluminium doped to ZnO (AZO) piezoelectric layers was chosen due to its low deposition temperature and no requirements of post-deposition annealing and poling compared to other materials. Two significant design parameters were chosen, namely the effect of the gap between electrodes and the number of interdigitated electrodes (IDE) pairs to the output voltage and resonant frequency. These two parameters have been simulated using a finite element simulation tool named COMSOL Multiphysics. The device was then fabricated by sputtering the AZO thin film followed by screen printing of the silver IDE pairs. The sputtered AZO on PET showed c-axis orientation at 002 peak with 2θ values of 34.45° which indicates piezoelectric behavior. The average measured d_{33} constant value was 1.8 pC/N. The energy harvester was capable of generating 0.867 V_{rms} output voltage when actuated at 49.6 Hz. This indicates that the AZO thin films with printed silver electrodes have the potential to be used as a flexible, d_{33} energy harvester for wearable sensors.

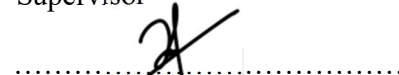
خلاصة البحث

التقدم الحديث في تكنولوجيا الاستشعار والاتصالات اللاسلكية قد أدى إلى تسريع تطور إنترنت الأشياء (IoT) والذي عمل على تعزيز استخدام أجهزة الاستشعار التي يمكن ارتداؤها. ثمة اتجاه ناشئ لتطوير أجهزة قابلة للارتداء ذاتية الاستدامة، مما يلغي ضرورة حمل المستخدمين بطاريات ضخمة. البحث الحالي يعمل على تطوير حسادة مرنة للطاقة الضغطكهربية والتي لها المقدرة على حصاد الطاقة من الاهتزاز المنخفض التردد. صممت تلك الحصادة مع تركيبة الكابول "cantilever" التي تتكون من طبقات من PET / AZO / Ag في وضع d33 والذي يمكنه أن يولد جهد كهربي كبير بواسطة إزاحات صغيرة. تم اختيار الألومنيوم, المعجون إلى ZnO (AZO), بسبب انخفاض درجة حرارة ترسيبه ولعدم حاجته للتلدين والطلاء بعد الترسيب مقارنةً بالمواد الأخرى كما نجد أيضاً أن AZO صديق للبيئة ولا يتسبب في تلوث خطير خلال عملية التصنيع. تم اختيار معاملين هامين في التصميم هما تأثير الفجوة بين الأقطاب الكهربائية وعدد الأقطاب الكهربائية الرقمية البينية (IDE) بالنسبة إلى الجهد الكهربي الناتج وتردد الرنين. تمت محاكاة هذين المعاملين باستخدام أداة محاكاة عنصر محدود يسمى (COMSOL Multiphysics). تم تصنيع الجهاز عن طريق رش شريحة رقيقة من AZO اتبعت بطباعة شاشة من أزواج الفضة IDE. أظهر AZO المرشوش على PET ميل لمحور c في ذروة 002 مع قيم θ يساوي 34.45 درجة مما يشير إلى السلوك الضغطكهربى. وكان متوسط القيمة الثابتة d33 قياساً 1.8 pC/N. وكان حسادة الطاقة قادرة على توليد $V_{rms} 0.867$ جهد كهربي عندما تم تشغيلها في 49.6 هرتز. وهذا يشير إلى أن الأفلام الرقيقة AZO مع أقطاب الفضة المطبوعة لديها القدرة على استخدامها كمحصّد طاقة مرن d33 لأجهزة الاستشعار القابلة للارتداء.


APPROVAL PAGE

I certify that I have supervised and read this study and that in my opinion, it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a thesis for the degree of Master of Science (Electronics Engineering)


.....
Anis Nurashikin Nordin
Supervisor


.....
Aliza Aini Md Ralib
Supervisor

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a thesis for the degree of Master of Science (Electronics Engineering)


.....
Muhammad Ibn Ibrahimy
Internal Examiner

This thesis was submitted to the Department of Electrical and Computer Engineering and is accepted as a fulfilment of the requirement for the degree of Master of Science (Electronics Engineering)

.....
Mohamed Hadi Habaebi
Head,
Department of Electrical &
Computer Engineering

This thesis was submitted to the Kulliyah of Engineering and is accepted as a fulfilment of the requirement for the degree of Master of Science (Electronics Engineering)

