THERMOELECTRIC POWER GENERATION ENHANCEMENT OF MICROFABRICATED METAL-BASED PLANAR THERMOPILES THROUGH GEOMETRICAL AND DEVICE STRUCTURE OPTIMIZATIONS

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"Stop complaining, giving up is not an option! Just trust Me…
You are no failure! You shall never fail in discernment to
My will and commitment to you. Now stand firm, carry
your cross in perseverance and walk with Me…"
– Trumpet words of Ascended Master Sananda (Yeshua) –

"A trustful petition on 26th July 1998 and a "little whisper" on
13th October 2012 had prepared my journey towards a Ph.D.
I am perpetually grateful to my beloved Hannah and Marianna
for their selfless and loving efforts in initiating and graciously
completing it 21 years later, despite all limitations and hurdles…
Not forgetting that ultimately, it was by one man's unceasing
faith and persistence on me that made me surrender
completely to his wisdom and stepping plans to achieve it.
He had always won and will always win in everything he does,
and all I was trying my level best so as not to disappoint
his believe, and worked incessantly for him…
Ever thankful to my dear Emmanuel for working through me…
for his simple words and directives had always been the light
for my path. This valuable treasure merely signifies a reflection
of five years of all our selfless work together for its creation,
and will endlessly remain commemorating it!"
~ Thesis author ~

Herewith, this precious study is eternally consecrated to
Mummy, Hannah, Marianna & Emmanuel
in honorary return for their sincere contributions,
guidance, encouragement, sacrifices, hardship, and pure love.

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"*Stay persistent in what you believe and passionate about,*
and sooner or later you will earn yourself
the fruits of your determination"
~ Thesis author ~

All praises and glory ever be to the Lord Sananda (Yeshua),
for this study will forever uphold His fragrance,
radiance, essence, light, and love. Amen.

ABSTRACT

Thermoelectricity converts heat energy into electricity through a simple mechanism, in which a potential difference is generated due to the temperature difference between the hot and cold contact electrodes (ΔT) of coupled thermoelements. There are many types of thermoelements used in developing thermoelectric generators. However, metal thermoelements offer cheaper solutions, easier fabrication processes, and can produce substantial electricity at smaller ΔT. The strong correlations of electrical and thermal conductivities in metal thermoelements have resulted in lower Seebeck coefficients along with reduced thermoelectric power-generating performances. Alternatively, a thermoleg cross-sectional area (A) optimization approach may optimize these disruptive correlations and improve their power-generating effectiveness. A sandwiched planar structure can also allow more thermopiles to be integrated without affecting the generator's size. In this study, thermoelectric devices based on a flexible copper (Cu)-clad polyimide substrate with simpler fabrications using Cu, nickel (Ni), and cobalt (Co) metal thermoelements were explored. Planar and lateral device structures may assist in generating larger ΔT and output power through their longer thermoleg length (l) and larger A. Thus, for the first time, Cu thermoleg-based generators were built on planar and lateral structures, and Co was introduced and implemented in this study too. This study also investigated the roles of previously unexplored geometrical structures such as the l and thermoleg width. Hereby, a sandwiched planar Cu/Co device was optimized by increasing the thermoleg thickness (t) of Co by 3.86 times the t of Cu, and this generator showed improvement factors of 23.5 and 40.2 times than the earlier-fabricated non-optimized Cu/Co and Cu/Ni generators, respectively. Promisingly, the A optimized sandwiched planar and lateral thick film device structures were found to be very compatible and favorable for metal-based thermoelectric generators.

