



**ENHANCEMENT OF PIEZOELECTRIC-BASED
ACOUSTIC ENERGY HARVESTING CIRCUITRY
EMPLOYING PASSIVE RECTIFICATION
TECHNIQUE**

by

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TABLE OF CONTENTS

	PAGE
THESIS DECLARATION	i
PERMISSION TO USE	ii
ACKNOWLEDGEMENT	iii
TABLE OF CONTENTS	iv
LIST OF TABLES	viii
LIST OF FIGURES	ix
LIST OF ABBREVIATIONS	xi
LIST OF SYMBOLS	xiii
ABSTRAK	xv
ABSTRACT	xvi
CHAPTER 1 INTRODUCTION	
1.1 Overview	1
1.2 Problem Statement and Motivation	3
1.3 Objectives of the Project	4
1.4 Scope of Work	4
1.5 Thesis Organization	5

CHAPTER 2 LITERATURE REVIEW

2.1	Introduction	6
2.2	Energy Harvesting System Overview	6
2.3	Vibration-to-Electrical Energy Harvesting	9
2.3.1	Piezoelectric-based Vibration Energy Harvesting	11
2.3.1.1	Piezoelectric Effects	12
2.3.1.2	Piezoelectric Materials	12
2.3.1.3	Piezoelectric Cantilever-based Energy Harvesting	14
2.4	Piezoelectric-based Acoustic Energy Harvesting	18
2.5	Piezoelectric Energy Harvesting Circuitry	24
2.5.1	Passive Rectification Techniques	24
2.5.2	Active Rectification Techniques	28
2.5.2.1	Synchronous Rectifier Circuits	29
2.5.2.2	Synchronized Switching Circuits	31
2.5.2.3	Self-Powered Synchronized Switching Circuits	34
2.6	Remarks from the Literature Review	40

CHAPTER 3 METHODOLOGY

3.1	Introduction	42
3.2	Piezoelectric-based Acoustic Sound Energy Harvesting	44
3.2.1	PZT-5A Harvester	46
3.2.2	PZT-5A Harvester Resonant Frequency Calculation	47
3.2.3	Experimental Setup and Measurement	49

3.2.3.1	Sound Pressure Level Measurement	51
3.2.3.2	PZT-5A Harvester Resonant Frequency Measurement	52
3.2.3.3	PZT-5A Harvester Power Output Measurement	52
3.3	Passive Multiplier Circuit	54
3.3.1	Transformer Design	55
3.3.1.1	Design Selection on Transformer Core and Material	57
3.3.1.2	Number of Turns Calculation	59
3.3.1.3	Effective Number of Turns Measurement	62
3.3.1.4	Voltage Ratio Measurement	63
3.3.1.5	Transformer Efficiency	64
3.3.2	Voltage Multiplier-Rectifier Circuits Design	65
3.3.2.1	Voltage Multiplier-Rectifier Simulation Circuits	68
3.3.2.2	Voltage Multiplier-Rectifier Prototype Circuits	69
3.4	Performance Evaluation of Passive Multiplier Circuit	70
3.5	Summary of the Chapter	71

CHAPTER 4 RESULTS AND DISCUSSION

4.1	Introduction	73
4.2	Piezoelectric based-Acoustic Energy Harvesting	73
4.2.1	Sound Pressure Level Measurement	74
4.2.2	PZT-5A Harvester Resonant Frequency Measurement	75

4.3	Passive Multiplier Circuit	77
4.3.1	Transformer Design	78
4.3.1.1	Effective Number of Turns Measurement	78
4.3.1.2	Voltage Ratio Measurement	80
4.3.2	Voltage Multiplier-Rectifier Circuit	82
4.3.2.1	Voltage Multiplier-Rectifier Simulation Circuits	83
4.3.2.2	Voltage Multiplier-Rectifier Prototype Circuits	84
4.3.3	Performance Evaluation of Passive Multiplier Circuit	86
4.3.4	Power Conversion Efficiency	87
4.4	Summary of the Chapter	92
CHAPTER 5 CONCLUSION AND RECOMMENDATIONS FOR FUTURE STUDIES		
5.1	Conclusion	94
5.2	Recommendations for Future Research	95
REFERENCES		96
APPENDIX A		109
LIST OF PUBLICATIONS		111

