# FLEXIBLE WEARABLE THERMOELECTRIC GENERATOR WITH VERTICALLY ALIGNED ARCHITECTURE OF PEDOT:PSS AND CARBON NANOTUBE FILMS

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## ABSTRACT


Energy harvesting has become pivotal for wearable electronics, which require a constant power supply. Recent research has paved the way for the development of a wide variety of self-powered devices that harvest energy from the human body. Thermoelectric generators (TEGs) facilitate maintenance-free sustainable energy transduction, making them an enticing and feasible option for harvesting energy. Notwithstanding, their energy conversion process suffers because of inadequate design and rigidity owing to the use of brittle and toxic inorganic material-based thermoelements, making them inappropriate for energy harvesting from the human body. To address the issues, flexible wearable TEGs have been developed by integrating flexible conducting polymer based thermoelements. Nonetheless, their performance suffered significantly due to the deficient TEG designs, where thermoelements were integrated into the lateral layout with cross-plane heat flow direction. The design and implementation of such lateral TEGs is challenging for harvesting energy from the human body, where the temperature gradient ($\Delta T$) lies between the body heat and the ambient temperature. Thus, developing a vertical structured TEG with flexible thermoelements with high deformability is a requisite. In this thesis, novel wearable TEGs with vertically aligned architecture of thermoelements based on flexible organic poly(3,4-ethylenedioxythiophene): polystyrene sulfonate (PEDOT:PSS) and single-wall carbon nanotube (SWCNT) films were designed and fabricated. Finite element analysis was performed to analyze the heat dissipation through the thermoelements as well as to optimize their length for the highest $\Delta T$ and enhanced output performance. Thermoelements were prepared via solution-processing and drop-cast techniques, while the overall architectures of the TEGs were developed through low-cost 3D printing followed by a sacrificial molding technique. Flexible polydimethylsiloxane was used to develop TEG structures and encapsulation layers for all the thermoelements. The structures possess a high degree of flexibility and can sustain a maximum bending angle of 52 degrees without significantly changing their electrical parameters. In addition, this thesis examined the effects of acid-based post-treatments and polyethylenimine concentration on the performance of the thermoelectric properties of PEDOT:PSS and SWCNT films, respectively. As a proof of concept, a TEG was initially developed using five pairs of *p*-type PEDOT:PSS film and *n*-type aluminum wire-based thermoelements that produced an open-circuit voltage ($V_{oc}$) and output power density ($P_d$) of 1.46 mV and 1.5 nWcm$^{-2}$, respectively, at a $\Delta T$ of 11.27 °C from the wrist. Likewise, another TEG was composed of five pairs of *p*-type PEDOT:PSS and *n*-type SWCNT film-based thermoelements that generated a $V_{oc}$ and $P_d$ of 1.75 mV and 10.17 nWcm$^{-2}$, respectively, at a $\Delta T$ of 11.24 °C from the wrist. The proposed design approaches represent a significant step toward developing next-generation flexible organic TEG that could pave the way for self-powered wearable electronics in a sustainable way by utilizing the body heat.