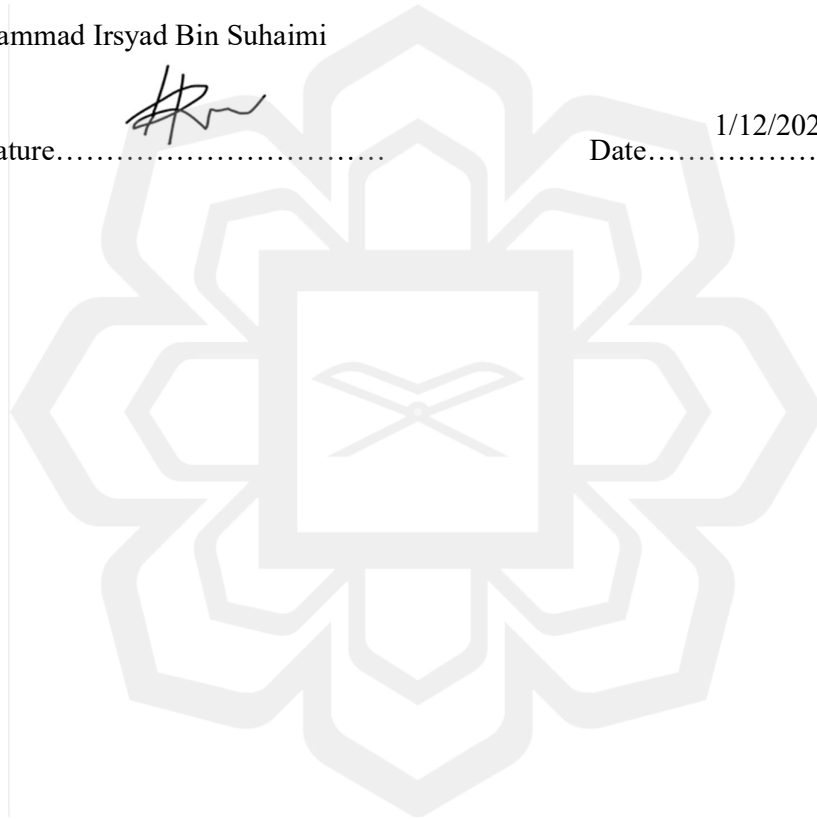
.....
Sany Izan Ihsan
Dean,
Kulliyah of Engineering

DECLARATION

I hereby declare that this thesis is the result of my own investigations, except where otherwise stated. I also declare that it has not been previously or concurrently submitted as a whole for any other degrees at IIUM or other institutions.

Muhammad Irsyad Bin Suhaimi

Signature.......... Date.....1/12/2020.....



INTERNATIONAL ISLAMIC UNIVERSITY MALAYSIA

**DECLARATION OF COPYRIGHT AND AFFIRMATION
OF FAIR USE OF UNPUBLISHED RESEARCH**

**DEVELOPMENT OF FLEXIBLE PIEZOELECTRIC ENERGY
HARVESTER FOR WEARABLE DEVICE**

I declare that the copyright holder of this thesis are jointly owned by the student and IIUM.

Copyright © 2020 Muhammad Irsyad Bin Suhaimi and International Islamic University Malaysia.
All rights reserved.

No part of this unpublished research may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording or otherwise without prior written permission of the copyright holder except as provided below:

1. Any material contained in or derived from this unpublished research may only be used by others in their writing with due acknowledgement.
2. IIUM or its library will have the right to make and transmit copies (print or electronic) for institutional and academic purposes.
3. The IIUM library will have the right to make, store in a retrieval system and supply copies of this unpublished research if requested by other universities and research libraries.

By signing this form, I acknowledged that I have read and understand the IIUM Intellectual Property Right and Commercialization policy.

Affirmed by Muhammad Irsyad Bin Suhaimi



.....

Signature

1/12/2020

.....

Date

ACKNOWLEDGEMENTS

*In the Name of Allah, the Most Compassionate, the Most Merciful.
May the blessings and peace of Allah be upon our prophet Muhammad ibn
Abdullah (peace be upon him), his families, his companions and
all of his righteous followers.*

All glory is due to Allah, the Almighty, whose Grace and Mercies has given me strength throughout the course to successfully accomplish this thesis.

Special appreciation goes to my supervisor, Prof Anis Nurashikin Nordin, who always guide and motivate me until the end of this research. Her patience in giving constructive comments throughout this project lead to the success of this research. Not to forget my beloved co-supervisor who always supports and sharing the knowledge and experience regarding this topic.