LIST OF TABLES

NO.		PAGE
1.1	List of low power electronics devices	1
2.1	Sources of potential energy in energy harvesting application	8
2.2	Maximum energy densities of three types of vibration transducer	10
2.3	SPL at different sources	19
2.4	Listing of previous works on acoustic energy harvesting	23
2.5	Summary of rectifier circuit developments in energy harvesting application to date	36
2.6	Summary of rectification techniques in energy harvesting circuitry	39
3.1	PZT-5A material properties and structural dimensions	47
3.2	Different material types and properties of transformer core	59
3.3	Number of turns calculation parameters	61
4.1	SPL at different modes of resonant frequency	75
4.2	PZT-5A open circuit output voltage at resonant frequency	77
4.3	The measured output voltage of prototype transformer with different turn ratio	81
4.4	The measured DC output voltage of the voltage multiplier prototype circuits	85
4.5	Open circuit output voltage measurement of passive multiplier circuit	86
4.6	Overall results on passive multiplier circuit	92

LIST OF FIGURES

NO.		PAGE
1.1	Improvement trend in laptop technology	2
2.1	Energy harvesting system block diagram	7
2.2	Comparison of output power using different piezoelectric materials	14
2.3	Operating mode of piezoelectric transducer	15
2.4	(a) A series bimorph piezoelectric piezoelectric (b) A parallel bimorph piezoelectric (c) A unimorph piezoelectric	16
2.5	Different configurations of piezoelectric device developed to date	18
2.6	Schematic of acoustic energy harvester with piezoelectric PVDF composite cantilever integrated with a Helmholtz resonator	20
2.7	Standard FBDR circuit in piezoelectric energy harvesting circuit	25
2.8	Voltage doubler for piezoelectric generator	27
2.9	Optimized voltage multiplier circuit	28
2.10	Voltage doubler using active diodes	30
2.11	Schematic of an SSHI energy harvesting circuit	31
2.12	Schematic of a Series-SSHI energy harvesting circuit	32
2.13	Normalized harvested powers under constant vibration magnitude	33
2.14	Schematic design concept of velocity control SSHI self-switched system	35
3.1	Framework diagram of the research methodology	44
3.2	Flow chart of sound energy harvesting methodology	45
3.3	PZT-5A bimorph cantilever structure	46
3.4	Experimental apparatus setup	50
3.5	Piezoelectric equivalent circuit with resistive load	53

3.6	Flow chart of the low voltage transformer design methodology	56
3.7	E-I-type transformer construction	57
3.8	Dimension outline of E-I lamination	58
3.9	B-H curve of silicon steel	62
3.10	Piezoelectric equivalent circuit with transformer	65
3.11	Flow chart of voltage multiplier design methodology	67
3.12	Voltage doubler simulation circuit	68
3.13	Voltage tripler simulation circuit	69
3.14	Acoustic energy harvesting system measurement setup	70
4.1	PZT-5A resonant frequencies at different distances	76
4.2	The measured effective number of turns of prototype transformer	79
4.3	Voltage doubler circuit simulation result	83
4.4	Voltage tripler circuit simulation result	84
4.5	PZT-5A maximum output power measurement	88
4.6	Prototype transformer maximum output power measurement	89
4.7	Voltage doubler maximum output power measurement	90
4.8	Voltage tripler maximum output power measurement	91

LIST OF ABBREVIATIONS

DC	-	Direct Current
AC	-	Alternating Current
Si	-	Silicon
Ge	-	Germanium
MOSFET	-	Metal–Oxide–Semiconductor Field Effect Transistor
RF	-	Electromagnetic Interference
WSN	-	Wireless Sensor Network
PZT	-	Lead-Zirconate-Titanate
PbTiO ₂	-	Lead-Titanate
PbZrO ₃	-	Lead-Zirconate
BaTiO ₃	-	Barium-Titanate
PVDF	-	Polyvinylidene fluoride
SPL	-	Sound Pressure Level
dB	-	Decibel
Hz	-	Herzt
V	-	Volt
nW	-	nanoWatts
DCM	-	Discontinuous Mode
EMHR	-	Electromechanical Helmholtz Resonator
NdFeB	-	Neodymium-Iron-Boron
mV	-	millivolt
FBDR	-	Full Bridge Diode Rectifier