# ABSTRAK

Penjanaan tenaga telah menjadi element penting untuk peranti elektronik boleh pakai yang memerlukan bekalan kuasa yang berterusan. Penyelidikan baru-baru ini telah membuka jalan kepada pembangunan pelbagai jenis peranti berkuasa sendiri yang menjana tenaga daripada haba badan manusia. Penjana termoelektrik (TEGs) menyediakan transduksi tenaga mampan tanpa penyelenggaraan, menjadikannya pilihan yang menarik dan boleh laksana untuk menjana tenaga. Walau bagaimanapun, proses penukaran tenaga ini menghadapi masalah pada reka bentuk dan ketegaran yang terhad disebabkan penggunaan termoelemen berasaskan bahan tidak organik yang rapuh dan toksik, menjadikannya tidak sesuai untuk pengunaan penjanaan tenaga daripada tubuh manusia. Untuk mengatasi masalah ini, TEG dibangunkan dengan mengunakan polimer pengalir elektrik fleksibel. Namun begitu, prestasi TEG terjejas dengan ketara akibat kelemahan reka bentuk TEG, di mana termoelemen telah diintegrasi ke dalam susun atur datar dengan arah aliran haba satah silang. Reka bentuk dan pelaksanaan TEG datar sangat mencabar, terutamanya untuk menjana tenaga daripada haba badan manusia, di mana perbezaan suhu ($\Delta T$) terletak di antara suhu badan dan suhu persekitaran. Oleh itu, pembangunan peranti TEG menegak mengunakan termoelemen polimer pengalir yang fleksibel amat diperlukan. Dalam tesis ini, TEG boleh pakai novel yang dilengkapi dengan termoelemen dijajar menegak berdasarkan organik fleksibel poli(3,4-etilena-dioksitiofen):polistirena sulfonat (PEDOT:PSS) dan tiub nano karbon dinding tunggal (SWCNT) telah direka bentuk dan dihasilkan. Analisis unsur terhingga telah dilakukan untuk menganalisis pelesapan haba melalui termoelemen serta untuk mengoptimumkan panjang struktur termoelemen untuk mencapai $\Delta T$ dan prestasi keluaran yang baik. Termoelemen telah disediakan melalui pemprosesan larutan dan teknik drop-cast, manakala struktur keseluruhan TEGs dibangunkan melalui percetakan 3D kos rendah diikuti dengan teknik pengacuan sementara. Bahan polydimethylsiloxane yang fleksibel digunakan untuk membangunkan struktur TEG dan lapisan enkapsulasi untuk semua termoelemen. Struktur TEG mempunyai tahap fleksibiliti yang tinggi dan boleh mengekalkan sudut lentur maksimum 52 darjah tanpa mengubah parameter elektriknya dengan ketara. Di samping itu, tesis ini juga mengkaji kesan pasca rawatan berasaskan asid dan kepekatan bahan polietilenimin terhadap prestasi sifat filem termoelektrik PEDOT:PSS dan SWCNT. Sebagai bukti konsep, TEG pada mulanya dibangunkan menggunakan lima pasang filem PEDOT:PSS jenis-*p* dan termoelemen berasaskan wayar aluminium jenis-*n* yang menghasilkan voltan litar terbuka ($V_{oc}$) dan ketumpatan kuasa keluaran ($P_d$) masing-masing sebanyak 1.46 mV dan 1.5 nWcm$^{-2}$, pada $\Delta T$ 11.27 °C dari pergelangan tangan. Dengan cara yang sama, satu lagi TEG yang terdiri daripada lima pasang PEDOT:PSS jenis-*p* dan termoelemen berasaskan filem SWCNT jenis-*n* yang menghasilkan $V_{oc}$ dan $P_d$ masing-masing 1.75 mV dan 10.17 nWcm$^{-2}$, pada $\Delta T$ 11.24 °C dari pergelangan tangan. Pendekatan reka bentuk yang dicadangkan ini merupakan langkah penting ke arah membangunkan TEG organik fleksibel generasi akan datang bagi peranti elektronik boleh pakai berkuasa sendiri dengan cara yang mampan dengan menggunakan haba badan.

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| | | |
|---|---|---|
| ABS | - | Acrylonitrile butadiene styrene |
| Ag | - | Silver |
| $BaTiO_3$ | - | Barium titanate |
| BHS | - | Benzenehexaselenolate |
| BHT | - | Butylated hydroxytoluene |
| Bi | - | Bismuth |
| $Bi_2Te_3$ | - | Bismuth telluride |
| BSA | - | Benzenesulfonic acid |
| Br | - | Boron |
| BZT | - | Barium Zirconate Titanate |
| Cd | - | Cadmium |
| CMOS | - | Complementary metal-oxide-semiconductor |
| CNTs | - | Carbon nanotubes |
| CSA | - | Camphorsulfonic acid |
| Cu | - | Copper |
| $Cu_2Se$ | - | Copper selenide |
| DMSO | - | Dimethyl sulfoxide |
| DWCNT | - | Double-walled carbon nanotubes |
| ECG | - | Electrocardiogram |
| EDOT | - | 3,4-ethylenedioxythiophene |
| EG | - | Ethylene glycol |
| FEA | - | Finite element analysis |
| FESEM | - | Field-emission scanning electron microscope |
| FinFET | - | Fin field-effect transistor |
| E-skin | - | Electronic skin |
| Ge | - | Germanium |
| GQDs | - | Graphene quantum dots |
| HAADF | - | High-angle annular dark-field |
| HCl | - | Hydrochloric acid |
| $HNO_3$ | - | Nitric acid |