ABSTRAK

Termoelektrik menukarkan tenaga haba kepada elektrik menerusi satu mekanisme yang mudah, di mana perbezaan potensi dijana disebabkan oleh perbezaan suhu di antara penghubung elektrod panas dan sejuk (ΔT) pada termogandingan. Terdapat banyak jenis bahan termoelektrik yang digunakan di dalam pembinaan penjana termoelektrik. Namun, bahan termoelektrik logam menawarkan penyelesaian yang murah, proses fabrikasi yang mudah, dan boleh menghasilkan elektrik yang ketara pada ΔT yang kecil. Korelasi kuat di antara kekonduksian elektrik dan haba dalam bahan termoelektrik logam menyebabkan pekali Seebeck menjadi rendah di samping prestasi penjanaan kuasa termoelektrik yang merosot. Secara alternatifnya, pendekatan pengoptimuman kawasan keratan rentas bahan termoelektrik (A) boleh mengoptimumkan korelasi yang menjejaskan ini dan meningkatkan keberkesanan penjanaan kuasa termoelektrik. Struktur satah berlapis juga akan membenarkan lebih banyak integrasi termogandingan tanpa mempengaruhi saiz penjana. Dalam kajian ini, peranti termoelektrik berdasarkan substrat fleksibel kuprum (Cu)-berlapik polyimide dengan fabrikasi mudah menggunakan bahan termoelektrik logam Cu, nikel (Ni), dan kobalt (Co) telah diterokai. Struktur peranti satah dan datar boleh membantu menghasilkan ΔT dan kuasa pengeluaran yang besar menerusi panjang bahan termoelektrik (l) yang memanjang dan A yang luas. Oleh itu, buat pertama kalinya, penjana berasaskan-bahan termoelektrik Cu dibina di atas struktur satah dan datar, dan Co turut diperkenalkan dan dilaksanakan dalam kajian ini. Kajian ini juga menyiasat peranan struktur geometri yang belum diterokai seperti l dan lebar bahan termoelektrik. Dengan ini, peranti satah berlapis Cu/Co dioptimumkan dengan meningkatkan ketebalan bahan termoelektrik (t) Co sebanyak 3.86 kali berbanding t Cu, dan penjana ini menandakan faktor peningkatan sebanyak 23.5 dan 40.2 kali masing-masing berbanding penjana Cu/Co dan Cu/Ni yang tidak dioptimumkan sebelumnya. Secara positifnya, peranti filem tebal berstruktur satah dan datar berlapis yang dioptimumkan A didapati sangat serasi dan sesuai untuk penjana termoelektrik berasaskan logam.

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LIST OF ABBREVIATIONS

CMOS - Complementary metal oxide semiconductor
CVD - Chemical vapor deposition
DC - Direct current
ECD - Electrochemical deposition
IR - Infrared
LIGA - ‘Lithographie, galvano-formung, abformung’
PEDOT - Poly (3,4-ethylenedioxythiophene)
PET - Polyethylene terephthalate
pH - Potential hydrogen
PSS - Poly (styrenesulfonate)
RF - Radio frequency
SU-8 - Epoxy-based negative photoresist
UV - Ultraviolet

LIST OF TERMINOLOGY

A - Cross-sectional area of thermoleg
A_n - Cross-sectional area of negative thermoleg
A_p - Cross-sectional area of positive thermoleg
C - Specific heat per unit volume of electron or phonon
$D(E)$ - Density of states
E - Energy level
e - Number of charge carriers
E_C - Conduction energy band
E_F - Fermi energy level
E_G - Band gap energy
E_V - Valence energy band
g - Gap between thermolegs
I_m - Thermocouple integration
k - Thermal conductivity
k_B - Boltzmann constant
k_e - Thermal conductivity of electrons
k_n - Thermal conductivity of negative thermoelement
k_p - Thermal conductivity of positive thermoelement
k_{ph} - Thermal conductivity of phonons
l - Length of thermoleg
L - Lorenz number
L_e - Length of contact electrode
L_G - Length of generator
l_o - Length of overlapped area
m - Number of thermocouples