LED	-	Light Emitting Diode
SCRs	-	Silicon-Controlled Rectifiers
TRIACs	-	TRIode for Alternating Current
BJT	-	Bipolar Junction Transistor
SSHI	-	Synchronous Switch Harvesting on Inductor
ADS	-	Advance Design System
T	-	Tesla
μF	-	microFarad

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LIST OF SYMBOLS

f_r	-	Resonant frequency
ω	-	Angular frequency
K	-	Spring constant at the tip of the cantilever
m_e	-	Effective mass of the cantilever
f_n	-	n_{th} mode resonant frequency
v_n	-	n_{th} mode eigenvalue for the fundamental vibration mode
l	-	Length of the cantilever
m	-	Mass per unit area of the cantilever beam
E_o	-	Young's modulus of the two materials
E_p	-	Young modulus of PZT-5A
E_s	-	Young modulus of brass
t_p	-	Thickness of PZT-5A
t_s	-	Thickness of brass
ρ_p	-	Density of PZT-5A
ρ_s	-	Density of brass
B_s	-	Flux density
N	-	Number of turns
V_{rms}	-	RMS Voltage
V_{dc}	-	DC Voltage
V_p	-	Peak Voltage
B_{max}	-	Maximum flux density

A_c	-	Core area
f	-	Frequency
R_{opt}	-	Optimal load resistance
P_{out}	-	Output power
P_{in}	-	Input power
E	-	Efficiency
I_{max}	-	Maximum current

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Peningkatan Litar Penuaian Tenaga Akustik Bunyi Berasaskan Piezoelektrik Menggunakan Teknik Penerus Pasif

ABSTRAK

Penggunaan peranti elektronik miniatur dan litar yang menggunakan arkitektur kuasa-rendah telah mendominasi pasaran terutamanya di dalam bidang peranti komunikasi mudah alih tanpa pengawasan dan rangkaian pengesan tanpa wayar. Bagi menampung masalah ini dalam menyediakan bekalan kuasa yang berkekalan, teknologi tenaga boleh diperbaharui perlu dibangunkan. Bunyi, sebagai satu punca tenaga yang berada secara semulajadi adalah unsur yang terbaik untuk memenuhi kriteria ini. Penyelidikan lampau banyak tertumpu kepada penuaian tenaga akustik yang menggunakan jambatan penuh penerus piawai dan teknik penerus aktif untuk menukar tenaga bunyi kepada tenaga elektrik yang boleh digunakan. Walaubagaimanapun, teknik penerus ini dan kepelbagaiannya di dalam bidang seperti teknik litar berkuasa sendiri mengalami beberapa kelemahan dari segi memerlukan penggunaan bateri untuk litar tersebut beroperasi. Penggunaan bekalan kuasa di dalam litar aktif adalah untuk menyelesaikan masalah voltan rendah yang tidak mampu melepasi tanjakan voltan diod di dalam litar jambatan penerus penuh piawai. Dalam kajian ini, pembangunan litar pengganda pasif untuk tujuan pendaraban dan penerus dikendalikan dalam keadaan voltan rendah telah dicadangkan. Litar pengganda pasif terdiri daripada pengubah dan voltan berganda-penerus litar telah direka untuk mengganda dan menerus voltan rendah akustik penuaian tenaga dengan menggunakan penuai piezoelektrik. Litar yang dicadangkan ini adalah amat berguna terutamanya dalam kes tahap voltan keluaran dari penuai PZT-5A adalah kurang daripada tahap voltan diod. Kaedah penerus voltan menggunakan litar pengganda dua dan litar pengganda tiga, bersama-sama dengan pengubah voltan. Hasil kajian ini telah mengambil voltan 128 mV_p ke 1.461 V_{dc} dgn menggunakan litar pengganda dua dan 1.874 V_{dc} menggunakan litar pengganda tiga. Semua ini telah dicapai dengan menggunakan teknik penerus pasif tanpa penggunaan bekalan kuasa.