| | | |
|---|---|---|
| $H_2SO_4$ | - | Sulphuric acid |
| $La_2O_3$ | - | Lanthanum oxide |
| Li | - | Lithium |
| LSM | - | Liquid state manipulation |
| Mg | - | Magnesium |
| $Mg_3Sb_2$ | - | Magnesium antimonide |
| Mn | - | Manganese |
| $Mn_2O_3$ | - | Manganese(III) oxide |
| MWCNT | - | Multi-walled carbon nanotubes |
| Na | - | Sodium |
| NaCl | - | Sodium chloride |
| NaOH | - | Sodium hydroxide |
| ND | - | Nano-diamond |
| *p*-TSA | - | *p*-toluenesulfonic acid |
| Pb | - | Lead |
| PDMS | - | Polydimethylsiloxane |
| PEDOT | - | Poly (3,4-ethylenedioxythiophene) |
| PEDOT:PSS | - | Poly(3,4-ethylenedioxythiophene): polystyrene sulfonate |
| PEGs | - | Piezoelectric generators |
| PEI | - | Polyethylenimine |
| PSS | - | Polystyrene sulfonate |
| PSSH | - | Polystyrene sulfonate acid |
| PVDF | - | Polyvinylidene fluoride |
| Se | - | Selenide |
| SEM | - | Scanning electron microscope |
| SiNW | - | Silicon nanowire |
| STEM | - | Scanning transmission electron microscopy |
| SnSe | - | Tin Selenide |
| Sn | - | Tin |
| SPS | - | Spark plasma sintering |
| SSA | - | Sulfosalicylic acid |
| SWCNT | - | Single-wall carbon nanotube |
| Te | - | Tellurium |

| | | |
|---|---|---|
| TEM | - | Transmission electron microscopy |
| TEGs | - | Thermoelectric generators |
| TEG | - | Thermoelectric generator |
| TENGs | - | Triboelectric nanogenerators |
| TFA | - | Trifluoroacetic acid |
| TSA | - | Trichostatin A |
| $Y_2O_3$ | - | Yttrium oxide |
| Zn | - | Zinc |

## LIST OF SYMBOLS

| | | |
|---|---|---|
| D | - | Dimensional |
| $\Delta T$ | - | Temperature gradient |
| $\sigma$ | - | Electrical conductivity |
| $\sigma_n$ | - | Electrical conductivity of *n*-type thermoelement |
| $\sigma_p$ | - | Electrical conductivity of *p*-type thermoelement |
| $\kappa_e$ | - | Thermal conductivity due to electron |
| $\kappa_{lat}$ | - | Lattice thermal conductivity |
| $\kappa_t$ | - | Thermal conductivity |
| $\mu$ | - | Mobility of charge carriers |
| $\rho$ | - | Electrical resistivity |
| $A$ | - | Thermoelement area |
| $A_n$ | - | Area of *n*-type thermoelement |
| $A_p$ | - | Area of *p*-type thermoelement |
| $A_{TEG}$ | - | Total surface area of TEG |
| $E_g$ | - | Bandgap energy |
| $i$ | - | Electrical current |
| $l$ | - | Length of a thermoelement |
| $l_n$ | - | Length of *n*-type thermoelement |
| $L$ | - | Lorenz number |
| $l_p$ | - | Length of *p*-type thermoelement |
| $n$ | - | Carrier concentration |
| $N_{TE}$ | - | Number of *p*-and *n*-type thermoelement pairs |
| $P_d$ | - | Power density |
| $P_{max}$ | - | Maximum output power |
| $P_o$ | - | Output power |
| $Q$ | - | Heat transfer rate |
| $q$ | - | Heat flux |
| $R_c$ | - | Contact resistance |
| $R_i$ | - | Internal resistance of thermoelements |
| $R_{in}$ | - | Internal resistance of a TEG |

| | | |
|---|---|---|
| $R_l$ | - | Load resistance |
| $S$ | - | Seebeck coefficient |
| $S_{pn}$ | - | Seebeck coefficient between *p*-and *n*-type thermoelements |
| $S_n$ | - | Seebeck coefficient of *n*-type thermoelement |
| $S_p$ | - | Seebeck coefficient of *p*-type thermoelement |
| $T$ | - | Operating temperature |
| $T_c$ | - | Cold side temperature |
| $T_h$ | - | Hot side temperature |
| $V_{oc}$ | - | Open-circuit voltage |
| $ZT$ | - | Dimensionless figure of merit |