m_c - Mass of charge carriers

n - Negative thermoelement

$n_{density}$ - Charge carrier density

$n_{thermoleg}$ - Negative thermoleg

p - Positive thermoelement

P_D - Areal output power density

P_{max} - Maximum output power

$p_{thermoleg}$ - Positive thermoleg

q - Heat flux

Q - Heat transfer rate

R_E - Internal electrical resistance

$R_{E,intersect}$ - Intersected electrical resistance

R_T - Internal thermal resistance

T - Absolute temperature

t - Thickness of thermoleg

T_C - Cold contact electrode temperature

T_H - Hot contact electrode temperature

t_n - Thickness of negative thermoleg

t_p - Thickness of positive thermoleg

v - Mean electron velocity or speed of sound for phonons

V_{oc} - Open circuit voltage

w - Width of thermoleg

W_e - Width of contact electrode

W_G - Width of generator

w_o - Width of overlapped area

z - Figure of merit

z_{pn} - Figure of merit of positive and negative thermoelements

LIST OF SYMBOLS

η	-	Conversion efficiency
σ	-	Electrical conductivity
σ_n	-	Electrical conductivity of negative thermoelement
σ_p	-	Electrical conductivity of positive thermoelement
λ_{mfp}	-	Mean free path of electron or phonon
τ	-	Mean free time
α_{pn}	-	Relative Seebeck coefficient of positive and negative thermoelements
α	-	Seebeck coefficient
α_n	-	Seebeck coefficient of negative thermoelement
α_p	-	Seebeck coefficient of positive thermoelement
ΔT	-	Temperature difference between hot and cold contact electrodes
ϕ	-	Thermoelectric efficiency factor

LIST OF STANDARD SCIENTIFIC NOTATIONS FROM THE PERIODIC TABLE

Ag - Silver
Al - Aluminum
Au - Gold
B - Boron
Ba - Barium
Be - Beryllium
Bi - Bismuth
C - Carbide
Ca - Calcium
Cd - Cadmium
Ce - Cerium
Cl - Chlorine
Co - Cobalt
Cr - Chromium
Cs - Caesium
Cu - Copper
Dy - Dysprosium
Er - Erbium
Eu - Europium
Fe - Iron
Ga - Gallium
Gd - Gadolinium
Ge - Germanium

H - Hydrogen
Hf - Hafnium
Ho - Holmium
I - Iodine
In - Indium
Ir - Iridium
K - Potassium
La - Lanthanum
Li - Lithium
Lu - Lutetium
Mg - Magnesium
Mn - Manganese
Mo - Molybdenum
N - Nitrogen
Na - Sodium
Nb - Niobium
Nd - Neodymium
Ni - Nickel
Np - Neptunium
O - Oxygen
Os - Osmium
P - Phosphorus
Pb - Lead
Pd - Palladium
Pr - Praseodymium
Pt - Platinum
Pu - Plutonium

Rb - Rubidium
Re - Rhenium
Rh - Rhodium
Ru - Ruthenium
S - Sulphur
Sb - Antimony
Sc - Scandium
Se - Selenium
Si - Silicon
Sm - Samarium
Sn - Tin
Sr - Strontium
Ta - Tantalum
Tb - Terbium
Te - Tellurium
Th - Thorium
Ti - Titanium
Tl - Thallium
Tm - Thulium
U - Uranium
V - Vanadium
W - Tungsten
Y - Yttrium
Yb - Ytterbium
Zn - Zinc
Zr - Zirconium

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CHAPTER 1

INTRODUCTION

1.1 Miniature Power Generators

Miniature power-generating is the process of harvesting small amount of electricity from external energy sources such as solar, thermal, wind, vibration, and chemical sources. The main motivations for small power-generating devices are to add simplicity and ease in daily life, lower cost, portability, and respect the nature of ecosystems. Besides, ambient energies and radiation can be a great solution as they are ecologically friendly and renewable. Also, in this way the life-times, capabilities, and reliability of such energy scavenging systems can be upgraded. Therefore, investigations of small energy harvesting methods are very much welcomed for easy powering of diminutive wireless and mobile electronics such as hand phones, cameras, chargers, watches, and laptops. The invention of alternative miniature power generators can augment or substitute for the use of conventional batteries [1]. Such energy harvesters are also applied in self-powered devices and wireless sensor networks as they can sustain operation and work independently without requiring an external power supply [2, 3].

Thermoelectric, thermo-photovoltaic, piezoelectric, and microbial fuel cells are among the most popular and earliest found power-generating mechanisms. A historical timeline on the emergence of these power generators is shown in Figure 1.1. Miniaturization efforts on the four power generators have drawn ample of attentions and so their recent performances and trends are investigated [4-6]. These four types of miniature power generator are also known for their potential as renewable power sources that can be applied for powering remote or wireless sensors [7]. In addition, the four power generators have undergone a vast evolution in their structures, capabilities, and applications. Abrupt changes are observed in their sizes from large-scale to micro- and nano-scales, leading to a better scope of mobile power harvester. They are now commonly fabricated using microfabrication approaches.

