Micro electret power generator for ambient vibration energy harvesting

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NANYANG
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**MICRO ELECTRET POWER
GENERATOR FOR AMBIENT
VIBRATION ENERGY HARVESTING**

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SCHOOL OF MECHANICAL AND AEROSPACE ENGINEERING

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Abstract

Ambient vibration sources are commonly available in abundance and characterized by low-level vibration of low frequency ($<100\text{Hz}$) and small acceleration ($<0.1g$). Vibration energy harvested from ambient environment offers a promising sustainable alternative or complementary source of power for electronic devices and systems such as wireless integrated sensor (WINS) nodes that require low power consumption. This is particularly so if they are to be used in embedded environment where maintenance of such devices and systems can be a challenge.

Electret-based electrostatic power generators, named micro electret power generators in this work, are explored as they are more compatible with the CMOS MEMS technology hence can be more easily fabricated in batches. As energy harvesters, micro inertial electret power generators with spring-mass structure can magnify the ambient vibration amplitude from several micro meters to hundreds of micro meters at resonance. Nevertheless, it was observed that its harvesting effectiveness would reduce drastically to minimal and unstable at very small volumes and low frequencies. From reviews conducted, it was reported that it would be a great challenge to achieve effectiveness of 5% at frequency less than 100Hz within volume less than 1cm^3 .

This thesis presents a novel sandwich structure in-plane inertial micro power generator with two capacitive configurations sharing a moveable mass plate in the middle that can operate effectively at low ambient vibration frequencies. The design of micro generator has necessitated the establishment of new theoretical formulation and modelling of the capacitance change and electromechanical coupling, adoption of new resonant spring-mass design configurations and charging methods for material fabrication.

For the vibration-mechanical interface, various spring configurations have been explored. Two spring configurations with folded beams have been designed and developed that are able to operate at resonant frequencies of less than 100Hz. Besides this, a three dimensional finite element model with fringing field effect incorporated is established for studying the electromechanical coupling for the parallel plate capacitive configuration of a power generator. From analysis based on the approach, two capacitive configurations with phase difference of π are found to reduce the restoring effect of electrostatic force on the dynamics of mass motion and therefore enhance the electromechanical coupling leading to improved electrical outputs.

To form micro electret array with high and stable surface potential, a new localised charging method has been developed with good charging efficiency, charge stability and slow charge decay characteristics for micro sized electrets. Experimental tests conducted on micro sized electrets (100um×100um) had found that its charge potential remains stable for a period of 240 days. A novel characterization approach for surface potential estimation on the micro-sized electrets has also been formulated. The approach is able to accurately map and evaluate the various charge distribution areas of the charged sample.

In fabrication of parallel-plate micro electrets power generators using silicon micromachining techniques adopted in MEMS technology, a double-sided alignment method is able to achieve pattern alignment error of less than 0.6 μ m. Measurements conducted found that the pin and hole alignment approach can achieve a plate assembly error of less than 5 μ m. In addition, heat management has been carried out in the fabrication process of spring-mass structure to increase the fabrication yield and accuracy. Experimental results have revealed that with good heat management involving the appropriate design of heat blocks, fabrication yield can be increased to

100%. Smaller deviations from the designed resonant frequencies are also observed from a reported figure of 43.7% to 26% therefore enabling greater predictability in design.

A micro electret power generator prototype integrated with locally charged LDPE thin film based on a sandwich structure containing two capacitive configurations has been fabricated and assembled. The prototype can generate more than three-fold increase in power output from a single capacitive configuration compared to a conventional two-plate power generator for quite similar set of design parameters. The sandwich structured power generator is also able to achieve a harvesting effectiveness of 7% within a volume of 0.35cm^3 at frequency of 44.2Hz having a mechanical quality factor of 89. In another experiment conducted, a two-plate micro electret power generator based on an outward type II S-spring configuration can even harvest the 48th harmonic component of a low vibration frequency of 2Hz with appreciable amount of electrical output. The quality factor for this configuration is however substantially higher at 121.

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Table of Selected Symbols

V_s	Surface potential on electret
$q(t)$	Generated charge
C_{var}	Variable capacitance
C_{max}	The maximum capacitance can be extracted from system
C_{min}	The minimum capacitance can be extracted from system
g	The gap of capacitor in capacitive system
d	The thickness of electrets
L_0	Length of capacitive cell
W_0	Width of capacitive cell
n	The number of capacitive cells
ε_0	Dielectric constant of vacuum
ε_1	Dielectric constant of air
ε_2	Dielectric constant of electret
F_m	Mechanical damping force
F_k	Spring force
F_e	Electrostatic force
k	Spring constant
m	Mass of inertial mass
$x(t)$	Relative displacement of inertial mass (Output)
$x_i(t)$	Absolute displacement of vibration source (Input)
$A(t)$	Overlapping area between an electret cell and an electrode cell

X_0	Amplitude of sinusoidal vibration source
X_m	The amplitude of mass relative motion
ω	Angular frequency of vibration source
ω_n	Resonant angular frequency of generator
f	Frequency of vibration source
f_r	Resonant frequency of spring-mass structure
Q	Total quality factor
c_m	Mechanical damping coefficient
ζ_m	Mechanical damping factor
R_L	Optimal resistive load
w_b	Spring beam width
l_b	Spring beam length
$F_e(x)$	Horizontal electrostatic force
$F_e(z)$	Vertical electrostatic force
E_c	the central surface electric field inside the dielectric material
E_f	the fringing field near the edges of the dielectric material
ΔE	the field gradient, $\Delta E = E_f - E_c$
V_c	Charging voltage
V_e	Biasing voltage applied at the back side of dielectric material
V_{as}	Average surface potential registered in non-contact voltmeter
CAF	Charged area factor equivalent
R_{conv}	Convective thermal resistance
$R_{cond,}$	Conductive thermal resistance

C_{par}	Parasitic capacitance
$V_o(t)$	Voltage across the resistive load
$i_o(t)$	Current flowing through the resistive load
$P(t)$	Power generated on the resistive load
C_L	Storage capacitor
ΔV	Voltage across the storage capacitor
ΔW	Energy in the storage capacitor
P_c	Harvesting power evaluated on the storage capacitor

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Chapter 1 Introduction

1.1 Project background

With the advent of the information technology age, there has been a rapid proliferation in the use of high technology products such as mobile phones, wireless equipment and sensor nodes. These products have been employed over a large range of applications in telecommunication, health care and wellness monitoring, analysis and diagnosis, smart metering and tracking, machine sensing, and automation. Typically, these products or configurations have two main aspects namely the “circuit” module for computation, processing and control functions and the “interface” module for providing interfaces to the outside macroscopic world.

According to a research study on future trends in information and communication related to access and adaptability, such products are expected to become smaller, lighter, consume less power and integrated with more features and functions [1]. It is envisaged that a significant number of small size products would be developed and deployed to handle various types of applications.

To cater for the increase need for such small size products, CMOS (Complementary metal–oxide–semiconductor (CMOS) technology and CMOS related MEMS (micro electro mechanical system) technology are currently employed to mass produce separately each module in the small size product. In CMOS technology, the electronic circuits are designed with microelectronic components such as transistors, capacitors, inductors, resistors, and diodes onto a chip. Figure 1.1 shows an example of a typical high performance peripheral interface controller (PIC) microcontroller from Microchip Company of a few centimetres square which serves as a core processor as well as perform memory and other input/output functions. Such PIC microcontrollers

have been incorporated into household and industrial products to assist in performing of domestic chores, automotive sensing and monitoring, smoke detection and information communications. These microcontrollers consume little power. For 8-bit microcontrollers, in sleep mode, the current requirements are of nano amperes at 1.8V whereas during active mode operation at 1MHz speed, dozens of micro amperes at 1.8V are consumed. Specifications of microcontroller model PIC (L) 10F320/322 including power features are listed in Appendix A.