# CHAPTER 1

# INTRODUCTION

## 1.1 Motivation

Over the last few decades, major transitions in the microelectronic industry, including size reduction, low-power consumption, and intensifying functionality, have triggered the development of various electronic devices. In particular, wearable technologies and biomedical devices have attracted considerable interest in recent times owing to their broad applications in medical diagnostics, precision therapy, and real-time health tracking, such as heart rate and blood pressure monitoring [1-3]. In addition, the convergence of these devices with the Internet-of-Things has recently gained significant attention. The convergence allows the devices to be equipped with wireless connectivity that directly transmits data into a cloud-based diagnostic server for further analysis and clinical evaluation. In particular, these devices could monitor an activity continuously using real-time data, thus having the potential to greatly minimize travel costs and the time needed for long-term monitoring [4, 5]. As an example, a cardiovascular disorder called arrhythmia prevents the heart from pumping enough oxygenated blood into and deoxygenated blood away from peripheral tissues, resulting in permanent damage to brain cells, congestive heart failure, and stroke [6, 7]. Continuous long-term monitoring of the heart is therefore essential for the prevention of this disease.

Self-powered devices facilitate the continuous monitoring of real-time data over a longer period of time; thus, power consumption is a crucial aspect. Figure 1.1 shows several vital sensors whose power consumption is within the range of nW to mW [8-12]. The power requirements of most of these devices are provided by conventional lithium-ion batteries due to their high $P_d$ and longevity. In addition to these, the latest batteries, such as metal-sulfur [13], sodium [14], and environmental

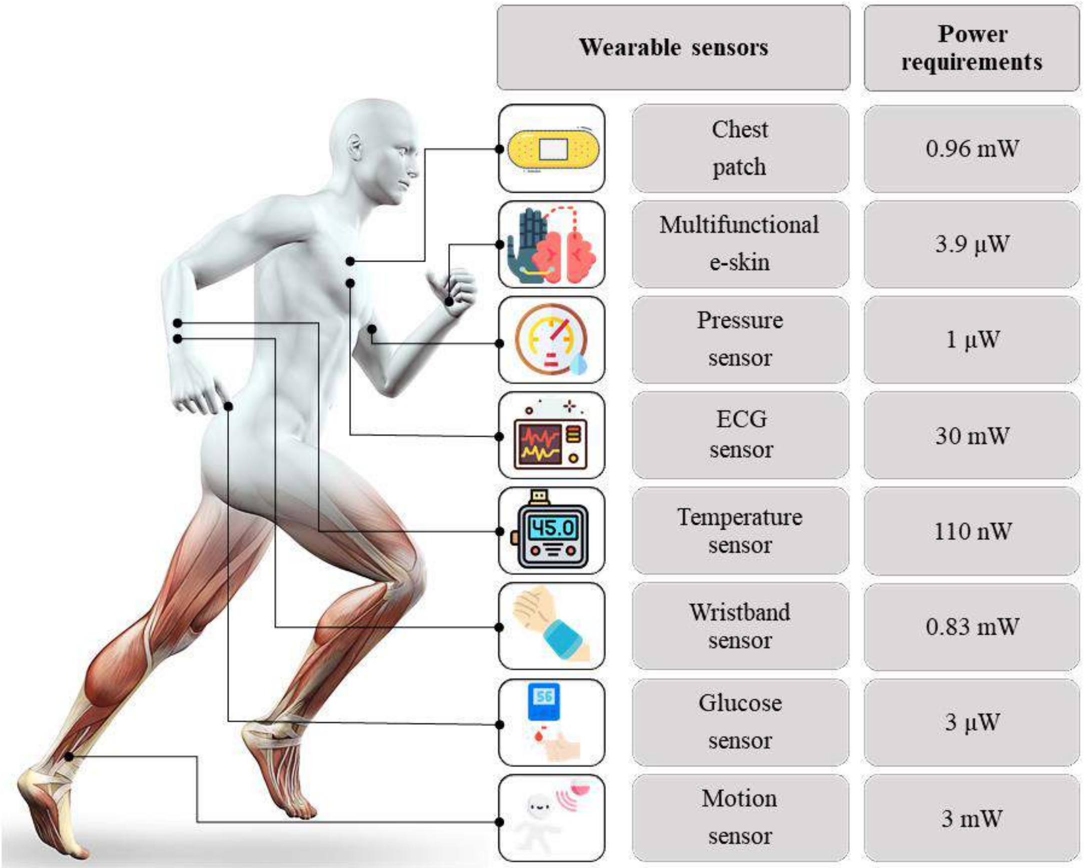


Figure 1.1 A schematic illustration of various wearable sensors capable of measuring physiological signals in the human body along with their power requirements

friendly aqueous zinc batteries [15], which are flexible and wearable, have also been developed as power sources for various electronic devices. However, most of these batteries either need to be replaced or recharged periodically. Although the present-day high-capacity batteries are compact and lightweight, and can provide sufficient energy to these devices, nonetheless, their versatility has been substantially reduced due to their restricted battery size and lifespan. Consequently, continuous power supply has become a major constraint for these devices.