Special thanks to all my colleagues in Jabil MTI Group; Zambri Samsudin, LM Lim, Idris Mansor, and Mohd Yusuf for sharing knowledge, thoughts, experience, and all the motivations. Not forgotten to all my friends that have been directly or indirectly morally support throughout this research. Thanks for all the friendship and memoirs.

I would like to extend my appreciation to my beloved parents; Suhaimi Awang and Rosidah Endut and siblings for their prayers and relentless encouragement. Finally, my sincere abundant thanks go to my wife, Salihah Mohamad Pauzi for her tremendous patience, support, and advice during the project execution and thesis writing and also to my daughter Aisyah Humaira as my source of spirit during facing the difficulties.

Last but not least, as it may not be possible to list all the names, who have contributed either directly or indirectly towards the completion of this work, please accept my apologies. I wish to convey my true appreciation for all the help.

TABLE OF CONTENT

| | |
|--------------------------------------------------------------------------------|-----------|
| Abstract | ii |
| Abstract in Arabic | iii |
| Approval Page..... | iv |
| Declaration | v |
| Copyright | vi |
| Acknowledgements..... | vii |
| Table of Content | viii |
| List of Tables | x |
| List of Figures..... | xi |
| List of Abbreviations | xiv |
| List of Symbols..... | xv |
| CHAPTER ONE: INTRODUCTION | 1 |
| 1.1 Introduction..... | 1 |
| 1.2 Problem Statement..... | 3 |
| 1.3 Research Objective | 4 |
| 1.4 Research Methodology | 4 |
| 1.5 Scope of Research..... | 5 |
| 1.6 Thesis Organization..... | 7 |
| CHAPTER TWO: LITERATURE REVIEW | 8 |
| 2.1 Introduction..... | 8 |
| 2.2 Existing Methods Of Vibration Energy Harvesting | 11 |
| 2.2.1 Electromagnetic Energy Harvesting..... | 11 |
| 2.2.2 Electrostatic Energy Harvesting..... | 12 |
| 2.2.3 Piezoelectric Energy Harvesting | 12 |
| 2.2.4 Comparison Of Vibration Based Energy Harvester | 14 |
| 2.3 Piezoelectric Energy Harvesting Concept | 15 |
| 2.3.1 Piezoelectric Principle And Design | 15 |
| 2.3.2 Piezoelectric Mode Of Conversion..... | 19 |
| 2.3.3 Factors Affecting The Performance Of Piezoelectric EH | 20 |
| 2.4 Selection Of Piezoelectric Material | 22 |
| 2.5 Selection Of Flexible Substrate | 23 |
| 2.6 Screen Printed Interdigitated (IDT) Electrodes | 25 |
| 2.7 Piezoelectric Transducer Structures | 27 |
| 2.8 Comparison Of Existing Flexible Piezoelectric Energy Harvesters..... | 28 |
| 2.9 Potential Application: Piezoelectric Placement Region Under The Foot... 31 | |
| 2.10 Summary..... | 32 |
| CHAPTER THREE: DESIGN AND SIMULATION | 33 |
| 3.1 Introduction..... | 33 |
| 3.2 Selection Of Piezoelectric Material | 33 |
| 3.3 Cantilever Design Considerations | 34 |

