# DEVELOPMENT OF FLEXIBLE PIEZOELECTRIC ENERGY HARVESTER FOR WEARABLE DEVICE

BY

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# 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 Vrms 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 فى 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 الحالى يعمل على تطوير حصادة مرنة للطاقة الضغطكهربية والتى لها المقدرة على حصاد الطاقة من الاهتزاز المنخفض التردد. صممت تلك الحصادة مع تركيبة الكابول "cantilever " التى تتكون من طبقات من PET / AZO / Ag في وضع d33 والذى يمكنه أن يولد جهد كهربى كبير بواسطة إزاحات صغيرة. تم اختيار الألومنيوم, المعجون إلى ZnO (AZO), بسبب انخفاض درجة حرارة ترسيبه ولعدم حوجته للتلدين والطلاء بعد الترسيب مقارنةً بالمواد الأخرى كما نجد أيضاً أن AZO صديق للبيئة ولا يتسبب فى تلوث خطير خلال عملية التصنيع. تم اختيار معاملين هامين فى التصميم هما تأثير الفجوة بين الأقطاب الكهربائية وعدد الأقطاب الكهربائية الرقمية البينية (IDE) بالنسبة إلى الجهد الكهربى 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 θ2 يساوى 34.45 درجة مما يشير إلى السلوك الضغطكهربى. وكان متوسط القيمة الثابتة d33 قياساً 1.8 pC/N. وكان حصادة الطاقة قادرة على توليد 0.867 Vrms جهد كهربى 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)

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# 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

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# 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.*

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# LIST OF ABBREVIATIONS

| | |
|---|---|
| Ag | Silver |
| AlN | Aluminum Nitride |
| AZO | Aluminium-Doped Zinc Oxide |
| $Bi_2Te_3$ | 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 |
| sccm | standard cubic centimeters per minute |
| V | volts |
| XRD | X-Ray Diffraction |
| Zn | Zinc |
| ZnO | Zinc oxide |
| μW | microwatt |

# LIST OF SYMBOLS

| | |
|---|---|
| $\delta$ | Strain components |
| $\sigma$ | Stress components |
| $D$ | Electric displacement |
| $E$ | Electric field |
| $s$ | Elastic compliance |
| $\varepsilon$ | Dielectric constant |
| $d$ | Piezoelectric coefficient |
| $T$ | Constant stress |
| $t$ | Transpose |
| $z$ | Mass' net displacement |
| $M$ | Lumped mass |
| $K$ | Spring constant |
| $C$ | Damping coefficient |
| $\omega_n$ | Natural frequency |
| $m$ | Seismic mass |
| $Y$ | Amplitude vibration |
| $\omega$ | Resonance frequency |
| $\xi$ | 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 |
| $\rho_s$ | Density of the substrate |
| $\rho_p$ | 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 |
| $\mathcal{E}_{33}$ | 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 |
| $\varsigma$ | Damping ratio |
| $k_p$ | Electromechanical coupling coefficient |
| $R$ | Load resistor |
| $C_p$ | Total capacitance between the electrodes |
| $\Omega$ | Ohm |
| wt% | Mass fraction |
| N | Newton |
| °C | Degree celcius |
| $\Delta$R | Electrical resistance rate |
| $R_o$ | Initial resistance |

| | |
|---|---|
| $\theta$ | 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.

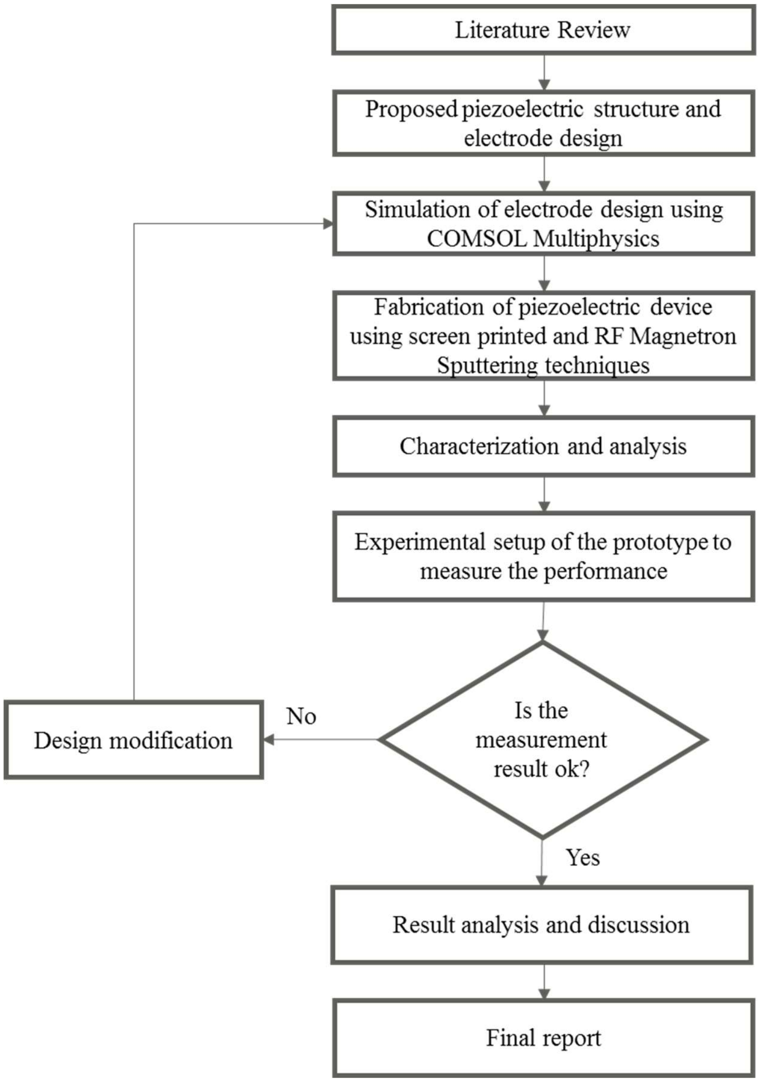

Figure 1.1 Research Methodology flow chart

## 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.