On the other hand, promising alternative approaches have been developed to transform small-scale ambient energies, such as heat, mechanical vibration, or movement, into electrical power by means of ubiquitous miniaturized renewable energy transducers, including piezoelectric generators (PEGs) [16-18], triboelectric nanogenerators (TENGs) [19-21], and thermoelectric generators (TEGs) [22-24]. These transducers can either be utilized as an extension to batteries to provide a long-term power supply or as a sole power supply. Table 1.1 presents a summary and comparison of the performance of these energy harvesting techniques. All these techniques have offered numerous advantages features, and are thus employed in several applications. Despite this progress, the use of such energy harvesters in a variety of wearable technologies is still in its infancy, with numerous challenges ahead. For example, PEG is capable of transmitting power across a wide range of frequencies and amplitudes without generating heat during operation. However, the majority of high-performance piezoelectric materials (such as lead zirconate titanate and barium zirconate titanate) are brittle and toxic, limiting their use in wearable flexible devices. TENG, on the other hand, offers high output performance as well as great flexibility; however, integration with wearable devices necessitates device miniaturization. Moreover, the performance of TENG devices is limited by the scarcity of triboelectric materials used in their fabrication as well as by the high abrasion rate of the materials.

Alternatively, among the energy transducers, TEGs are envisaged as a type of heat energy transducer with unique traits that make them attractive for a variety of applications. More precisely, since heat is one of the most widely accessible sources of energy that is also produced by the human body, TEGs hold advantages for harvesting energy and powering wearable technologies and biomedical devices without requiring any maintenance. Moreover, a wide range of non-poisonous highly flexible thermoelectric materials is also available. The efforts to reduce or eliminate the reliance on batteries through the use of body-worn TEG may thus intensify in tandem with the advancement of technologies to improve the continuous functionality of such devices.

## 1.2 Problem Statements and Research Gaps

Harvesting energy from the human body with TEGs has encountered several difficulties, as their ttemperature gradient ($\Delta T$) is low due to the low human body heat.

Table 1.1 Miniaturized energy harvesting techniques and their characteristics

| Energy Harvesting Techniques | Working Mechanism | Energy sources | Advantageous | Disadvantageous |
|---|---|---|---|---|
| PEG [25-29] | Piezoelectric effect | Cardiac motion, saliva swallowing, carotid artery pulse, and vibration of the pacemaker | No heating impact when the device is in use, fast response, tinier size, compact structure, highly sensitive to applied strain, provides reasonable $P_d$, and has greater life cycle | Highly efficient piezoelectric materials are poisonous, brittle, and expensive; need high-thermal processing for the integration of piezo materials and less efficient at low-frequency |
| TENG [30-33] | Electrostatic induction and contact electrification | Cardiac motion, blood flow, human body motion, finger friction, and wind blows | It can be utilized at high frequency, provides decent $P_d$, has a high energy conversion rate, easily scalable, highly bendable, lightweight, and maintenance-free | Its polarity and induced charge are highly dependent on the materials, and triboelectric materials have a high abrasion rate |
| TEG [34-36] | Seebeck effect | Human body heat and solar radiation | It has no moving parts, lightweight, high reliability, easily scalable, easy to integrate with other devices, and requires low-cost fabrication techniques | It requires a thermal gradient and is less efficient at converting energy |

To overcome this challenge, simultaneous advances in the design of thermoelement, heat flow direction, as well as thermoelectric materials are required [37, 38]. For harvesting energy from the human body, both vertical and lateral-structured wearable TEGs have been widely used. Thermoelements are positioned perpendicularly to the substrate in vertically structured TEGs, and the heat flows in a cross-plane direction. In contrast, thermoelements in lateral structures are placed parallel to the substrate with a lateral heat flow direction [37]. A limited number of papers have been reported on vertically structured TEGs with all inorganic thermoelectric materials, notably with bismuth telluride ($Bi_2Te_3$) [38, 39] and antimony-telluride [40, 41] for energy harvesting from the human body because of their high performance at near-room temperatures. Regrettably, the practical applications of these flexible TEGs with such thermoelements for harvesting energy from the human body have been impeded on account of the toxicity and hazardous nature of the materials used. Moreover, inorganic materials are very expensive and require a dedicated fabrication process to achieve the desired thermoelement shape for incorporation into a flexible structure, which is a vital requirement for wearable devices.