| | |
|------------------------------------------------------------------------------------------------------|-----------|
| 3.3.1 Effect Of Ide Pairs To The Resonant Frequency and Output Voltage | 39 |
| 3.3.2 Effect Of The Gap Between Electrodes To The Output Voltage | 42 |
| 3.4 Finite Element Simulation | 43 |
| 3.4.1 Effect Of Gap Between Electrodes To The Generated Output Voltages And The Resonant Frequency | 49 |
| 3.4.2 Effect Of Ide Pairs To The Output Voltage And The Resonant Frequency | 50 |
| 3.5 Proposed Piezoelectric EH Design | 51 |
| 3.6 Summary | 52 |
| CHAPTER FOUR: EXPERIMENTAL WORK | 53 |
| 4.1 Introduction | 53 |
| 4.2 Deposition Of Azo Using Rf Magnetron Sputtering | 54 |
| 4.3 Fabrication Of Electrode Using Screen Printed Technique | 56 |
| 4.4 Characterization | 57 |
| 4.4.1 X-Ray Diffraction (XRD) Analysis | 57 |
| 4.4.2 Field-Emission Scanning Electron Microscopy (FESEM) And Energy Dispersive X-Ray (EDS) Analysis | 58 |
| 4.4.3 Piezoelectric Constant (d_{33}) Measurement | 58 |
| 4.4.4 Sheet Resistivity | 59 |
| 4.5 Mechanical Endurance Test | 59 |
| 4.6 Experimental Measurement Of Resonant Frequency And Output Voltage | 62 |
| 4.7 Summary | 63 |
| CHAPTER FIVE: RESULTS AND DISCUSSION | 64 |
| 5.1 Introduction | 64 |
| 5.2 Fabrication Of Piezoelectric Device | 64 |
| 5.3 Characterization | 66 |
| 5.3.1 X-Ray Diffraction (XRD) Analysis | 66 |
| 5.3.2 Field-Emission Scanning Electron Microscopy (FESEM) Analysis | 67 |
| 5.3.3 EDS | 68 |
| 5.3.4 Piezoelectric Constant (d_{33}) Measurement | 69 |
| 5.3.5 Sheet Resistivity | 69 |
| 5.4 Mechanical Endurance Test | 70 |
| 5.5 Experimental Measurement Of Resonant Frequency And Output Voltage | 73 |
| 5.6 Summary | 81 |
| CHAPTER SIX: CONCLUSION AND RECOMMENDATION | 83 |
| 6.1 Conclusion | 83 |
| 6.2 Recommendation | 84 |
| REFERENCES | 86 |
| PUBLICATIONS | 94 |

LIST OF TABLES

| | |
|------------------------------------------------------------------------------------|----|
| Table 2.1 Energy sources comparison with regards to power density | 10 |
| Table 2.2 Characteristics of the potential vibration sources | 10 |
| Table 2.3 Comparison of different types of vibration energy harvesting | 15 |
| Table 2.4 Material properties of piezoelectric material | 23 |
| Table 2.5: Types of substrates used and their dimension based on the previous work | 25 |
| Table 2.6: Previous work in piezoelectric | 29 |
| Table 2.7: Previous work done on piezoelectric EH placement under the foot | 32 |
| Table 3.1. Material properties used for the theoretical calculation | 37 |
| Table 3.2. Design parameters used for the theoretical calculation | 38 |
| Table 3.3. The theoretical mass of the device and its resonant frequency | 40 |
| Table 3.4 Design parameter for simulation work | 45 |
| Table 3.5 Finalized design parameters | 52 |
| Table 4.1 Sputtering parameters | 56 |
| Table 5.1 Each layer thickness of the piezoelectric device | 68 |
| Table 5.2 EDS analysis | 68 |
| Table 5.3 Resistivity of a different layer of the piezoelectric film | 70 |
| Table 5.4. Summarized measurement results | 77 |
| Table 5.5 Output voltage result comparison | 79 |
| Table 5.6 Resonant frequency result comparison | 80 |
| Table 5.7 Performance comparison with previous work | 82 |

LIST OF FIGURES

| | | |
|------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----|
| Figure 1.1 | Research Methodology flow chart | 6 |
| Figure 2.1 | Example of potential energy harvesting sources | 9 |
| Figure 2.2 | a) Electricity is generated when the force is applied to the piezoelectric material. b) The piezoelectric material deforms when it is applied to the electrical field. | 13 |
| Figure 2.3 | The direct piezoelectric effect causes crystal materials to generate an electric charge when compressed or pulled. The reverse effect causes the crystal materials to compress or expand when an electric voltage is applied (B. Yang et al. 2014) | 16 |
| Figure 2.4 | Cantilever beam with tip mass (A. A. Ralib and Nurashikin 2009) | 17 |
| Figure 2.5 | Generic vibration converter schematic (A. A. Ralib and Nurashikin 2009) | 18 |
| Figure 2.6 | Piezoelectric transducer operating modes (A. A. Ralib and Nurashikin 2009) | 20 |
| Figure 2.7 | Examples of printed electronics application (Reddy et al. 2011), (Emamian et al. 2015) | 26 |
| Figure 2.8 | Examples of piezoelectric transducer structures a) flat plate type, b) arch type, c) cantilever type (Xin et al. 2016) | 27 |
| Figure 3.1 | a) Dimension of the case b) The location of piezoelectric energy harvester inside the shoes | 35 |
| Figure 3.2 | a) Concept of d33 and d31 mode of Piezoelectric energy harvester. b) The cross-section of the d33 piezoelectric device | 36 |
| Figure 3.3 | Theoretical calculation of resonant frequency versus length of the cantilever beam | 39 |
| Figure 3.4 | Electrode design with different number of IDE pair for the theoretical calculation | 40 |
| Figure 3.5 | Theoretical calculation of resonant frequency versus number of IDE pairs | 41 |