Enhancement of Piezoelectric-Based Acoustic Sound Energy Harvesting Circuitry Employing Passive Rectification Technique

ABSTRACT

The vast influx of miniature electronic devices and circuitry utilizing low-powered architecture has dominated the market especially in the field of remotely-deployed unattended mobile communication devices and wireless sensor network. To cater for this predicament of providing perpetual power supply, a renewable energy technology needs to be developed. Sound, being the most abundance energy in the environment, is the likely candidate to fill this slot. Past researches of acoustic energy harvesting utilized standard full bridge rectifier and active rectification technique to convert the sound energy into usable electrical energy. However, these rectification techniques together with its derivative such as self-powered circuitry technique suffer some drawbacks in terms of requires the inclusion of battery to operate the circuit. The inclusion of power supply into the active circuit was to solve the problem of low voltage unable to exceed the diode threshold voltage in the standard full bridge rectifier circuit. In this study, the development of passive multiplier circuit for multiplication and rectification purposes operated in low voltage condition has been proposed. The passive multiplier circuit comprises of a step-up transformer and voltage multiplier-rectifier circuit was designed to multiply and rectify the low voltage acoustic energy harvesting utilizing piezoelectric harvester. The proposed circuit is extremely useful in solving the limitation of low output voltage level from the PZT-5A harvester where, the output is less than the forward voltage of diode. The method of rectification utilizes the voltage doubler and tripler circuit together with the step up transformer. The outcome of this research has taken the voltage of 128 mV_p into 1.461 V_{dc} using doubler and 1.874 V_{dc} using tripler. All these were accomplished using a truly passive rectification technique free of power supply.

CHAPTER 1

INTRODUCTION

1.1 Overview

The advancement of portable electronics devices and the ever-increasing integrated functions which has become a necessity in smartphone, tablet and the likes has prompted the industry to look for portable power supply due to endurance required in operating those electronics devices. It is also interesting to note that the advancement of most electronics devices is moving towards low power consumption architecture which is in the range of micro to milli-watts. The appended Table 1.1 further shows the importance of the ever-increasing development of the low power electronics devices.

Table 1.1: List of low power electronics devices (Worthington 2010).

Device	Power (Watt)
RFID Tag	10uW
Hearing aid	100uW
Automotive light sensor (OSRAM)	1.03mW
Accelerometer (ADXL103)	3.35mW
WSN operating Zigbee circuit	10mW
1.9 GHz radio operating range of 10m	12mW
Autonomous sensor module	20mW
Bluetooth Transceiver	45mW
MP3	100mW

These devices are mostly battery powered. Therefore, the common challenge is a durability of power provided by battery which has a finite lifespan and requires battery charging or replacement at stipulated timing. For example, in wireless sensor network applications, for a huge numbers of sensor nodes, the battery replacing and charging exercise will become tedious and impractical.

Looking at the history of battery evolution versus other electronic technologies as seen in Figure 1.1, it can be clearly seen that the development is reaching its plateau while the electronic technologies still show a “sky-rocketed” speed towards the future.

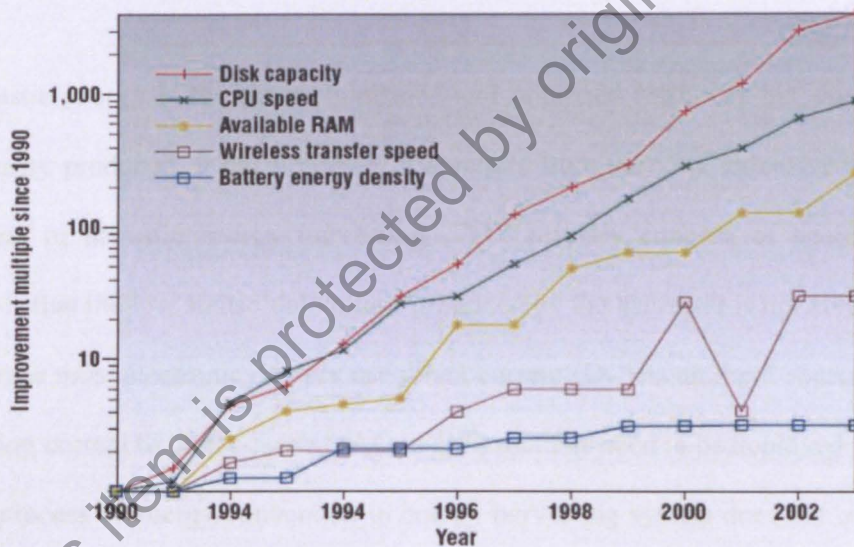


Figure 1.1: Improvement trend in laptop technology (Paradiso 2005).