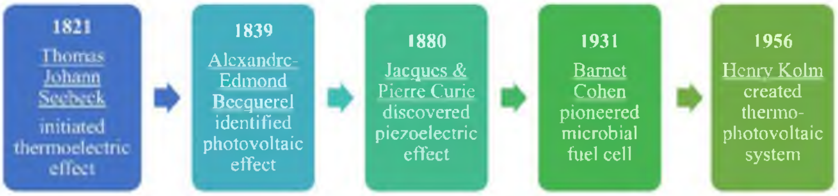

Figure 1.1 Timeline of the development of basic power generators

Microfabrication is a process of fabricating miniature devices, structures, sensors or actuators in micrometer dimension. It is another alternative to conventional complementary metal oxide semiconductor (CMOS) fabrication processes that utilizes

[1]Si wafers mostly, to build its integrated circuit. Microfabrication offers more sophisticated and modified techniques and has a flexible usage over variety of substrates such as Si wafer, polyimide, polymethyl methacrylate, polyethylene terephthalate (PET), polystyrene, and glass. Microfabrication techniques have been adapted to fabricate wide ranging of microdevices like micro-pump [8-10], micro-heater [11, 12], micro-beam [13-16], acoustic sensor [17-19], wireless sensor [20-22], fluidic or gas sensor [23-26], micro-actuator [27-29], and micro-power generator [30-32]. In the following Section 1.2, the study is converged into thermoelectric power generators, discussing on their operating principles and research overview.

1.2 Thermoelectric Generators

Thermoelectric generator is among the earliest initiated energy harvesting methods. It is a very potential small power generator that can convert wasted thermal energy into useful electricity. A thermoelectric generator operates when two distinct thermoelements (or thermoelectric materials) are attached together by hot and cold contact electrodes. As the heat is supplied to the hot contact electrodes, the temperature difference between hot and cold contact electrodes (ΔT) derived open circuit voltage (V_{oc}) at the cold contact electrodes. As a whole, this basic two

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[1] In this thesis, chemical elements are written based on the universal annotations provided in the list of standard scientific notations from the periodic table.

thermoelements coupled configuration is known as thermocouple, and a series of multiple thermocouples is called a thermopile. The thermoelements are also named as thermolegs when they are incorporated into thermocouple or thermopiles. However, this thermoelectric generator often suffers from low energy conversion rate due to its inconsistent heat source, inefficient material performance, and incompetent structural issues.

In a thermoelectric generator, the generated V_{oc} are in direct relativity with the amount of heat supplied to the device. Thus, the heat sources applied to the thermoelectric generators play a huge role in ensuring maximum output power (P_{max}) and high energy conversion. A constant heat source will ensure better conversion efficiency and the generator may work for extended hours. Heat sources like diesel engine [33, 34], radioactive isotope [35], thermo-photovoltaic combustion [36], exhaust pipe [37], gas turbine [38], wood stove [39], biomass waste [40], and combustor [41] are very suitable to be adapted into large thermoelectric power generators due to their high temperatures. However, these sources are hazardous to the surrounding environment. Heat sources from daily appliances like central processing unit [42], table lamp [43], and water heater [44] as well as from natural resources such as solar radiation [45, 46] and the human body [47, 48] may be applicable for low power generation. Nonetheless, a heater has always been a preferred choice in most of the thermoelectric experimental works as it is a constantly available and reliable heat source, and operates at various temperatures.

Over the past years, many thermoelectric generator researches are reported on Si wafer substrate [49-57]. However, the costs for production of these devices are higher because they are made based on expensive Si semiconductors. Despite the cost issues, Si wafer substrate also undergoes complex device fabrication processes. Instead, flexible polymer substrates like polyimide and PET can be practiced into thermoelectric generators, as they are low-cost and require less complicated fabrication processes. Moreover, flexible polymers can be easily attached on uneven heat source surfaces.