| | | |
|-------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----|
| Figure 3.6 | Theoretical calculations of the output voltage versus the number of IDE pair | 42 |
| Figure 3.7 | Electrode design with the different gap between electrode for the theoretical calculation | 43 |
| Figure 3.8 | Theoretical calculation of the output voltage versus the gap between electrodes | 43 |
| Figure 3.9 | General flow chart of the simulation process | 44 |
| Figure 3.10 | a) Cross-section view of piezoelectric cantilever design b) Mesh of the device c) Simulation result of output voltage and displacement of the energy harvester d) Simulation result of displacement mode | 48 |
| Figure 3.11 | The effect of the gap between electrodes to the output voltage | 49 |
| Figure 3.12 | The effect of IDE pairs to the output voltage | 50 |
| Figure 3.13 | The effect of IDE pairs to the resonant frequency | 51 |
| Figure 4.1 | Flowchart of the experimental work | 54 |
| Figure 4.2 | a) ULVAC RF Magnetron sputtering machine b) During the sputtering process of AZO | 55 |
| Figure 4.3 | a) Fabrication sequence, b) Fabricated device | 57 |
| Figure 4.4 | d33/d31 meter Model ZJ-6B quasi-static used to measure d33 piezoelectric constant measurement | 59 |
| Figure 4.5 | a) Four-point probe used to measure sheet resistivity b) Close-up photo of the probe during measuring the resistivity | 59 |
| Figure 4.6 | A serpentine test pattern with 1.00mm widths, length 339.00mm and the trace to trace spacing is 3.00mm | 60 |
| Figure 4.7 | a) Bending test before the actuator hit the sample and b) during actuator hit the sample | 61 |
| Figure 4.8 | a) Illustration of tensile stress during the outer bending b) Illustration of compressive stress during the inner bending | 61 |
| Figure 4.9 | a) Setup for inner bending, the sample facing downward b) Setup for outer bending, the sample facing upward | 61 |
| Figure 4.10 | Schematic representation of the experimental setup | 62 |

| | | |
|-------------|----------------------------------------------------------------------------------------------------------------------------------|----|
| Figure 5.1 | Sputtered AZO on PET substrate | 65 |
| Figure 5.2 | Screen-printed electrode over the AZO | 65 |
| Figure 5.3 | XRD measurements performed on the AZO/PET layers | 66 |
| Figure 5.4 | a) Columnar ZnO structures in the AZO layer b), c) Cross-section of the piezoelectric films | 67 |
| Figure 5.5 | a) EDS analysis for Ag/AZO/PET b) The EDS distribution area of Zn and Ag | 69 |
| Figure 5.6 | (a) The resistance value and (b) Change in resistance, ΔR of outer bending test result with increasing lifted height. | 71 |
| Figure 5.7 | (a) The resistance value and (b) Change in resistance, ΔR of inner bending test results with increasing lifted height. | 71 |
| Figure 5.8 | Cyclic outer bending test result | 73 |
| Figure 5.9 | The close-up picture of the silver traces before and after 30,000 cycles of bending test | 73 |
| Figure 5.10 | DSA result of the 1.0mm electrode gap with a) 2 pairs of the electrode, b) 3 pairs of the electrode, c) 4 pairs of the electrode | 75 |
| Figure 5.11 | DSA result of the 1.2mm electrode gap with a) 2 pairs of the electrode, b) 3 pairs of the electrode, c) 4 pairs of the electrode | 76 |
| Figure 5.12 | Summarized graph for output voltage over the number of IDE pair of a) 1.0mm gap and b) 1.2mm gap | 78 |
| Figure 5.13 | Simulation result of resonant frequency at fundamental mode | 81 |
| Figure 5.14 | Illustration of device during resonant frequency of a) 2 IDE pairs device and b) 4 IDE pairs device | 81 |