Figure 1.1 Microcontrollers from Microchip

MEMS technology, derived from CMOS technology, is used to produce microstructure devices. According to Paul [2], microstructure devices could have at least one dimension in the micrometer range, whilst the other dimensions remain in the millimetre range. Those microstructure devices are usually designed to act as an interface mechanism between sensing and gathering information about the desired surrounding parameters and the circuit module. One main type of microstructure devices is micro sensors which are used to monitor the physical or environmental conditions such as temperature, sound, vibration, pressure, or motion applications in industries and environment. Figure 1.2 shows two examples of silicon-based micro

sensors. The thermal sensor in Figure 1.2(a) is used for air flow measurement and the acceleration sensor in Figure 1.2(b) could be employed for motion detection.

Figure 1.2 (a) Micro thermal sensor [3]; (b) Micro acceleration sensor[4]

The power consumptions of these micro sensors are typically from a few microwatts to a few milliwatts. Table 1.1 lists the power consumption of different micro sensors available from Zigbee alliance.

Table 1.1 Power consumption of different micro sensors from Zigbee alliance[5]

Sensor	Voltage (V)	Current (mA)	Power (mW)
Temperature	3.3	0.008	0.026
Light	3.3	0.03	0.099
Humidity	3.3	0.3	0.99
Vibration	3.3	0.6	1.98
Barometric	5.0	7.0	35.0

For the micro sensor to function, it needs to be integrated with a microelectronic processor or device where its data could be relayed, computed, processed and stored for later use and analysis. Figure 1.3 shows a micro product with a resistivity humidity micro sensor with a built-in sensing circuit that is integrated onto a chip of 2mm^2 . The power consumption of the integrated chip is about 2.7mW .

Figure 1.3 (a) Schematic structure of a micro unit with the integrated humidity sensor and circuit; (b) Photo image of the micro unit [6]

Figure 1.4 (a) Configuration of Tyndall 25; (b) PCB sensor layer in Tyndall 25[7]

Another example of a micro product is the wireless integrated sensor (WINS) node configuration as shown in Figure 1.4(a). The integrated micro product composes of a sensor layer, a processing layer, a RF communication layer and a Li-Ion battery as its power source. In the PCB sensor layer, two types of micro sensors, temperature and humidity fabricated using MEMS technology, are integrated onto a single chip which is mounted on a 25mm×25mm PCB layer as in Figure 1.4(b). The processing layer consists of an analogue-to-digital converter (ADC) capable of collecting and processing data from multiple sensors. After processing, the data are relayed to the communication layer for transmission to the receiver unit for analysis and diagnosis where appropriate. This two-sensor WINS node has a combined volume of about 30cm³.

The physical size requirement of WINS is dependent on application and its operating environment. For embedded applications, sensors have been deployed in aerospace and military platforms (civil/military aircraft, weapons), passenger cars (engine, body, chassis) and medical equipment including medical imagery, drug delivery, implantable devices and homecare devices (Appendix B). When deployed abundantly, these sensors can serve as “environmental microscopes” that can be used to monitor and detect normal and unusual conditions and occurrences [8]. The targeted WINS volume size is 1cm^3 as highlighted by Roundy and Rabaey [9]. At this WINS size, it could be readily deployed in physically challenged and hazardous situations with limited accessibility.

On the overall power consumption of a WINS node, this would depend on the type of sensing, processing, and transmitting duty cycle. For the WINS node, in Figure 1.4, it consists of two sensors, a 8-bit processor operating at a 0.065% duty cycle with an average power consumption of $133\mu\text{W}$ per cycle [10]. With the advances in low power circuit design of low duty cycles, it is envisaged that the power requirements of WINS nodes could reduce to tens of microwatts [11].

Currently, lithium batteries are commonly used to power small electronic products such as watches, calculators, pace makers, hearing aids and WINS nodes. One common battery type is the Sony CR2477 lithium coin battery which has a diameter size of 24mm and a 7.7mm thickness. Another battery type is the cell battery having a 50.5mm length with a diameter ranging from 13.5 to 145.5mm. For a targeted WINS node volume of 1cm^3 or less, this would mean that these batteries would be rather large (occupying a sizeable portion of the intended volume) and hence unsuitable for use in such applications. To address this challenge, thin film lithium micro battery has been developed with a footprint area of less than a few square millimetres [12-14].

But still the use of batteries in implanted devices and remote sensors in dire environment also poses maintenance challenges via either in the form of replacement, recharging them periodically or disposal owing to its chemical toxicity. To alleviate these shortcomings, one approach is to look at alternative power sources where energy can be harvested in ambient environment as replacements or complements to existing batteries. Such energy sources are in great abundance, clean with little or no adverse effects on the environment.

Figure 1.5 compares the continuous power per cm^3 that can be derived from batteries (lithium, alkaline, NiMH and zinc air), solar energy and vibration energy based on a research study conducted. Lithium batteries, the most durable battery form of power, can last for over a few years if the power consumption is less than $10\mu\text{W}$. For continuous power requirements of approximately $100\mu\text{W}$, the battery life could reduce drastically to only a few months. The study findings also reveal that vibration and solar energy sources can offer longer, sustainable and greater amount of power. Such vibration energy and solar energy are in abundance and readily available in the environment.

Figure 1.5 Electrical power delivered over time from various sources [11]

1.2 Energy harvesting technologies

This section looks into various energy harvesting technologies that are being employed to extract from various ambient energy sources predominantly light, vibration, heat and RF (radio frequency) emissions. Emphasis is also made to review various research work done in the development of micro energy harvesters from these ambient energy sources.

1.2.1 Light energy

Silicon solar cell is commonly used to harness the solar or light energy to power electronic products and devices based on photovoltaic effect [15, 16]. In photovoltaic effect, energy of the absorbed light is used to excite the electrons in the silicon semiconductor material thereby enabling an electric current to flow. The amount of power derived from solar cells varies widely depending on the illumination level of the indoor or outdoor environment. In direct sunlight, solar cells can derive substantial power density of 15-20 mW/cm² [17]. In this regard, various solar micro ambient energy harvesters have been conceptualized.

Jiang et al. [18] has developed a hybrid solar powered WINS. Power is derived from a small 37mm×82mm solar cell that stores its energy into a set of super-capacitors and lithium-ion-polymer batteries. This is as shown in Figure 1.6(a). For a 1% duty cycle, the unit would only require five hours of direct light per month in order for it to operate. The expected life time of the unit is around 43 years. Another example is the solar powered wireless temperature sensor node developed by Danesh and Long [19]. The sensor node consumes an average power of 10μW when transmitting 1 kb/s every minute using OOK wideband FM data bursts. The power is derived from a single 2×2cm² solar cell that can generate up to 20mW of peak power when placed outdoor as shown in Figure 1.6(b). Other sensor nodes that are powered

by solar cells can be found in [20-22] Solar energy offers an efficient and viable energy harvesting option if these electronic units are placed in outdoor locations under direct sunlight. Nevertheless, its effectiveness would be curtailed if they are deployed in light scarce areas where the power generated could drop drastically to near zero particularly in embedded or implanted applications.

Figure 1.6 Wireless sensor network mote powered by solar cell (a) [18]; (b)[19]

1.2.2 Kinetic energy

Kinetic or mechanical energy is a ubiquitous energy source which exists in different motions such as airflow, mechanical vibration, and human motion. Mechanical vibration energy can be readily available and found in sensing and monitoring applications such as buildings, bridges, industrial manufacturing processes, vehicles, aircrafts and machineries [11, 23, 24] [25]. Such ambient vibration energy sources tend to exhibit low-level vibration characterized by frequency of less than hundreds of hertz and acceleration of less than 1g [11].