Thermoelectric generators are divided into three types: bulk, thick, and thin films, depending on their thermoelement thickness. Technically, bulk refers to a very thick device while a device having more than 10 μm thickness is considered as thick film, and less than 10 μm is called a thin film device. Even though the bulk thermoelectric generators offer higher P_{max} than the thick and thin films, the bulk device needs to endure complex fabrications and requires high budgets. Subjected to low-cost fabrications, thick and thin film devices are more countable due to easier thermoelement deposition or growth. They also offer much greater flexibility in terms of application than the bulk devices. Thick and thin films concern on low energy consumptions and provide better mechanical properties than bulk in terms of smaller grain size, less surface roughness, and high purity [58]. Thick and thin film structures also eventually increase a crucial thermoelectric parameter called thermopower or Seebeck coefficient (α) and reduce thermal conductivity (k), which provides slower heat transfer for a better thermoelectric conversion [59]. Despite the easier device fabrications and thermoelement depositions, as in general, the thick film structures can produce more P_{max} than the thin films.

In this research, microfabrication-based thermoelectric generator is focused due to its basic fabrication process, plain configuration, and easy implementation. Overall, this research is made to improve its power-generating efficiency. Henceforth, the problem statements, research gaps, and motivations in the study of thermoelectric generators are described in the succeeding Section 1.3.

1.3 Problem Statements, Research Gaps, and Motivations

The material performance in thermoelectric generators is very closely related to the figure of merit (z) parameter that needs to be sustained well in order to attain high power generation. Lately, there are many thermoelements composed to possess high z as compared to conventional metals or alloys. Nevertheless, the potential of metals as thermoelements ought to be studied too, as it possess high electrical conductivity (σ) and higher Fermi energy level (E_F) with less band gap energy (E_G) than any other types of thermoelements [60, 61], and thus, highly feasible to be adapted into low heat power-generating applications. Furthermore, metals can be deposited easily on substrate through electroplating without much complex setups. Besides, the fabrication cost of thermoelectric generators that utilize metals is cheaper than the cost of those using doped semiconductors or any other types of thermoelements. So far, there are very few studies reported on the usage of metals till to date [53, 54, 62-80], and the metals implemented in all these past studies are Sb, Cu, Ag, and Cr as their positive thermoelement (p), whereas, Bi and Ni as their negative thermoelement (n). There are many other metals such as Co, as yet unexplored that have potentials for application in thermoelectric power generation. Since the α and z of metals are lower than other types of thermoelements, their power-generating capabilities can only be enhanced through proper structural geometrical implementations and device structure manipulations, as been realized in 50% of the past metal-oriented generator studies [54, 68, 69, 78, 79].

In a thick or thin film generator, the applications of vertical device structure often deliver lower ΔT and P_{max} due to its shorter thermoleg length (l) (from fabrication and deposition limitations). These issues can be alleviated through a planar lateral device structure. In the planar lateral structure, thermolegs may have longer l and thicker deposition [which enlarges the thermoleg cross-sectional area (A)] that can concurrently increase their ΔT and P_{max} [66, 68]. Preceding metal-oriented thermoelectric generators have been developed on planar and lateral device structures using Sb/Bi [62, 69, 70], Ag/Ni [74-77], and Cr/Ni [53, 54] thermoelements. Cu is an easily available low-cost thermoelement with easier and compatible deposition options to most substrates. It has higher α and z than most other metals (especially than the frequently used Ag) and can be easily electroplated for thicker deposition. Since Cu is very commonly used as the contact electrode material [81], there are very limited studies reported using Cu as thermoelement. Only Cu/Ni generator studies have been reported [63-68], in which they are built on corrugated [63-65] and vertically-configured [66-68] device structures, and there is no Cu/Ni generator developed on planar and lateral device structures till to date. This occurred most probably because planar structure always require larger sizes to achieve good power performances and attaching such device structure to the heat source may also be a difficult task. But, with proper device structure modifications, these issues can be alleviated. A Cu-clad polyimide substrate can be used to fabricate the Cu thermolegs-based generators, without any need for Cu deposition, which may provide easier device fabrication.

On the other hand, very few studies are reported to date on the geometrical characteristics and design structures of a thermoelectric generator [82-86]. Moreover, previous studies on planar and lateral device structures using metal thermoelements only include studies on the variation effects of substrates [62], number of thermocouples (m) [69, 70], hot contact electrode temperature (T_H) [69, 70, 74, 75], and thermoleg thickness (t) [54]. Thus, studies on the geometrical effects of l and thermoleg width

(w) on the enhancement of thermoelectric power generation are lacking. Such geometrical analysis is essential for optimizing P_{max}, as internal electrical resistance (R_E), internal thermal resistance (R_T), and ΔT are closely associated with l and A (as such $A = w \times t$). In the same way, the strong correlation of σ and k from the Wiedemann-Franz law, which limits the performances of metal thermoelements, can be idealized.