In addition, the disk capacity development has increased over 1,200 times since 1990 but battery’s energy density has only increased about 3 times. Thus, there will be a great advantage if free or renewable source energy from the environment can be captured to

augment the limitation of batteries with a goal to introduce an unlimited power supply to allow the extension of power usage perpetually.

Be that as it may, there are occurrences where devices deployed may be away from power source, thus energy harvesting technology can be the best solution to solve this predicament. Energy harvesting can be a good augment to provide self-powered system for low power consumption electronics devices or to complement with the battery devices in expanding duty cycle of these devices.

1.2 Problem Statement and Motivation

Acoustic energy is the most abundance and untapped resources but due to its low energy density produced, it has hindered researchers from carrying extensive work in the development of acoustic energy harvesting. The primary concern of acoustic energy harvesting is that the low sinusoidal voltage produced by the harvester is not able to be used directly. Since most electronic devices use direct current (DC) as an input source, therefore an alternating current to direct current (AC-to-DC) rectifier need to be deployed.

The process of energy conversion in energy harvesting system does not end with the harvester; typically, the integration of harvesting circuitry is also required in order to provide the usable electrical power to the applications of electronics system.

Typically, the standard energy harvesting interface commonly used is a standard Full Bridge-Diode Rectifier (FBDR) circuit for AC-to-DC passive rectification technique. However, due to the fundamental limitation of diode rectifier, the voltage produced by the generator does not exceed the forward voltage of the diode. For example, the forward voltage

of Silicon (Si) and Germanium (Ge) based P-N junction diodes are about 0.7 V and 0.3 V, respectively. Therefore, the generator voltage output must be larger than the forward voltage of diode in order to enable the rectification process.

Several research works have been carried out to overcome this limitation by introducing active rectifier circuit. The active rectifier circuit utilizes the active diode (example: MOSFET transistor) to replace the conventional diode. However, the main setback of the active rectifier circuit is that it utilizes additional power supply to be operated and comes with circuit complexity.

1.3 Objectives of the Project

The objective of the present work is to develop piezoelectric energy harvesting circuitry employing passive rectification technique in enhancing the low voltage acoustic energy harvesting into usable voltage. Thus, the objectives can be summarized as follows:

- i. To harvest sound energy using piezoelectric device in low energy environment.
- ii. To design the passive multiplier circuit for voltage multiplication and rectification in low voltage condition.
- iii. To evaluate the performance of passive multiplier circuit in low voltage acoustic energy harvesting system.

1.4 Scope of Work

This original work involves a design of passive multiplier circuit for low voltage application in acoustic energy harvesting particularly using piezoelectric bimorph cantilever

structure as piezoelectric energy harvester. Preliminary investigation of piezoelectric energy harvester is carried out to ascertain the resonant frequency of the PZT-5A bimorph cantilever analytically and experimentally to match with the sound energy for optimal acoustic energy extraction.

The passive multiplier circuit comprises of a step-up transformer designed for low voltage application and integrated with voltage multiplier-rectifier circuits. The prototypes of both circuits are then fabricated and measurements are carried out to gauge the performance experimentally. The performance of the passive multiplier circuit is evaluated based-on its capability to regulate the low AC voltage input, specifically in cases of below diode's forward voltage condition.

1.5 Thesis Organization

This thesis consists of five chapters. Chapter 1 sets the layout of this research by giving relevant background to the research from the historical perspective. Problem statement, objectives, approaches and scope of study to this research are also discussed in this chapter. Literature review pertaining to previous studies in the fields of piezoelectric-based acoustic energy harvesting and development of harvesting circuitry are presented in Chapter 2. In Chapter 3, some fundamentals into piezoelectric transducer, passive multiplier circuit design and relevant theories are presented through theoretically, simulation, fabrication and experimental work with the objective to collect, collate and analyze the data. Results and discussion are stated in Chapter 4 while Chapter 5 gives the conclusion, findings and contribution as well as setting the pace for future development and works in the similar areas.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The literature review begins by focusing on the principle of piezoelectric conversion from vibration energy with emphasis on acoustic energy harvesting application. By evaluating the harvesting capability, the improvement technique on piezoelectric energy harvesting system will be reviewed starting from development of piezoelectric materials, structures, shapes and harvesting circuitry. In harvesting circuitry, the review outlines extensively the recent developments in passive and active rectification techniques. The advantages and disadvantages of each circuitry technique will be evaluated in order to justify the proposed solution in this study.