Research on vibration energy harvesters are based on three main mechanisms: electromagnetic induction, piezoelectric effect and electrostatic induction. In electromagnetic induction, voltage is induced in the coils owing to the movements of

magnets. As for the piezoelectric effect, a surface charge is formed owing to a mechanical strain being applied to a piezoelectric material layer. Finally in electrostatic induction, charges on capacitors are “pumped” owing to capacitance change due to motion. These energy conversion mechanisms will be further deliberated in Chapter 2.

The use of ambient vibration as an energy source to power electronic devices have been well reviewed in [24]. Research into the development of vibration energy harvesters to scavenge energy based on human and machine motions for wireless sensor nodes have been outlined and discussed in Roundy’s work [26]. It is noted that inertial vibration energy harvesters with spring-mass structure can sense acceleration movement via a point contact attached to a structure subject to vibrations thereby giving them greater flexibility for deployment in embedded environment. A key metric in the performance evaluation of power generator is harvesting effectiveness. Harvesting effectiveness for a power generator with spring-mass structure is defined as [27]:

$$E_H = \frac{P_{out}}{\frac{1}{2} X_0 X_m \omega^3 m} \quad \mathbf{1-1}$$

Where P_{out} is the power output generated, X_0 equals to the amplitude of external vibration, X_m is the amplitude of internal displacement of mass, ω is the angular frequency of vibration source motion, and m is weight of the vibrating mass. Based on a published review of the three types of power generators [24], Figure 1.7 shows the harvesting effectiveness plotted against the size volume (cm^3) of various types of power generators for vibration energy harvesting (EM: electromagnetic, ES: electrostatic and PZ: piezoelectric). It can be seen that as the energy harvesters become smaller, its effectiveness is reduced to less than 1%.

Figure 1.7 Harvesting effectiveness of reported power generator devices versus device volume, adapted from [24]

Figure 1.8 Harvesting effectiveness of reported power generator devices versus operating frequency, adapted from [24]

Table 1.2 Comparison of effectiveness of published power generators ($f < 100\text{Hz}$, Volume $< 1\text{cm}^3$) for vibration energy harvesting

Mechanism	Reference	f (Hz)	Volume (cm^3)	Mass (g)	X_0 (μm)	X_m (μm)	P_{out} (μW)	E_H (%)
Electromagnetic	[28]	60	1	0.22	200	5000	100	1.7
	[29]	100	0.04	0.03	50	5200	1.44	0.14
Piezoelectric	[30]	85	1	7.5	7.9	143	207	14
	[30]	60	1	8.2	16	150	365	34
	[31]	80.1	0.53	/	/	800	1.5	/
	[32]	100	0.2	0.96	184	/	35.5	/
Electrostatic (with charge pump)	[33]	20	0.6	0.12	1130	100	2.4	17.9
	[34]	250	0.06	2.46	1	50	0.06	1.37

Table 1.2 compares the harvesting effectiveness of energy harvesters extracted from Figure 1.7 and Figure 1.8 having a volume of less than 1cm^3 with an operating frequency of less than 100Hz. Electromagnetic energy harvesters tend to operate at a higher frequency range and lower harvesting effectiveness as highlighted in Figure 1.8 when compared with piezoelectric and electrostatic power ones. It was also noted that piezoelectric power generators are most effective but tend to be heavier than electrostatic power ones probably owing to the additional mass required for the cantilever-like spring structure so as to decrease the natural frequency. For electrostatic generators, it was highlighted that they are easier to fabricate and miniaturise using MEMS technology compared with the other two mechanisms. Electrostatic ones lend itself therefore to be integrated with microelectronics fabricated by CMOS technology [24]. MEMS technology will also enable mass or batch fabrication of small-sized energy harvesters instead of individually handcrafted large ones.

A practical restriction of electrostatic power generators is that they need extra voltage sources/charge pumps in order to operate. This can be overcome by the use of an integrated electret implanted with charges into the device structure to provide bias voltage. Hence, an electret power generator based on the electrostatic principle can potentially be fully self-sustaining without the need for any external voltage source [35]. However, the stability of micro sized electret in a miniaturized power generator is in doubt. Experimental results from published work show that micro sized electret currently encountered low charging efficiency and fast charge decay when implanted with charges [36, 37]. This will inevitably impair the harvesting effectiveness of electret power generator deployed for long-term use. Table 1.3 lists the harvesting effectiveness of electret-based resonant electrostatic energy harvesters. As highlighted

in the table, to achieve low resonant frequency ($<100\text{Hz}$) within volume of 1cm^3 is still a challenge and harvesting effectiveness is generally poor. For reported works [38] and [39] based on parallel in-plane configuration, less than 1% of harvesting effectiveness is observed. For the work [40] with a high harvesting effectiveness, this is based on an out-of-plane configuration in which the resonant frequency can be reduced by adding mass block, but the out-of-plane mass relative displacement is constrained by mechanical structure. Hence, in-plane configuration is normally preferred. This aspect would be further discussed in Chapter 2.

Table 1.3 Comparison of effectiveness of published electret-based resonant electrostatic energy harvesters

Reference	f (Hz)	Q -factor	a (ms^{-2})	Size (cm^3)	m (g)	X_0^* (μm)	X_m (μm)	P_{out} (μW)	E_H (%)
[41]	50	/	5.84	50cm^3	/	59	/	18	/
[38]	63	8.6	20	0.3cm^3	0.1	128	1000	1	0.25
[39]	1110	/	2	0.018cm^3	0.00038	0.04	24	1×10^{-8}	1.57×10^{-5}
[40]	110	6.59	20	4cm^2	0.358	41.9	120	20.7	6.9
[42]	596	/	/	0.56cm^2	/	/	/	1	/
[43]	37	7.8	/	1.14cm^3	/	/	/	0.28	/

*calculated value based on data provided in reference ($X_0 = a/(2\pi f)^2$)

1.2.3 Heat energy

Another energy harvesting technology relates to heat energy which involves the flow of heat across thermal gradient based on the Seebeck effect [44-46]. The effect involves making use of a set of thermoelectric pair of materials. Owing to a sizeable temperature gradient, an electric potential between a material pair junction is formed that could give rise to a current flow which could then be used for energy. For energy harvesting, thermal or temperature gradients could be found in a number of ambient environments. An example is the temperature difference between a human skin typically at about 32°C and that of a cool indoor temperature at 22°C . This works out

to a temperature difference of 10°C. To harvest the body heat energy, Seiko has developed a wristwatch thermal energy harvester which operates at a derived 10μA current at 3V with a temperature difference of 5 degrees. This is shown in Figure 1.9.

Figure 1.9 The Seiko thermic wristwatch:(a) The product; (b) Thermoelectric power generator [47]

Another example is the thermal gradient between the waste heat energy generated from machines. This has led to the development of another ambient heat energy harvester as in Figure 1.10 [48]. In this harvester, a Bi₂Te₃ thermoelectric power generator TEC1-12709 of 30×34×3.2mm is used to extract heat energy from a radiator and subsequently converted to electrical energy to power a set of ZigBee electronics. A maximum power of 150mW can be generated based on a temperature difference of 77K.

Figure 1.10 Thermoelectric power generator to harvest heat energy from radiator [48]

It must be highlighted that current thermoelectric energy harvesters developed do have their limitations. Although industry provides abundant sources of waste heat, such heat energy from engine exhaust gases and material burning can sometimes be as high as several hundred degrees which is above the melting temperature of the solder thereby causing the harvester to malfunction. Another limitation is that thermoelectric energy harvesters require a consistent and large temperature gradient to enable a steady electrical output to the energy harvester. Of note is that for micro scale devices, it is very difficult to achieve a sufficiently large temperature gradient over short lengths for electrical current or energy to be generated despite attempts have been made to incorporate heat dissipation methods via applying air convection cooling on one side of the generator to create the gradient heat flow [49, 50]. This aspect is of great challenge if the harvester is to be deployed in embedded applications where air flow may not be so readily present.