Thermoelectric power generation can be extensively optimized via structural geometries. One way is to optimize R_E and R_T (or σ and k) through A ratios. This is theoretically because both R_E and R_T are interrelated with their l and A, and since the l is oftentimes similar, only the A ratio is included. Such theoretical optimization is introduced by Nolas *et al.* [87], and has only been implemented by several past studies [88-91] on planar and lateral-structured thick and thin film thermoelectric generators. These past studies [88-91] only directly applied the introduced A optimization formula into developing their thermoelectric devices. However, the effects of such optimization on power-generating performances have not been investigated and analyzed till now. This is the only available geometrical optimization for thermoelectric generators and such optimization is only favorable to be performed in planar and lateral structures, due to their wider length of generator (L_G) and width of generator (W_G). Increasing m in planar and lateral structures can raise the R_E [69, 70] and W_G. However, the A optimization approach can optimize ΔT and R_E and together by implementing a sandwiched planar device structure, it can help in raising the V_{oc} and P_{max} by stacking more thermopiles (which increases m) without increasing the L_G and W_G at all. Hereby, the ΔT is never disrupted by the increase in m because the ΔT is only affected by changes in l, A, and contact electrode sizes. Previously, the sandwiched planar structure has only been implemented by Kim and Lee [92], Kim [93], and Markowski *et al.* [94] using chalcogenides and metal/miscellaneous alloy thermoelements.

The original conversion efficiency (η) formula is shown in Equation (1.1), wherein T is absolute temperature and T_C is the cold contact electrode temperature. This η formula only correlates the z and ΔT, and seems rather irrelevant and inappropriate for small-scale generators made of lower z thermoelements. Therefore, Strasser *et al.* [95] introduced a new parameter known as the thermoelectric efficiency factor (ϕ) to evaluate the performances of thermoelectric generators.

$$\eta = \frac{\Delta T}{T_H}\frac{\sqrt{1+zT}-1}{\sqrt{1+zT}+\frac{T_C}{T_H}} \tag{1.1}$$

The ϕ is expressed as a division of the P_{max} over the L_G, W_G, and the squared ΔT. This parameter displays the optimized performances of the overall thermoelectric device, not only at its P_{max} but also at its ΔT, L_G, W_G, m, l, and A. Hence, this parameter has been accepted and used widely in the study of thermoelectric generators [6]. Areal output power density (P_D) is another important parameter for measuring the optimized power performance in conjunction to its L_G, W_G, m, l, and A. The P_D is calculated as a division of P_{max} over the L_G and W_G. LeBlanc [96] stated that the measure P_D is necessary to deliver effective information on the device size for possible integration into applications. Therefore, the measure P_D conveys more compact information on a device than the P_{max} only. However, these P_D and ϕ measures are rarely utilized in most of the previous studies of thermoelectric generators. Thenceforth, the succeeding Sections 1.4–1.8 elaborate the research objectives, scopes, contributions, significances, and the outlines of thesis.

1.4 Research Objectives

Although the large-sized bulk thermoelectric generators can outperform the small-sized thick and thin film generators, their complex fabrications need higher cost. The highly-acclaimed planar device structure can be implemented easily on thick and thin film devices. Besides, the thick film devices may provide better performances than the thin films. The device fabrications using flexible substrates are simpler and easier than using complicated CMOS fabrications on Si wafer substrate. Even though only few studies are reported till to date on metal-based thermoelectric generators, metals are very potential as thermoelement, low-cost, and own many other beneficial features as described earlier in Section 1.3. Hereafter, the purpose of the research is to design and fabricate planar thick film and small-sized thermoelectric devices using a plain microfabrication technology on flexible Cu-clad polyimide substrate and metal thermoelements, wherein the devices are then characterized using a simple fabricated micro-heater.