LIST OF ABBREVIATIONS

| | |
|---------------------------------|--------------------------------------------------------|
| Ag | Silver |
| AlN | Aluminum Nitride |
| AZO | Aluminium-Doped Zinc Oxide |
| Bi ₂ Te ₃ | Bismuth telluride |
| CVD | chemical vapor deposition |
| DSA | Dynamic Signal Analyser |
| EDS | energy-dispersive X-ray spectroscopy spectrum analysis |
| EH | Energy Harvester |
| etc | et cetera |
| FESEM | Field-Emission Scanning Electron |
| FWHM | full-wave half maximum |
| IDE | Interdigitated electrode |
| MEMS | micro-electromechanical system |
| min | minutes |
| mW | miliwatts |
| n.d. | no date |
| Pa | Pascal |
| PE | Printed electronics |
| PET | Polyethylene terephthalate |
| PI | polyimide |
| PVDF | Polyvinylidene fluoride |
| PZT | Lead zirconium titanate |
| RF | Radiofrequency |
| rpm | rotation per minute |
| scm | standard cubic centimeters per minute |
| V | volts |
| XRD | X-Ray Diffraction |
| Zn | Zinc |
| ZnO | Zinc oxide |
| μW | microwatt |

LIST OF SYMBOLS

| | |
|------------|-------------------------------------------------------------------------|
| δ | Strain components |
| σ | Stress components |
| D | Electric displacement |
| E | Electric field |
| s | Elastic compliance |
| ϵ | Dielectric constant |
| d | Piezoelectric coefficient |
| T | Constant stress |
| t | Transpose |
| z | Mass' net displacement |
| M | Lumped mass |
| K | Spring constant |
| C | Damping coefficient |
| ω_n | Natural frequency |
| m | Seismic mass |
| Y | Amplitude vibration |
| ω | Resonance frequency |
| ξ | Relative damping ratio |
| d_{33} | Applied force is parallel to the direction of the obtained voltage |
| d_{31} | Applied force is perpendicular to the direction of the obtained voltage |
| f_n | Resonant frequency |
| V_n | Nth mode eigenvalue |

| | |
|-----------------|-----------------------------------------------------------------------------------------------|
| L | Length of the cantilever |
| W | Width of the cantilever beam |
| Y | Young's moduli |
| I | The area moment of inertia about the neutral axis |
| ρ_s | Density of the substrate |
| ρ_p | Density of piezoelectric material |
| t_s | Thickness of the substrate |
| t_p | Thickness of the piezoelectric material |
| N | Number of interdigitated finger pairs |
| d_{33} | Piezoelectric constant |
| ϵ_{33} | Dielectric constant |
| C_2 | Ratio of the stress of the piezoelectric layer to the vertical displacement of the proof mass |
| g | Gap between the interdigitated electrodes |
| ζ | Damping ratio |
| k_p | Electromechanical coupling coefficient |
| R | Load resistor |
| C_p | Total capacitance between the electrodes |
| Ω | Ohm |
| wt% | Mass fraction |
| N | Newton |
| °C | Degree celcius |
| ΔR | Electrical resistance rate |
| R_o | Initial resistance |

- θ Theta; an angle of incidence that the incident X-ray beam makes with the plane of atoms (hkl)
- Degree



CHAPTER ONE

INTRODUCTION

1.1 INTRODUCTION

Research and development of renewable energy harvesting (EH) technologies began during the early 21st century. From then on, numerous EH technologies have progressed and even successfully turned into hardware prototypes to serve as a proof of concept (Tan 2011). Many researchers have spent a significant amount of time and efforts to find new and realistic ways to harvest energy from solar (Y. Zhou et al. 2018), light (Carvalho and Paulino 2014), thermal (Sultana et al. 2018), and kinetic energy (Magno et al. 2018) to a desired usable energy. Usage of EH improves the sustainability of low-power electronic devices such as smart wireless sensor networks, smart mobile gadgets, and yields better operational lifetimes. Venture capitalists and industrial players are also getting involved in EH technologies for business development and commercialization. Current energy sources like the battery are bulky, hazardous, and not environment friendly. Hence, EH is a promising solution since it harvests renewable energy from the ambient environment and will be utilized as energy storage devices for particular applications (Tan 2011). EH technology has potential in various applications ranging from health, structural health monitoring, agriculture, to localization, logistics, and security (Tentzeris, Georgiadis, and Roselli 2014). Examples of energy sources include solar (H. Wang et al. 2015), thermoelectric (Y. Yang et al. 2012) ambient vibration source (H. S. Kim, Kim, and Kim 2011), and radiofrequency (RF) (Visser and Vullers 2013). The solar cell is limited due to the time and its location (Jiang, Polastre, and Culler 2005)(Roundy et al. 2003). For the thermoelectric device, it is hard to achieve

the desire temperature gradient due to its small size (Böttner et al. 2004). Therefore, the vibration source can be considered as a potential candidate for the EH device. The vibration sources can simply benefit from ambient vibration sources such as from car engine compartment, clothes dryer, blender casing, and even from walking or running activity (Roundy, Wright, and Rabaey 2003).