1.2.4 RF (radio frequency) energy

RF energy harvesting is a process in which radio frequency energy is emitted at source to generate high electromagnetic fields such as TV signals, wireless radio networks and cell phone towers. The ambient RF energy sources are generated usually from public telecommunication services such as GSM900 in Europe with a downlink of 935–960 MHz), GSM1800 having a downlink of 1805.2–1879.8 MHz and WiFi of 2.4 GHz [51]. From the signals, a set of power generating circuit is used to capture them via an antenna and convert them into usable DC voltage. The amount of power to be harvested from GSM or WiFi frequencies is small. For a transmission power of 1W over a 5 meter distance, it has been reported that the power received at the sensor node would be only 50 μ W [52]. Research is currently being done to look at improving the energy conversion efficiency over the transmission and receiving of

signals. Vullers RJM et al [53] has developed an RF energy harvester of 6cm×10cm that could generate 1.5mW based on a transmission power of 100mW over an uninterrupted air distance of 20cm. However, the amount of power reduced significantly to 200μW when the transmission distance is lengthened to 2m [54].

RF energy harvesting offers a potential means to power electronic devices in embedded structures and environment. Its radiation energy is however found to decrease very rapidly over long transmission distances. As such, these power harvesters need to be placed near the RF emitting sources for them to be able to power electronic devices adequately. This limits the usage of RF energy harvesting technology in environment where RF energy base station is not available or far away. Another challenge is that more energy losses would need to be factored in owing to the difference in the transmission medium [55].

1.2.5 Review of Findings

Table 1.4 provides a summary of the amount of power per unit that can be harvested from the four ambient energy sources. The table highlights that the best ambient harvesting energy source is direct outdoor sunlight. However for indoor lighting, the power density is fairly comparable with thermal and vibration energy. Vibration energy is the most versatile and ubiquitous ambient energy source available and the deployment of vibration energy harvesters is less constrained by the interior or exterior locations. It is also more suitable for embedded applications. As for heat energy, it is difficult to achieve large thermal gradient in micro scale thermoelectric power generator. The technique of adding heat sink to increase thermal gradient is not feasible for thermoelectric energy harvesters that seek to operate in embedded environment because air convection may not be available. For RF energy, the amount

of energy available is at least an order of magnitude less than that of other three forms of energy sources.

Table 1.4 Energy harvesting estimates, source: Texas Instruments, Energy Harvesting-White paper 2009 [56]

Energy sources	Harvested Power
Vibration/Motion	
Human	$4\mu\text{W}/\text{cm}^2$
Industry	$100\mu\text{W}/\text{cm}^2$
Temperature Gradient	
Human	$25\mu\text{W}/\text{cm}^2$
Industry	$1\text{-}10\text{mW}/\text{cm}^2$
Light	
Indoor	$10\mu\text{W}/\text{cm}^2$
Outdoor	$10\text{ mW}/\text{cm}^2$
RF	
GSM	$0.1\mu\text{W}/\text{cm}^2$
WiFi	$0.001\mu\text{W}/\text{cm}^2$

1.3 Objectives and scope

From the above findings, the project seeks to develop a novel highly effective micro electret power generator having a volume less than 1cm^3 for harvesting ambient vibration energy of frequency less than 100Hz and acceleration less than 0.1g. This has necessitated the following objectives to be explored:

- (a) To establish and model the various key parameter relationships of a spring-mass structure on a vibration-mechanical interface for energy harvesting at low frequency and low amplitude.
- (b) To investigate into the characteristics and establish a theoretical model to predict the electromechanical coupling behaviour of a micro electret power generator for harvesting of low-level vibration.

- (c) To investigate into the formation and characterisation of the micro sized electret.
- (d) To develop the appropriate fabrication and assembly techniques for prototyping of the proposed micro electret power generator design as well as characterize its performance.

The scope of the study would be in the following:

- (a) To conduct a comprehensive review into various micro vibration power generators for energy harvesting.
- (b) To investigate the spring-mass structure in vibration-mechanical interface, and capacitance and electrostatic forces in electromechanical interface of micro electret generators at low-level vibration conditions (low frequency, low acceleration).
- (c) To study and model the mechanism of charging micro sized electret. This would include developing the characterization method to map the surface charge distribution and measure the surface potential on micro sized electret area.
- (d) To develop the fabrication process of micro electret power generators for the novel designed architecture. Investigations into the Deep Reactive Ion Etching process for fabricating large mass and small spring structure and the alignment method for aligning the electrode patterns on different plates of power generator devices would be made.
- (e) To characterize the vibration-mechanical and electromechanical interface characteristics of the power generators at low frequency and low acceleration.
- (f) To evaluate the system performance of the micro electret power generator in harvesting of the fundamental frequency and harmonic components of low level vibration sources.

1.4 Thesis organization

This thesis is organized into seven main chapters. Following the introduction, Chapter 2 presents the literature review of characteristics of vibration sources and the vibration energy conversion mechanisms. Current works and their relative merits of the different vibration energy conversion working mechanisms in micro scale power generators are also discussed and compared with emphasis placed on micro electrostatic/electret conversion mechanism.

Chapter 3 looks into the modelling and analysis of parallel-plate micro electret power generators for harvesting ambient vibration energy characterized by low frequencies and small acceleration amplitudes. The vibration to mechanical structure interface is first examined along with its key design parameters. This is then followed by looking into the electromechanical interface. The effect of fringing field in micro electrets power generators has also been incorporated into the modelling of interfaces. A proposed sandwich structured micro electret power generator for more effective energy conversion along with its theoretical modelling is also discussed.

Chapter 4 highlights present challenges encountered when producing high and stable surface potential on micro sized electrets. A proposed method has been developed to overcoming present shortcomings while forming micro sized electret array via corona charging for power generators. The approach is able to design electret cell array in micro size and yet offer large offset area which facilitates large capacitance change when power generator with parallel-plate configuration is driven by low frequency and small acceleration amplitude vibration energy.

Chapter 5 details the development and fabrication of micro electret power generators by MEMS technology. Challenges in fabricating mechanical structure with feature sizes that are of micro scale are discussed. This has led to the development of a new

alignment method that could precisely perform low temperature stack assembly of silicon plates for power generator devices. Besides this, a thermal circuit model for computing the heat distribution and transfer via using appropriate heat block design is also established. This has enabled better heat management during the etching process. Chapter 6 presents the testing and characterization on power generators. The prototype of Sandwiched Structured Power Generator (SSPG) with outward type I springs have been characterized for harvesting the fundamental component of vibration. Another prototype of micro electret power generator with outward type II S-springs is also presented and suitable for use in harvesting the harmonic component of vibration sources.

Chapter 7 summarizes the results and contributions of this thesis and present recommendations and areas for future work.

Chapter 2 Literature Review

This chapter begins with a review of the various ambient vibration sources and their characteristics. It then looks into different mechanisms adopted in vibration-driven power generators, with power equations under different preconditions are summarized and compared in Appendix C. Emphasis on micro inertial power generators based on MEMS technology would also be discussed.

2.1 Ambient vibration source and its characteristics

Vibration is a mechanical oscillatory motion that can either occur in a periodic or random manner. In ambience, vibration sources could be generated from human movements, motions of a machinery or appliance and displacements in buildings. Figure 2.1 show three typical types of vibration spectra signals derived from a human walking motion, a micro wave casing and a milling machine base, respectively. These vibration sources tend to exhibit a periodic, sinusoidal wave profile with peak acceleration recorded at fixed time intervals.

(a)

Figure 2.1 (a) Typically shifted antero-posterior and vertical acceleration pattern while walking. Sensors are placed on the low back (up) or on the thorax (low) [57]; (b) Vibration spectra of microwave casing (left) and Base of a milling machine (right) [26]; (c) Acceleration over time for a microwave over casing showing the sinusoidal nature of the vibrations [26].