Metal thermoelement is a basic electrical charge conducting element with lower α and z, and unlike any other types of thermoelements, it does not undergo material engineering or modification processes to raise its z. Therefore, the major key to improve the power-generating performances of using metal-based thermopiles is just through structural geometrics and device structure modifications. At the same time, the thermoelectric power-generating improvements represented in this research are analyzed using P_D and ϕ measures. Specifically, the research objectives to be achieved through this metal-oriented thermoelectric generator study are:

a) To demonstrate the power-generating competences of planar and lateral device structures of Cu/Ni and Cu/Co thermopiles.

b) To verify the geometrical effects of l and w on power generations of planar and lateral device structures of Cu/Ni and Cu/Co thermopiles.

c) To prove the efficacies of power generations through A optimization on Cu/Co planar device structure.

d) To validate the power-generating effectiveness of Cu/Co sandwiched planar device structure.

1.5 Research Scopes

A huge collection of past studies on fabricated bulk, thick, and thin film thermoelectric generators is gathered in this study to analyze their performances over the past years. The P_D and ϕ are the key performance measures in this study and since most past studies do not include these two measures in their works, thus only those works having mentioned these two measures or provided information such as P_{max}, L_G, W_G, and ΔT to allow P_D and ϕ to be calculated are included in this data collection. Technically, this collected data of past studies is used thoroughly to support this conducted research work. Special attention is given into finding and recording all the past thermoelectric generator research works that utilizes metal thermoelements (in conjunction to the research objective). This helps to identify the research gaps and to support the performance analysis and comparisons for this metal-oriented thermoelectric generator study.

Mainly, the research is concentrated on developing planar and lateral-structured thick film thermoelectric devices on flexible Cu-clad polyimide substrate by utilizing Cu, Ni, and Co metals as thermoelements. Basic microfabrication techniques are used to fabricate these devices. In this study, the design structures are developed based on the selected geometrical ranges feasible for fabrications. This study also analyses the influences of structural geometric and device structure in enhancing the thermoelectric power generations. Therefore, three prototypes are designated in this study; the first and second are for investigating on the influences of thermopile's geometrical design structures (l and w), and the third is to explore the power delivering effectiveness through A optimization and sandwiched planar device structure. Simulation works are done on the designated thermopile structures to estimate their ΔT and P_{max} before finalizing and choosing the designs to fabricate. The fabricated devices are then characterized using micro-heater and compared their P_D and ϕ to the previous works to evaluate their performances. Furthermore, the maximum target performances to be achieved in this study are ϕ of 7.55×10^{-3} μWcm^{-2}K^{-2} [71-73] (the highest achievement in metal-based thermoelectric generators till to date) and P_D of 10 μWcm^{-2} (to attain P_{max} of 50 μW) for possible power application of a miniature wireless remote sensor [97].

1.6 Research Contributions and Novelties

The highlights of research contributions and novelties from this whole research work are:

a) A huge collection of bulk, thick, and thin film thermoelectric generators established up to date are highlighted, and from here, the focus of research interests, tremendous breakthroughs, and a novel quantitative analyses of ϕ achievements fulfilled by fabricated thermoelectric generators until today are emphasized for the first time in this study.

b) Although there are only a few studies reported up to today upon using metal thermoelements, this research promotes the capability and potential use of metals in thermoelectric generation by gathering and analyzing all the past research works related to sole metallic thermoelectric generators for the first time in this study.

c) The potential integration of an unexplored and unexploited Co metal thermoelement into thermoelectric generation has been firstly implemented in this research work.

d) The effectiveness of planar and lateral device structures in uplifting the power generation of metal thermoelements through longer l and allowing thicker depositions for larger ΔT and P_{max} is explored in this study.

e) Preceding studies on Cu/Ni generators are built on corrugated and vertical device structures only, thus by using Cu/Ni and Cu/Co thermoelements, this study has developed the first Cu thermoleg-based planar and lateral-structured thermoelectric generators.

f) This research also proposes a simple, easier, novel, and out of cleanroom device microfabrication technique for Cu/Ni and Cu/Co planar, lateral, and thick film thermoelectric devices on flexible Cu-clad polyimide substrate without any need for Cu thermoelement deposition, which are later tested using an economically fabricated micro-heater.

g) The past studies on metal-based lateral device structures till today are focused on the effects of different substrates, m, T_H, and t only, therefore in this study, the geometrical effects of l and w on improving power generations are analyzed through two metrics: P_D and ϕ.

h) The power generations of the developed planar thermoelectric devices are further improved by A optimization and for the very first time, this A optimization is studied and implemented in metal-based thermoelectric generators.

i) A sandwiched planar device structure is introduced for the first time into metal-oriented thermoelectric generators to further improve their power-generating performances.