To address these issues, a viable contemporary approach is to incorporate organic materials as thermoelements into TEGs, which could alleviate these problems for low-temperature thermoelectric applications. Organic materials exhibit high flexibility and an imponderous nature, and they require easy solutions and fabrication processes to make them into a versatile form. Among various organic materials, conducting polymers, notably poly(3,4-ethylenedioxythiophene):polystyrene sulfonate (PEDOT:PSS), and carbon nanomaterial composites, notably, single-wall carbon nanotube (SWCNT), have shown great potential for thermoelectric applications due to their high tenable electrical conductivity ($\sigma$) and Seebeck coefficient ($S$) values, and stable chemical properties [42]. Moreover, the simple doping process enables them to tune the properties of the material to *n*- and *p*-type with a high thermoelectric property value. Realizing these benefits, a limited number of studies have synthesized and utilized PEDOT:PSS film as a *p*-type thermoelement and fabricated flexible TEGs for harvesting energy from the human body, which is typically laterally structured with an in-plan heat flow [43].

Even though the preceding studies showed significant flexibility in terms of the TEG structure and appreciable output performance with organic materials, such as PEDOT:PSS and SWCNT, their performance suffered significantly due to the low $\Delta T$ because of the laterally placed thermoelements in the TEGs. In addition, the TEGs were designed in such a way that they were not flexible enough and arduous to incorporate into the human body. Furthermore, none of the studies optimized the length of the PEDOT:PSS and SWCNT thin film thermoelements, which was required to achieve a high $P_o$, $P_{max}$, and an elevated $P_d$. As a result, it is desirable to fabricate a flexible wearable TEG with optimized vertically aligned thermoelements to ensure better heat transfer capability that can fit well with the human body.

## 1.3 Research Objectives

Wearable TEGs combined with thermoelements made of flexible organic materials have the potential to harvest energy from the human body. They have numerous advantages, including instantaneous energy conversion without having any moving parts, high reliability and stability, and inexpensive fabrication costs. Herein, the purpose of this research is to develop TEGs with vertically aligned organic thermoelements based on PEDOT:PSS and SWCNT thin films and characterize their performances. This design concept intends to maximize heat dissipation through thermoelements, enhance $\Delta T$ and output performance, while also alleviating the issue of wearability. To be more specific, the following are the research objectives to be achieved through this study:

(a) To design and synthesize PEDOT: PSS and SWCNT thin films to achieve optimal length with highest $\Delta T$ for thermoelectric energy harvesting from the human body.

(b) To design and fabricate a novel flexible wearable TEG comprised of vertically aligned architecture of PEDOT:PSS thin film thermoelements.

(c) To design and fabricate a novel flexible wearable TEG comprised of vertically aligned architecture of PEDOT:PSS and SWCNT thin film thermoelements.

(d) To experimentally characterize the performance of synthesized PEDOT:PSS and SWCNT thin films and the fabricated flexible wearable TEGs, as well as validate them for thermoelectric energy harvesting from the human body.

## 1.4 Research Scopes

The purpose of this research is to design and fabricate flexible wearable TEGs integrated with vertically aligned PEDOT:PSS and SWCNT film thermoelements. In this study, COMSOL Multiphysics® was used to perform finite element analysis (FEA) on the PEDOT:PSS and SWCNT thin films in order to determine their optimal length in order to attain the maximum $\Delta T$ for thermoelectric energy harvesting from the human body. Throughout the simulation, the electrical properties of the PEDOT:PSS and SWCNT films were assumed to be constant with increasing temperature. Moreover, no convection or heat radiation losses to the environment were accounted for on all surfaces of the PEDOT:PSS and SWCNT films. In terms of the synthesis of the PEDOT:PSS and SWCNT thin films, this study followed standard techniques, including solution-processing and drop-cast techniques. Meanwhile, SolidWorks®, 3D printing and sacrificial molding techniques were utilized to design and develop the TEG structures with the desired dimensions based on polydimethylsiloxane (PDMS).