Table 2.1 provides a list of acceleration magnitudes and frequencies that can be commonly found in the ambient environment. The findings derived from these studies on vibration sources reveal that the magnitudes of acceleration are usually less than 1g, sometimes even below 0.1g, operating at a vibration frequency range of about 100Hz. This would be the focus of this research work which would be to develop a power generator capable of harvesting energy from such vibration sources of sinusoidal wave profiles.

Table 2.1 Characteristics of ambient vibration sources

Category of vibration sources	Vibration source	Frequency, $f(\text{Hz})$	Acceleration, $a(g)$ $1g=10\text{ms}^{-2}$
Human[57]	Human walking analysis	2	0.5
Appliance[11]	Small microwave oven	121	0.25
	CD on notebook computer	75	0.06
	Cloth dryer	121	0.35
Living environment[11]	Second story floor of busy office	100	0.02
	Windows next a busy road	100	0.07
	HVAC vents in office building	60	0.02-0.15
Machinery	Car engine compartment[11]	200	1.2
	Base of 3-direction machine tool [11]	70	1
	Deep-groove ball bearing type FAG 6209 [58]	35-50	/
	Rotor of squirrel-cage induction machines 5-hp/460-V /6-pole[59]	60	/
	Wheel of a VW Passat running tyre with tyre pressure of 1.79 bar[60]	13.5	0.05

Harmonics are commonly presented in vibration machine and can also be utilized for energy harvesting. This is for a vibration source frequently contains significant contributions from harmonics[61]. The frequency of the harmonic component is an integer multiple of the fundamental frequency, $f_h=N\times f$. N is the number of the harmonic component. Figure 2.2 shows an example of vibration frequency spectrum of a bearing.

Figure 2.2 Typical solid-borne vibration spectrum of a bearing with inner race defect measured with a velocity sensor [58]

2.2 Vibration-driven power generators

Currently, mechanical energy, in the form of displacement or velocity, can be inputted to a power generator in two major ways. The first approach involves a vibrating object imposing a direct force on the generator device, and the second approach makes use of inertial force by means of acceleration to drive the generator device which is attached to the vibrating object.

2.2.1 Direct force power generators

Figure 2.3 Vibration-driven power generator using direct force approach

In the direct force approach, the power generator makes mechanical contact with a force and a supporting structure for the mass to generate relative motion, as shown in Figure 2.3. In this case, the driving force F acts on the mass supported on a spring of constant, k . A damper, which exerts an opposing force to the mass relative motion, is implemented via a transduction mechanism (electromagnetic, piezoelectric, or electrostatic) to convert the mechanical energy into electrical energy.

Assume the maximum relative displacement of mass is X_m . For a given excitation period $2\pi/\omega$, the maximum amount of mechanical power, $P_{mech,max}$, available for extraction can be derived from the following equation:

$$P_{mech,max,direct} = \frac{\omega F X_m}{2\pi} \quad 2-1$$

For direct force power generators, most of them make use of the piezoelectric mechanism which is subject to an applied pressure from an external body causing it to deform. This amount of deformation experienced is a function of the magnitude of the force and the material properties[62].

$$X_{m,direct} = \frac{FX}{AY} \quad 2-2$$

Where X is the height of piezoelectric material with no load, and X_m is the deformation of material after loading, A is the area over which the force is applied, and Y is the elastic modulus of piezoelectric material. Substituting Equation 2-2 into Equation 2-1 yields

$$P_{mech,max,piezo,direct} = \frac{\omega F^2 X}{2\pi A Y} \quad 2-3$$

An example of power generator using direct force approach is the embedded piezoelectric element in the sole of a shoe[63], as shown in Figure 2.4. A 7cm×7cm of prebent lead zirconate titanate (PZT) unimorph is flattened out against a back plate and a 8cm×10cm of PVDF laminate placed in the front of the shoe. The piezoelectric sole and heel generators could produce around 2 and 8mW, respectively.

Figure 2.4 Exploded view showing integration of piezoelectric material [63]

2.2.2 Inertial power generators

Figure 2.5 Vibration-driven power generator using acceleration approach

In the acceleration approach, the mass is suspended by springs in the power generator. When the mass is accelerated, this results in a relative displacement $x(t)$, as shown in schematic drawing of Figure 2.5. At resonance (resonant frequency of spring-mass structure in the power generator is equal to or close to the frequency of vibration source), this amplitude of relative displacement would be greater than amplitude of the input displacement $x_i(t)$ [64] [27].

To model this process, an input sinusoidal vibration wave profile, $x_i(t) = X_0 \sin \omega t$, is assumed where X_0 is the motion amplitude and ω is the angular frequency. If the

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amplitude of relative displacement of mass at resonance is X_m , the corresponding amount of mechanical power available for extraction $P_{mech,max}$ is equal to the following [65]:

$$P_{mech,max,iner} = \frac{2}{\pi} X_0 X_m \omega^3 m \quad 2-4$$

The relationship between X_m and X_0 is dependent on the quality factor, Q :

$$X_{m,iner} = QX_0 \quad 2-5$$

Substituting Equation 2-5 into Equation 2-4 yields

$$P_{mech,max,iner} = \frac{2}{\pi} X_0^2 Q \omega^3 m \quad 2-6$$

As X_0 and ω are predetermined by the vibration source, the maximum amount of mechanical power, as in Equation 2-6, can therefore be derived when the mass m and quality factor Q are at their permissible maximum.

Figure 2.6 shows an example of an electromagnetic power generator used to harvest traffic-induced vibration energy for structural health monitoring and sensing in bridges. The generator is simply attached underneath the bridge grider. Vibrations of very small acceleration ($0.1\text{--}0.5\text{ms}^{-2}$) operating at low frequency ($2\text{--}30\text{Hz}$) are observed. The power generator is reported to produce an average power of $0.5\text{--}0.75\mu\text{W}$ without manipulation during installation or tuning at each of the bridge locations [66].

For this research, inertial generators are preferred over direct force generators as inertial ones require only one point of attachment to a vibrating object for the transmission of the acceleration force. This is in contrast to direct force ones which need a sufficient large loading force. In addition, if the force is not oriented, the material may not deform adequately. This challenge is further compounded for at low

levels of sinusoidal vibration where the frequencies, f , are less than 100Hz with acceleration, a , less than 0.1g and the amplitude of vibration $X_0=a/(2\pi f)^2$ which is only in the order of a few microns. In the inertial generator, the quality factor at resonance can however amplify the displacement, making it more effective to extract maximum mechanical power from the vibration source. Besides, it is also easier to attach or mount the generator to a single point than that of a contact area in embedded applications where these power generators would need to be inserted and installed inside a vibrating object. This advantage is enhanced if the generator is to be miniaturised. As such, it has been reported that most of current power generators are based on inertial rather than direct ones [24].

Figure 2.6 Photograph of the power generator attached underneath the bridge girder, adapted from [66]

2.3 Micro inertial power generators

The typical schematic model for an inertial power generator based on a spring-mass structure is first proposed by Williams and Yates based on electromechanical power generators [67]. This model is described in Equation 2-7.

$$m \frac{d^2 x(t)}{d^2 t} + c \frac{dx(t)}{dt} + kx(t) = -m \frac{d^2 x_i(t)}{d^2 t} \quad 2-7$$

Figure 2.7 Schematic diagram of the model of an inertial power generator, adapted from [67]

In this inertial generator configuration, the mass, m , is suspended by a spring of constant k , which is attached to a frame, as shown in Figure 2.7. Work is done when the mass is moving against the damping force, $c \frac{dx(t)}{dt}$. This mechanical energy can then be extracted and converted into electrical energy through an appropriate electromechanical transducer (electromagnetic, piezoelectric, or electrostatic). Owing to the energy losses particularly in the mechanical damping, the electrical energy obtained would be a fraction of the amount of mechanical energy. This second-order differential model is applicable to a number of electromagnetic power generators where the damping can be assumed linearly and proportional to the velocity $\frac{dx(t)}{dt}$ [68]. The damping, for such generator consists of electrical damping and mechanical damping. The electrical damping force is represented by $c_e \frac{dx(t)}{dt}$, where c_e is the electrical damping coefficient, and mechanical damping force is represented by $c_m \frac{dx(t)}{dt}$, where c_m is the mechanical damping coefficient. It should be noted that for piezoelectric and electrostatic power generators, this model would need to be modified as the electrical damping may not be linear.