1.7 Research Significances

Thermoelectric generators is a green energy source with simple configurations that can convert wasteful heat into useful electricity. Predominantly, this research reviews the emerging trends of thermoelectric generators over the last years. Accordingly, the growing research trends and evolutions of research works in thermoelectric generators are analyzed, to further insight their most research interests and the breakthroughs achieved till to date. This also includes the highlights of promising ϕ ranges for bulk, thick, and thin film devices. Above all, this research explores the past metal-oriented thermoelectric generator studies and their potentials, evolutions, and research gaps so as to endorse the credibility of metal thermoelements to equally outperform with other types of thermoelements. Precisely, this research has focused on the power-generating enhancements of planar and lateral device structures through structural geometrical and device structure optimizations. The geometrical effects on the planar and lateral-structured thermoelectric power generations are discussed in further detail. Herein, all the aforementioned research works and methodologies are novel and introduced primarily in this study. This study has also proven the efficiencies of planar device structure in uplifting the thermoelectric power-generating capabilities and metal thermoelements to perform equally outstanding among other types of thermoelements. Moreover, this research has realized a simple microfabrication method for developing thermoelectric generators, and planar and lateral device structures are found to be very encouraging for metal-oriented thermoelectric generators.

1.8 Thesis Outlines

This thesis is divided into six chapters, with each chapter having significance contributions to this thesis presentation. Chapter 1 discusses briefly on the miniature power generators, thermoelectric generators, problem statements, research gaps, and motivations, objectives of the research, research scopes, contributions, and significances of the study. Chapter 2 provides the literatures needed to understand the research that has been carried out. Here, discussion about thermoelectricity is provided, including its working principles, power applications studies, performances, and research trends analyses of thermoelectric generators. The chapter ends with detail descriptions of past thermoelectric generators related to metal thermoelements and the research plans for this study. Chapter 3 begins with details of research methodology using a flow chart. It also elaborates the rules of designing, simulations, and microfabrication works involve in the fabrication of metal-based plain and optimized lateral-structured thermoelectric devices. Chapter 4 holds the testing and validation results as well as the performance comparisons and analysis for the fabricated lateral-structured generators (first and second prototypes). Similarly, all the testing results obtained from the optimized lateral-structured generators (third prototype), and their related performance comparisons and analysis are gathered in Chapter 5. Finally, Chapter 6 summarizes the research findings and achievements of the research objectives, and then several research limitations and recommendations for future works are also included in this chapter.

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LIST OF PUBLICATIONS

Journals with Impact Factor

1. **Selvan, K. V.** and Ali, M. S. M. (2016). Micro-scale energy harvesting devices: Review of methodological performances in the last decade. *Renewable and Sustainable Energy Reviews*, *54*, 1035–1047. https://doi.org/10.1016/j.rser.2015.10.046. (**Q1, IF: 10.556**)

2. **Selvan, K. V.** and Ali, M. S. M. (2018). Copper–nickel and copper–cobalt thermoelectric generators: Power-generating optimization through structural geometrics. *IEEE Transactions on Electron Devices*, *65*, 3394–3400. https://doi.org/10.1109/TED.2018.2840105. (**Q2, IF: 2.704**)

3. **Selvan, K. V.,** Hasan, M. N., and Ali, M. S. M. (2019). Methodological reviews and analyses on the emerging research trends and progresses of thermoelectric generators. *International Journal of Energy Research*, *43*, 113–140. https://doi.org/10.1002/er.4206. (**Q1, IF: 3.343**)

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1. **Selvan, K. V.** and Ali, M. S. M. (2018). Design, fabrication, and characterization of lateral-structured Cu-Ni thermoelectric devices. In *31st IEEE International Conference on Micro Electro Mechanical Systems* (pp. 665–668). IEEE. https://doi.org/10.1109/MEMSYS.2018.8346642. **(Indexed by SCOPUS)**