To characterize the morphological properties of the PEDOT:PSS film, a scanning electron microscope (SEM) was utilized. On the other hand, a field-emission scanning electron microscope (FESEM) was used to characterize the morphological properties of the SWCNT film, inspect their homogeneity, and determine the diameter of specific nanotube branches or bundle networks. A laboratory-built measurement setup was used for characterization of the synthesized PEDOT:PSS and SWCNT thin films, as well as the fabricated TEGs, and to validate the performance of TEGs for thermoelectric energy harvesting from the human body. The measurement setup includes an infrared thermal camera, a hot plate, an aluminum heatsink, a computer, and a digital multimeter. The infrared images of the temperature distribution profile over the TEGs were captured to determine their $\Delta T$ to ease the characterization process.

## 1.5 Research Significances

Wearable electronics, which include electronic skins, smart band-aids, and health monitoring sensors, have emerged as a prevalent category of devices in today's technological landscape. These devices are widely utilized to monitor human physiological conditions non-invasively, allowing for early detection of health complications and the provision of tailored medical treatment. Regrettably, the absence of a stable, compact power supply is a major concern for most of the devices. While renewable energy sources have the potential to be used as a way to solve the issue, nonetheless, on-board sustainable energy harvester-based electronic devices are exceedingly rare due to their complex operating mechanisms, size, and high cost. To address this issue of constant power, TEG has been considered as a promising sustainable option that has the potential to replace a battery entirely or work in conjunction with conventional batteries to power a variety of wearable devices. This research predominantly discusses the detailed TEG working mechanism to generate useable power and its optimization factors, which include both device configurations and novel breakthrough thermoelectric materials that are pertinent to various applications. In addition, this research delves into the details of promising inorganic and organic materials with thermoelectric properties, including $S$, $\sigma$, $\kappa_t$, and $ZT$. More precisely, this research investigated ways to increase power generation via architectural solutions and thermoelement length optimizations. The proposed flexible wearable TEG with vertically aligned PEDOT:PSS and SWCNT thin film thermoelements overcomes the limitation of continuous power generation. Since the thermoelements were constructed using inexpensive fabrication techniques, the overall cost of the TEGs was also reduced. Eventually, the low-cost TEGs could contribute significantly to the development of sustainable energy harvesting for wearable electronics via body heat, resulting in self-powered devices.

## 1.6 Thesis Outlines

This thesis is comprised of six chapters, each of which makes a significant contribution to the overall thesis. Chapter 1 outlines the background of the study, including the need for self-powered wearable and biomedical devices, as well as the potential for energy harvesters, particularly TEG, to power such devices. In addition, the problem statements are presented, followed by the objectives, scopes, and potential impacts of the research.

Chapter 2 begins with an overview of the energy harvesters, followed by the fundamental working mechanism of the TEG and its associated equations. This chapter included a comprehensive and in-depth review of the literature regarding the classification of TEGs based on the heat flow and layout of thermoelement pairs. Moreover, the previous work on both high-performance inorganic and organic thermoelectric materials is also reviewed. The chapter concludes with a discussion of the challenges associated with the concurrent TEG and research plans for this study.

Chapter 3 delves into the research methodology used to accomplish the objectives of the study. It details the design of the TEGs and FEA studies for the PEDOT:PSS and SWCNT thin films. Moreover, the experimental setup and characterization details for the study are included at the end of the chapter.

Chapter 4 presents a novel vertically aligned PEDOT:PSS thin film thermoelement integrated wearable TEG. Starting with the FEA to optimize and determine of the heat distribution through the PEDOT:PSS thermoelement, the design of the novel TEG structure is presented. The synthesis of the PEDOT:PSS material and TEG fabrication processes is also discussed. An experimental setup is built to characterize the thermoelectric properties, mainly $\sigma$ and $S$ values, of the PEDOT:PSS film and to evaluate the TEG characterization results. Eventually, energy harvesting from the wrist via the fabricated TEG is demonstrated.

Likewise, in Chapter 5, vertically aligned PEDOT:PSS and SWCNT thin film thermoelements are integrated into a novel wearable TEG. It also covers the FEA for optimizing and determining heat transfer through PEDOT:PSS and SWCNT thin film thermoelements, TEG structural design, as well as synthesis of the thermoelectric materials and TEG fabrication processes. The experimental setup is described, as are the results of materials characterization and device fabrication. Finally, energy harvesting from the wrist using the TEG is demonstrated.