To characterize the frequency response of this second order differential equation, an unitless damping factor ζ is used to provide a mathematical means of expressing the level of damping in a system relative to critical damping.

$$\zeta = \frac{c}{c_c} \quad \mathbf{2-8}$$

Where c_c is the critical damping, equal to $2m\omega_n$, ω_n is the resonant angular frequency of the system, ζ represents the sum of electrical damping ratio ζ_e and mechanical damping ratio ζ_m . $\zeta = \zeta_e + \zeta_m$. Damping coefficient and damping factor can be evaluated as

$$c = 2m\zeta\omega_n \quad \mathbf{2-9}$$

The quality factor Q and the damping ratio has the following relationship:

$$Q = \frac{1}{2\zeta} \quad \mathbf{2-10}$$

Electrical power generated can be determined as follows:

$$P_{elec,iner} = \int_0^v F_e dv \quad \mathbf{2-11}$$

Where $F_e = c_e v$, and v is the velocity of mass. Replacing v with the equivalent $\frac{dx(t)}{dt}$

yields the solution of Equation 2-12 [11]:

$$P_{elec,iner} = \frac{1}{2} c_e \left(\frac{dx(t)}{dt} \right)^2 \quad \mathbf{2-12}$$

An analytical expression for the amplitude of $\frac{dx(t)}{dt}$ can be derived from Equation 2-7,

as shown below:

$$\left(\frac{dx(t)}{dt}\right)_m = \frac{-j\omega\left(\frac{\omega}{\omega_n^2}\right)}{2\zeta\frac{j\omega}{\omega_n} + 1 - \left(\frac{\omega}{\omega_n}\right)^2} X_0 \quad 2-13$$

Substituting Equation 2-13 into 2-12 and rearranging the terms, the electrical power of generator at resonance (when $\omega=\omega_n$) can be derived as follows:

$$P_{elec,maxiner} = \frac{m\zeta_e\omega^3 X_0^2}{4(\zeta_e + \zeta_m)^2} \quad 2-14$$

Substituting Equation 2-10 into 2-6 and rearranging with Equation 2-14, this yields:

$$P_{elec,maxiner} = \frac{P_{mech,max}\zeta_e\pi}{4(\zeta_e + \zeta_m)} \quad 2-15$$

Equation 2-15 establish the direct relationship between mechanical input $P_{mech,max}$ and electrical output $P_{elec,max}$. Using this equation to estimate $P_{mech,max}$ and $P_{elec,max}$ is more applicable for electromagnetic conversion principle, as damping factor is linear and being constant in micro electromagnetic power generators. From the denominator of the term on the right side of Equations 2-14, to derive maximum electrical power from the vibration energy sources at resonance, the mechanical power available $P_{mech,max}$ and electrical damping should be at its largest permissible. However, the increase of ζ_e will also add to the total damping factor ζ in the nominator and $P_{mech,max}$. This aspect needs to be considered in the design of these power generators.

2.3.1 Types of micro inertial power generators

This section examines the various types of inertial micro generators and their relative merits for low frequency and small acceleration amplitude applications.

2.3.1.1 Micro electromagnetic power generators

Electromagnetic generator designs are based on Faraday's law of electromagnetic induction [69].

Figure 2.8 Principle of electromagnetic conversion, adapted from [24]

In these designs, a permanent magnet is used to act or form part of the inertial mass which moves relative to N number of coil turns. Permanent magnets are made from ferromagnetic or ferromagnetic materials that remain magnetic after the application of a magnetisation process. Samarium cobalt (SmCo) and neodymium iron boron (NdFeB) are commonly used in these generators due to their high magnetic field. When the magnet moves relative to the coil, a magnetic flux is created. This leads to a voltage $V(t)$ being formed in coils which generate a current $i(t)$, flowing into the load, R , in the circuit. $V(t)$ is proportional to the time rate of change of the magnetic flux:

$$V(t) = -\frac{d\Phi}{dt} \quad 2-16$$

Where Φ is the total flux generated for N number of coil turns. The voltage induced in the coil can then be expressed in terms of the number of coils, flux gradient and the magnet velocity.

$$V(t) = -\frac{d\Phi}{dt} = -N \frac{d\phi}{dx} \frac{dx(t)}{dt}$$

2-17

In this case, ϕ can be interpreted as the average flux per turn. As the flux gradient is largely dependent on the magnets used to produce the magnetic field, current research has been made to investigate into the arrangement of these magnets, the magnetic properties of magnets, the device structure and the type of fabrication technology so as to enhance the voltage output or power output. The ensuing sections discuss the various designs that have been developed for micro electromagnetic generators.

Williams et al. [67] formulated and analysed one of the earliest models on inertial micro magnetic generator. With refinement, Shearwood and Yates, [70] reported that the micro magnetic generator would be able to produce a peak power of $0.3\mu\text{W}$ having a vibration frequency at 4.4kHz on a 25mm^3 device. Figure 2.9 shows a millimetre-size bulk-manufactured SmCo permanent magnet that attaches to a polyimide membrane, which spans across a cavity etched in a GaAs wafer. This membrane acts like a spring in the resonant system. A planar Au coil is located at the back of the device. It was noted that the measured electrical power output was found to be considerably lower than the predicted value. This was probably due to the non-linear effects arising from the membrane spring. Suggestions to maximise the power output for this design were also made in [68].

Figure 2.9 Schematic of electromagnetic generator[70]

Amirtharajah and Chandrakasan[71] developed another micro magnetic generator that seeks to harness energy from human walking/motion. The design involves a 23.5cm^3 electromagnetic generator using a set of spring, wire coil, and permanent magnet as shown in Figure 2.10.

Figure 2.10 Generator mechanical schematic [71]

At resonance frequency of 2Hz, the device was reported to be able to generate a maximum $400\mu\text{W}$ of power having amplitude of 2cm. It was claimed that this amount of power is able to operate a low-powered DSP circuit.

To make the design more compact, another group from the Chinese University of Hong Kong [72] has developed a resonant device design using a NdFeB magnet supported by a laser-machined spiral Cu spring structure as in Figure 2.11. The total volume is around 1cm^3 and the resonant frequency of the device is 110Hz. The device was able to achieve a maximum power output of $830\mu\text{W}$ having a $200\mu\text{m}$ displacement at this frequency.

Figure 2.11 (a) Structure of power generator; (b) Laser-micromachined copper springs [72]

A group from the University of Southampton then worked on a new resonant cantilever beam design for micro inertial magnetic generator [26, 73, 74]. One of the early designs involves a pair of NdFeB permanents connected via a U-shaped iron core to provide a constant field across an air gap, as shown in Figure 2.12(a). This magnetic assembly resided on a cantilever beam and vibrated with respect to a stationary coil winding. The coil is made up of 27 turns of 0.2mm diameter and is fixed in position between the poles of the magnets. The 240mm³ device is found to be able to generate 0.53mW of power at a vibration amplitude of only 25μm at 320 Hz [26].

Figure 2.12 Electromagnetic generator: (a) With one pair of magnets; (b) With two pairs of magnets[26]

The early design was further refined in which the device would compose four permanent magnets creating two flux paths flowing in opposite directions of each other, as shown in Figure 2.12(b). It has a design volume of 840mm³ and is capable of generating an average 157μW of power when attached to an automobile engine. The rate of change of the linked flux for this configuration design is found to be doubled when compared with a two-pole design.