2.2 Energy Harvesting System Overview

Energy harvesting is defined as a process of capturing ambient waste energy available in our environment and converting it into useable electrical energy. There are lots of potential energy sources such as solar, wind, thermal, sound, radio frequency and mechanical vibration which are readily available and abundance in our surrounding. By utilizing these entire energy sources, the dependency on battery or power generator can be reduced.

Energy harvesting system is formed from a combination of several modules which have their own particular task. As illustrated in Figure 2.1, the system typically consists of energy harvester, the harvesting circuitry, the storage unit and load which depend on its application.

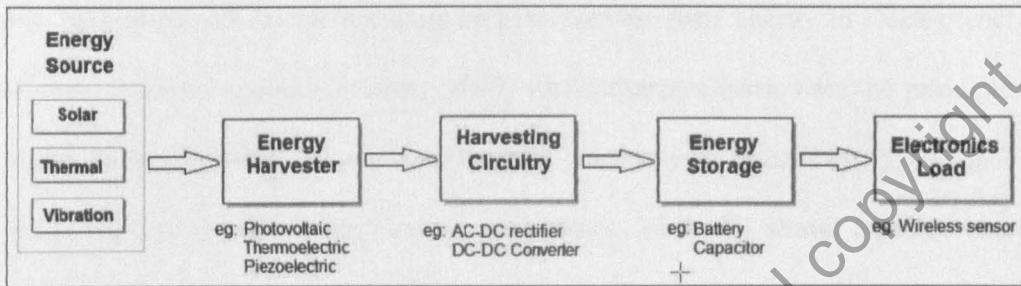


Figure 2.1: Energy harvesting system block diagram.

The term energy harvester can also be referred as generator device. Each generator will have different conversion mechanisms in producing electrical energy and depending on the types of energy source. For instance, a conversion of vibration energy commonly use a piezoelectric, while photovoltaic cell is used to convert solar energy to electrical energy.

In the next module, harvesting circuitry plays a role in regulating the form of electrical energy produced from the energy harvester into appropriate form of electrical signal that depend on intended application. The output of the energy harvester can be categorized into two forms of electrical energy namely; direct current (DC) output such as solar and thermal energy harvesting and alternating current (AC) output as in the case of vibration and radio frequency (RF) energy harvesting (D'Souza et al., 2007; Le et al., 2008; Sample et al., 2008). The DC output requires a DC-to-DC converter while the AC output will require AC-to-DC rectifier circuit and then both outputs will be conditioned

by harvesting circuit before it can be used to charge capacitor or battery in order to power any electronics devices.

There are several types of energy harvester fabricated from different materials with various conversion mechanisms to produce electric energy. As examples, solar energy harvesting utilizes photovoltaic cells to convert solar energy to electric energy (Guilar et al., 2009; Khaligh & Onar., 2009) while, thermoelectric uses the principle of “Seebeck Effect” for the conversion of thermal gradient into electric energy (Leonov et al., 2005; Stordeur & Stark, 1997; Leanov et al., 2007). Table 2.1 shows types of energy harvesting sources, their example and corresponding energy level. It is interesting to note that the energy level falls in the range of micro to milli-watts power.

Table 2.1: Sources of potential energy in energy harvesting application.

Energy Source	Solar	Vibration	Fluid Flow	Thermal	Ambient Radiation
Source Example	Sunlight Illumination	Machine Vibration Human Motion	Wind Ventilation Piping Wave	Temperature Different	RF Signal
Energy Level	100mW/cm ² (bright Sunlight) 100uW/cm ² (office Illumination)	4-800u W/cm ³	200-800u W/cm ³ (Air) 500mW/cm ³ (Water)	60u W/cm ² at 5°C difference	< 1uW/cm ²
Conversion Mechanism	Photovoltaic	Piezoelectric Electromagnetic Electrostatic	Electromagnetic Piezoelectric	Thermoelectric	Electromagnetic
Reference	Mateu & Moll (2005)	Roundy et al. (2003)	Knight et al., (2008)	Vuller et al. (2009)	Yildiz (2007)