The key findings of this research and the research contributions to this study are summarized in Chapter 6. Recommendations for future work are made to assist others in developing this technology and enhance the quality of this work.

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# LIST OF PUBLICATIONS

## Indexed Journals

1. **M. N. Hasan**, M. Nafea, N. Nayan, and M. S. Mohamed Ali, "Thermoelectric Generator: Materials and Applications in Wearable Health Monitoring Sensors and Internet of Things Devices," *Advanced Materials Technologies*, p. 2101203, 2021. (**Q1**, **IF: 8.856)** (Part of Chapter 2)

2. **M. N. Hasan** and M. S. Mohamed Ali, "Influence of leg geometry on the performance of Bismuth Telluride-based Thermoelectric Generator," *ELEKTRIKA-Journal of Electrical Engineering*, 20(2-2), 25-29. **(Scopus Indexed)** (Part of Chapter 4 and Chapter 5)

3. **M. N. Hasan**, S. Sahlan, K. Osman, and M. S. Mohamed Ali, "Energy harvesters for wearable electronics and biomedical devices," *Advanced Materials Technologies*, vol. 6, no. 3, p. 2000771, 2021. (**Q1**, **IF: 8.856)** (Part of Chapter 2)

4. **M. N. Hasan**, H. A. Rahim, M. A. Ahmad, and M. S. M. Ali, "Modelling and simulation of magnesium antimonide based thermoelectric generator," *Indonesian Journal of Electrical Engineering and Computer Science*, vol. 19, no. 2, pp. 686-692, 2020. **(Scopus Indexed)** (Part of Chapter 3 and Chapter 4)

5. **M. N. Hasan**, H. Wahid, N. Nayan, and M. S. Mohamed Ali, "Inorganic thermoelectric materials: A review," *International Journal of Energy Research*, vol. 44, no. 8, pp. 6170-6222, 2020. (**Q1**, **IF: 4.672)** (Part of Chapter 2)

6. K. V. Selvan, **M. N. Hasan**, and M. S. Mohamed Ali, "Methodological reviews and analyses on the emerging research trends and progresses of thermoelectric generators," *International Journal of Energy Research*, vol. 43, no. 1, pp. 113-140, 2019. (**Q1**, **IF: 4.672)** (Part of Chapter 2)

7. K. V. Selvan, **M. N. Hasan**, and M. S. Mohamed Ali, "State-of-the-art reviews and analyses of emerging research findings and achievements of thermoelectric materials over the past years," *Journal of Electronic Materials,* vol. 48, p. 745-777, 2019. (**Q3**, **IF: 2.047)** (Part of Chapter 2)

8. **M. N. Hasan**, N. Nayan, M. Nafea, A. G. Muthalif, and M. S. Mohamed Ali, "Novel structural design of wearable thermoelectric generator with vertically oriented thermoelements," *Energy*, vol. 259, p. 125032, 2022. (**Q1**, **IF: 8.857)** (Part of Chapter 4)

9. **M. N. Hasan**, M. I. A. Asri, T. Saleh, A. G. Muthalif, and M. S. Mohamed Ali, " Wearable Thermoelectric Generator with Vertically Aligned PEDOT:PSS And Carbon Nanotubes Thermoelements for Energy Harvesting," *International Journal of Energy Research,* 2022. https://doi.org/10.1002/er.8283 (**Q1**, **IF: 4.672)** (Part of Chapter 5)

**Indexed Conference Proceedings**

1. **M. N. Hasan**, Y. M. Yunos, and M. S. M. Ali, "Structural Optimization of a Bismuth Telluride-Based Thermoelectric Generator Using Finite Element Analysis," in *2021 IEEE International Power and Renewable Energy Conference* (IPRECON), 2021: IEEE, pp. 1-4. (Part of Chapter 3 and Chapter 4)

2. **M. N. Hasan**, M. Y. B. Hashem, M. A. Siddique, M. A. M. Yunus, and M. S. M. Ali, "Finite Element Analysis of Thermoelectric Power Generation from Human Wrist," in 2021 *IEEE Symposium on Industrial Electronics & Applications (ISIEA)*, 2021: IEEE, pp. 1-5. (Part of Chapter 4 and Chapter 5)

3. **M. N. Hasan** and M. S. Mohamed Ali, "Optimal Design of Thermoelectric Generator with Vertically Aligned PEDOT:PSS Thermoelements," *AIP Conference Proceedings,* 2022. **Accepted** (Part of Chapter 4)