Figure 2.13 Micro cantilever electromagnetic power generator [74]

Figure 2.13 shows a four permanent magnet structure used on a small electromagnetic generator having a volume of 0.15cm^3 . The employment of a cantilever instead of membrane has lowered resonant frequency where $46\mu\text{W}$ having a resistive load of $4\text{k}\Omega$ is produced from 0.59m/s^2 acceleration level at a resonant frequency of 52Hz [74].

2.3.1.2 Micro piezoelectric power generators

Piezoelectric generator designs are based on piezoelectric effect in which voltage is produced between surfaces of piezoelectric material, notably crystals, such as Zinc Oxide (ZnO) and Aluminium Nitride (AlN), and certain ceramics, such as lead zirconate titanate (PZT), when a mechanical stress is applied on it. These piezoelectric materials have been used on cantilevers and beam structures. PZT has been commonly used as it has the highest piezoelectric constant among these three types of piezoelectric materials[75]. When subjected to vibration, the cantilever exhibits an oscillatory bending motion which gives rise to an induced strain across the whole piezoelectric material structure. This results in an electric potential or charge being formed [76].

To model this strain-charge conversion, one could make use of the following set of equations [11]:

$$D = \varepsilon E + d_{ij} \sigma$$

2-18

Where D is the electrical displacement, E the electric field inside material, ε the permittivity of piezoelectric material, σ the mechanical stress and d_{ij} is the piezoelectric strain coefficient. The two subscripts: the first one indicates the direction of the electric displacement and the second one shows the direction of the strain. The open circuit voltage, V_{oc} , resulting from Equation 2-18 when the electrical displacement is at zero is given by:

$$V_{oc} = -\frac{d_{ij} t}{\varepsilon} \sigma$$

2-19

Where t is the thickness of the piezoelectric material.

Piezoelectric generators typically work in either 31 mode or 33 mode due to higher piezoelectric strain coefficient in these two modes. In the 31 mode, the stress is applied in direction 1 that is perpendicular to the electric displacement in direction 3 where the bending cantilever is poled at its top and bottom surfaces. Whereas in the 33 mode, for a piezoelectric block that is poled on its top and bottom surfaces, the stress acts in the same direction as that of electric displacement in direction 3.

Figure 2.14 Illustration of two modes operation for piezoelectric material: (a) 31 mode; (b) 33 mode [11]

It was reported that for piezoelectric material, the coupling coefficient d_{31} is less than d_{33} [62]. Yang et al [77] have found that a higher coupling coefficient will lead to more power generated under similar strain condition. Although the 31 mode has a lower coupling coefficient d_{31} , common power generator structures such as cantilevers or double-clamped beam typically work in the 31 mode as larger lateral strains can be derived with smaller input forces. On scaling of feature size, a difference in the magnitude of piezoelectric constant between thin/thick film and bulk material was reported [78]. The piezoelectric strain coefficient is observed to be smaller for film than that of bulk. Thus, a modification is needed on d_{33} when piezoelectric material exists in the form of thin film in micro power generators.

To improve the micro piezoelectric power generator performances, research into various design structures have been made that seek to either modify the piezoelectric materials, alter the electrode pattern, change the poling or stress direction. Some of these micro generator designs are discussed in the ensuing sections.

P. Glynn-Jones et al. [31, 79, 80], a team from the University of Southampton, proposed a micro piezoelectric generator using PZT 31 mode to harvest vibration energy. The generator operates at a resonant frequency of 80.1Hz with 0.8mm beam tip motion amplitude, as shown in Figure 2.15. The maximum power generated from the prototype in resonant mode was 2 μ W.

Figure 2.15 The beam-based piezoelectric micro-generator [76]

Y.B. Jeon et al. [81] developed another micro Piezoelectric Micro Power Generator (PMPG) device based on the PZT cantilever with interdigitated electrodes placed on the top side of the cantilever, as shown in Figure 2.16(a). Through this, the generator aims to derive its power in 33 mode which makes use of higher piezoelectric strain coefficient d_{33} as well as the larger strain produced in cantilever structure. A proof mass made of SU-8 was attached at the tip of cantilever on the piezoelectric generator to increase the mechanical energy available for harvesting, as shown in Figure 2.16(b). Operating at a resonant frequency of 13.9kHz having a $170\mu\text{m} \times 260\mu\text{m}$ PZT beam size, it was found that a voltage of 2.4V with a maximum power output of $1.01\mu\text{W}$ can be obtained when a $5.2\text{M}\Omega$ load was applied to the system.

(a)

(b)

Figure 2.16 (a) 33mode with interdigitated electrodes; (b) SEM of the fabricated PMPG device with bond pads[81]

It was further reported that although voltage output in 33 mode is theoretically bigger than at 31 mode, this may not necessary result in a larger power output value than that in the 31 mode. To this, Lee et al. [82] conducted experimental tests on two micro piezoelectric generators of 31 mode and 33 mode with the interdigitated electrodes, having a cantilever made by a silicon micromachining process. The beam structure sizes are of $0.5 \times 1.5 \times 0.5\text{mm}$ and $0.75 \times 1.5 \times 0.5\text{mm}$ for 31 and 33 modes respectively. The schematic diagram of 31 mode and 33 mode configurations can be found in Figure 2.17. The experimental results showed that 31 mode micro-generator could generate output power of $2.765\mu\text{W}$ excited at 2.5g amplitude and 255.9Hz resonant frequency, whereas the 33 mode generator could only generate an output power of $1.288\mu\text{W}$ under 2g amplitude and 214Hz. It was highlighted that the output power of 33 mode generator was smaller than that of 31 mode generator. This is because the piezoelectric material in 33 mode is poled by the interdigitated electrodes which results in a non-uniform poling direction thereby reducing the conversion efficiency.

Figure 2.17 Schematic diagram of the micro piezoelectric generators: (a) 31 mode configuration; (b) 33 mode configuration[82]

Elfrink et al. [83] uses AlN, a less commonly used piezoelectric material in the design of a fabricated cantilever micro piezoelectric generator. The cantilever consists of a beam of length, 1.01mm and width, 5.0mm and mass over a length of 5.0mm, as shown in Figure 2.18. The device could generate an output power of $60\mu\text{W}$ subject to a 2g acceleration at resonant frequency of 572Hz. AlN material was chosen for its ease of fabrication as it is CMOS compatible and can be produced using standard deposition process. This is a major advantage compared with PZT thin film which is fabricated using complex deposition process. One limitation is that the piezoelectric constant e_{ij} of AlN is approximately 8 times less than that of PZT, resulting in a less efficient electromechanical coupling.

Figure 2.18 Power generator packaged in between glass substrates [83]

2.3.1.3 Micro electrostatic power generators

The concept of electrostatic generator originates from electrostatic induction where the electrical charges on one electrode of a variable capacitor are re-distributed owing to the influence of nearby charges on the other electrode. The magnitude of these

charges, q , is determined by the potential difference, V , between the electrodes and the variable capacitance, C , as expressed by $q=CV$.

Figure 2.19 Principle of electrostatic conversion: (a) Constant charge mode; (b) Constant voltage mode, adapted from[24]

If the charge on the electrodes is held constant, as shown in Figure 2.19(a), the change of capacitance will induce a voltage change across the capacitor. On the other hand, if the voltage between the plates is held constant, as shown in Figure 2.19(b), the change of capacitance will induce a change in the magnitude of charges, leading to current flowing in the outer circuit.

Comb drive is one of the common design structures adopted by the electrostatic generator. The design composes of multiple capacitors in parallel. The motion of mass changes the overlap positions of the electrodes of capacitors. Two types of electrostatic comb drive generators have been used namely in-plane overlap varying and in-plane gap closing, as shown in Figure 2.20. Both two in-plane configurations create two variable capacitors that have capacitances which are 180° out of phase.

Figure 2.20 (a) In-plane overlap varying; (b) In-plane gap closing, adapted from [84]

A group at MIT, Chandrakasan [85] reported the development of an in-plane overlap varying micro electrostatic power generator, as shown in Figure 2.21. Simulations of the device show that this generator is able to generate $8\mu\text{W}$ of power based on a 2.5kHz input motion operating at an in-plane overlap varying mode [86].