Converting energy from mechanical excitation typically involves three transduction mechanisms: electromagnetic (Li et al. 2013), electrostatic (Boisseau, Despesse, and Ahmed 2012), and piezoelectric (A. A. M. Ralib et al. 2011). The electromagnetic EH is capable of generating high power through the induction of the magnetic field within the device schemes. However, due to miniaturization, producing a magnetic field with a micro-electromechanical system (MEMS) is not a direct process, it requires external voltage sources and a high frequency (Meninger et al. 2001), (Oza et al. 2007). The electrostatic EH also can produce high energy density, however, it still requires a polarizing charge or voltage for initial excitation (Beeby, Tudor, and White 2006).

Piezoelectric EH device provides a promising solution for wearable energy harvester. This is because the piezoelectric energy harvester is capable to directly convert vibration sources into usable energy in both macroscopic and micro-scale applications (Choi et al. 2006), (Paradiso and Starner 2005). It is also considered as the simplest EH type that can be used for fabrication as it does not need to have additional components and complex geometry (Paradiso and Starner 2005). Compared to other types such as electrostatic and electromagnetic transducers, the piezoelectric EH has the highest energy densities (A. A. M. Ralib et al. 2011). The current piezoelectric EH mostly has a rigid and brittle structure which is not suitable for the wearable device. Hence, this study will discuss the development of flexible piezoelectric EH that is

suitable for wearable device applications. The flexibility of the piezoelectric energy harvester is a must to ensure the user's comfort.

1.2 PROBLEM STATEMENT

Numerous technological advancements in terms of reduction of power, size, and cost in the field of integrated circuit technology have catalyzed the rapid evolution of wearable devices. Unfortunately, these new advancements are still constrained by the current battery technology which creates expensive, bulky, and short lifespan devices. A promising alternative is a vibration EH where it has the potential to harvest ambient energy sources. There are a few methods of vibration EH such as electrostatic, electromagnetic, and piezoelectric. However, electrostatic EH requires external voltage sources and a high-frequency vibration while electromagnetic EH has a complex configuration and very difficult to reduce down its size. Piezoelectric EH might be a solution since it is considered the simplest energy harvester type as it does not have additional components and complex geometry and also capable of delivering high output voltage. Lead zirconium titanate (PZT) is among the famous piezoelectric materials since it is the most effective due to the high piezoelectric coefficient. However, PZT material is not environmentally friendly and the current trend of the new technology nowadays is emphasizing the lead-free product. Other than that, PZT material is also not flexible, needs poling, and not suitable for the wearable device. Some other piezoelectric materials such as AZO have been also studied as a potential alternative to the PZT. AZO also is a piezoelectric material that does not need post poling and can be deposited on a substrate using various methods such as sputtering, chemical vapor deposition, sol-gel, etc (Kolev et al. 2017). Hence, AZO can be

sputtered on a flexible substrate such as Polyethylene terephthalate (PET), Polyimide (PI) film, etc to give comfort to the users of the wearable device.

1.3 RESEARCH OBJECTIVE

This thesis is focused on the development of a flexible piezoelectric energy harvester that can be used for the wearable device. The objectives of this research are:

- I. To design, simulate, and fabricate a prototype of the flexible piezoelectric energy harvester.
- II. To optimize the key parameters that maximize the power output of a flexible piezoelectric energy harvester.
- III. To validate the design of the fabricated energy harvester using experimental measurements.

1.4 RESEARCH METHODOLOGY

In this thesis, the research methodology will be sequentially elaborated in this section. The research methodology starts with the literature review of the piezoelectric energy harvester. Then the design of the piezoelectric energy harvester is proposed. Next, the finite element simulation of piezoelectric energy harvester will be implemented using COMSOL Multiphysics to test the proposed design. Afterward, the design will be fabricated using screen-printing method and RF Magnetron sputtering technique. The device will then undergo the characterization process. Then, the device will be tested to evaluate its performance in terms of the output voltage and the resonant frequency. Finally, the result will be analyzed and discussed.

1.5 SCOPE OF RESEARCH

This research covers on d_{33} conversion mode of piezoelectric energy harvester and the simulation of the design is conducted in 2D model using COMSOL Multiphysics. The deposition of AZO as the piezoelectric material is performed using RF magnetron sputtering process while the silver ink is deposited as the electrode using screen printing method. To ensure the quality and its piezoelectricity performance, characterization of sputtered AZO thin film is implemented using X-Ray Diffraction (XRD) analysis, Field-Emission Scanning Electron Microscopy (FESEM) and Energy Dispersive X-Ray (EDS) spectroscopy, piezoelectric constant (d_{33}) measurement, and sheet resistivity. Then, the reliability and durability of silver ink material as an electrode is investigated through bending test while the electrical measurement of the device is evaluated using electromagnetic shaker and Dynamic Signal Analyzer. The formulation of new theories and modeling of the design are not included in this study.

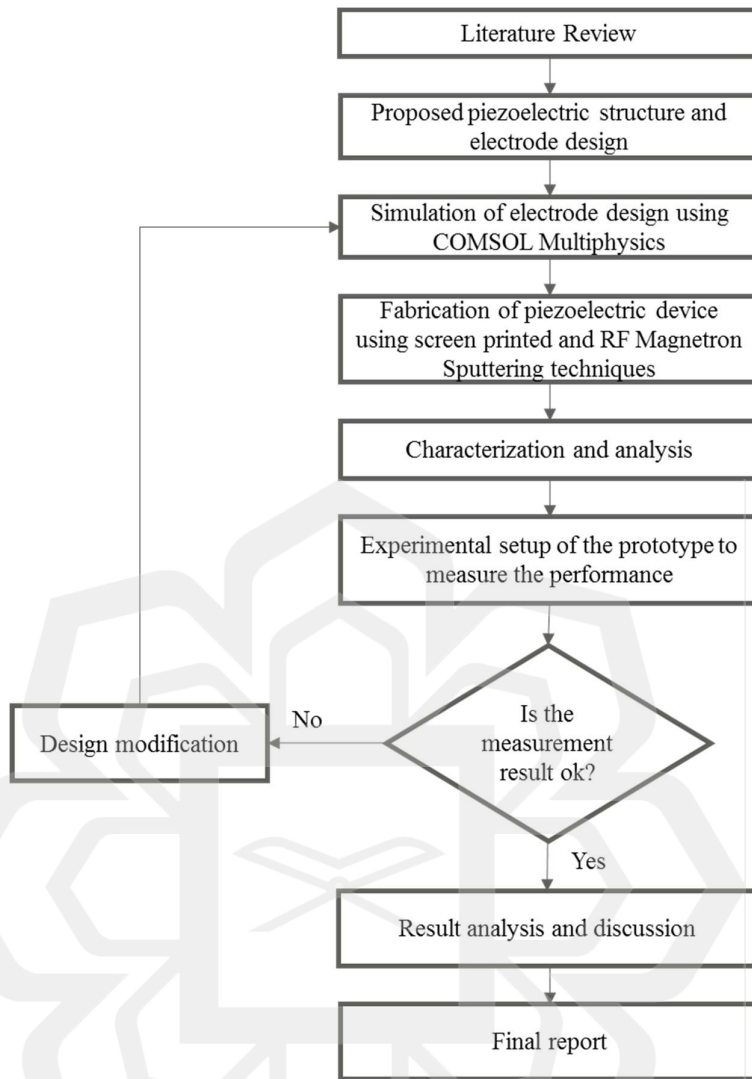


Figure 1.1 Research Methodology flow chart

1.6 THESIS ORGANIZATION

Chapter 1 is the introduction that consists of the problem statement, objectives, and methodology of the research. Chapter 2 discusses the literature review of the fundamental of piezoelectric energy harvester, the selection of piezoelectric material, various types of substrate, and the potential applications of the technology, as well as the previous work of the piezoelectric energy harvester. Chapter 3 reports the design of the piezoelectric energy harvester. This chapter also discusses the simulation on the effect of the gap between the electrode and the number of electrodes pairs on the output voltage and resonant frequency. Chapter 4 discusses the methodology of the piezoelectric fabrication, characterization process, mechanical endurance test, and the experimental measurement. Chapter 5 reports the result of the piezoelectric fabrication, characterization, mechanical endurance test, and experimental measurements. Chapter 6 concludes all the works in this research and discussed the recommendation of future work.