Figure 2.21 (a) SEM image of comb drive structure; (b) Schematic of comb drive structure of power generator with dimensions [85]

Yang et al [87] developed another capacitive generator which makes use of an in-plane rotary combs. The ladder spring, as shown in Figure 2.22, operates at a low resonant frequency of 110Hz . The measured output power is found to be $0.11\mu\text{W}$ when the acceleration vibration amplitude is at $0.5g$.

Figure 2.22 Scanning electron microscope (SEM) image of a rotary comb capacitive generator with 6- μm wide ladder spring [87]

Figure 2.23 Schematic of the charge pump circuits for power generators [34]

One drawback for the generator based on a comb drive structure is that an extra voltage source is needed to provide initial charge to the capacitor, as shown in Figure 2.23. On its own, the micro power generator is not able to operate on a self-sustaining mode. Besides, this extra voltage source also increases its volume size as well as the complexity of the power generator system.

To address this drawback, micro electrostatic generators integrated with electret, also known as micro electret power generators, have been developed. Such generators do not require extra voltage sources/charge pumps. Electrets are thin dielectric material, containing implanted and highly persistent surface and space charges. As the electrets are implanted with charges, the need for a charge pump to provide the initial charge is

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therefore not required. Besides, electrets can generate internal and external fields which would enable charges to be continuously induced on a paired set of electrodes in a variable capacitive system. Electrets can be formed either from inorganic material such as $\text{SiO}_2/\text{Si}_3\text{N}_4$ multilayers, or organic dielectric material, such as CYTOP, PTFE, and Teflon AF [88]. SiO_2 thin film can be thermally grown[89, 90] as well as both SiO_2 and Si_3N_4 thin films can be deposited via plasma-enhanced chemical vapour (PECVD)[91]. However, the low deposition speed and high residual stress of these techniques to fabricate SiO_2 and Si_3N_4 thin film lead to difficulties to prepare thick layers ($>2\mu\text{m}$). For micro electret power generators, organic electrets can easily have thickness more than $10\mu\text{m}$. Thick electrets are more commonly used and beneficial for low parasitic capacitance in generator devices [92].

Figure 2.24 highlights three major design configurations of electret generators adopted by current researchers. The capacitance changes vary according to the configuration type. These configurations are highlighted in Figure 2.24(a) an in-plane oscillating electret power generator in which the capacitance change relies on the change in the overlapping area of two electrodes; (b) a gap-closing type in which capacitance change relies on the change of gap between two electrodes; and (c) an in-plane oscillating type having an insert medium with high permittivity oscillating inside the air gap with the capacitance change dependent on the position of medium inside capacitor[35]. Among these three configurations, in-plane oscillation design requires fewer components than medium oscillation type devices. Besides, in-plane oscillation type is less susceptible to electrostatic sticking in the vertical direction than gap closing type. For the gap closing type, the spring is normally stiff along the gap closing axis, and to achieve low resonant frequency, additional mass is required.

Figure 2.24 Configurations of micro electrets power generators: (a) In-plane oscillating; (b) Gap-closing; (c) In-plane oscillating type having an insert medium

The maximum electrical power output for the in-plane micro electret power generator can be modelled using the following equation without considering fringing field effect[93]:

$$P_{elec,max_{electret}} = \frac{\sigma^2}{\frac{4\varepsilon_0\varepsilon_2}{d}(\frac{\varepsilon_2 g}{\varepsilon_1 d} + 1)} \cdot \frac{dA(t)}{dt} \quad 2-20$$

Where σ is the surface charge density, ε_0 is the vacuum permittivity, ε_2 is the dielectric constant of the electret, ε_1 is the dielectric constant of air, g is the gap distance from the top electrode to the electret surface, d is the electret thickness and

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$A(t)$ is the variable overlap area between the top and bottom electrode. This power formula is directly calculated from mechanical output of device and electrical parameters of device without incorporating the environmental mechanical input. Since the electrical power output is proportional to the square of surface charge density of electrets, further exploration could be made to increase the amount of charge density. It has to be said that a high surface voltage operating within a small gap will create a large electrostatic force between the electrets which runs counter to electrodes leading to electrostatic sticking. To avoid this phenomenon, an appropriate gap size would need to be maintained.

Various integrated micro electret generators for energy harvesting have been developed. Yuji Suzuki's group in Tokyo University[38], had come up with a power generator that can resonate at low frequency. CYTOP is used as the electret material which was charged to a surface density of 1.5mC/m^2 . This electrostatic generator based on electret seeks to operate at a resonant frequency of 63Hz having in-plane amplitude of 1mm. To minimize the electrostatic force influence and improve the dynamic performance of the electrostatic generator, patterned electrets are formed on both the proof mass and the bottom substrate. This helps to alleviate the pull-in effect by the vertical electrostatic attraction force by converting them into repulsive ones. Total power of $1\mu\text{W}$ could be obtained from the generator, at an acceleration of $2g$ operating at 63Hz.

Figure 2.25 Electrets generator prototype [38]

An attempt to further miniaturize electret generators using MEMS technology has been made by Norio Sato et al [39], in Figure 2.26. The volume of the device is 0.018cm^3 . An ethylene-tetrafluoroethylene copolymer film is used as electrets. The generator is able to achieve a charge density of 3.5nC/cm^2 . Power output of 10^{-14}W is obtained from the generator at resonance. However, its resonant frequency is at 1166Hz. This is owing to the stiff single-beam spring design given the tightly constrained space in the device. The authors proposed that folded spring should be employed in the future work as this will not only make the device more compact, but could lower the resonant frequency.

Figure 2.26 SEM images of two plates of electret power generator: (a) Lower plate, (b) Upper plate [39]

2.3.2 Fabrication of micro power generator devices

One key selection for a suitable power generator concerns the fabrication of small scale power generators. This could involve the fabrication of special material for

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electromechanical conversion (piezoelectric material, magnet, and electrets) as well as the movable mechanical structure. Some of the geometric features could be of macro and micro scale which would likely require a hybrid integration between manufacturing technologies, such as conventional machining and micro-fabrication.

To miniaturize power generators as well as fabricate micro power generators of varying volumes ranging from a few mm^3 to a few cm^3 and in batches, this would usually involve machining geometric features via either by precision machining, micro tools, laser machining or MEMS technology. Of these, MEMS technology is commonly adopted for its dual functionality in being able to perform material removal by bulk micro machining techniques as well as build material using surface micro machining techniques. Fabrication techniques in MEMS technology can be used to create mechanical components such as cantilevers, diaphragms, springs in micro inertial power generators through surface or bulk silicon micro machining techniques. In surface micro machining techniques, layer deposition and etching processes are used to create additional structural materials on the surface of substrate [94], in which thin films are deposited and patterned on the surface structure on the substrate surface. Figure 2.27 illustrates the steps used in the layer deposition process to create a MEMS feature arrangement where hollow gaps are present to allow movements of the components.

Figure 2.27 Schematic diagram of the steps used in the surface micromachining process[95]

For etching, a silicon bulk micromachining process, this could be performed either wet or dry etching. In wet etching, the material is made to dissolve using a chemical solution. In dry etching, the substrate is exposed through the chemical and physical interactions between the ions in the plasma and the atoms of the substrate material. Compared to wet etching, dry etching has advantages of etching characteristics such as fine pattern resolution and anisotropy in a depth direction. Deep reactive ion etching (DRIE), a highly anisotropic etch process, is widely used to create steep-sided holes and trenches typically of high aspect ratio of up to 30:1 [96] with good anisotropy (>99%) that can even be achieved in small structures (<2 μm) [97]. This etching technique has been commonly used to create movable mechanical structures as earlier highlighted. Besides, it was also noted that manufacturing efficiency could be enhanced with significant cost reduction using MEMS fabrication technology developed out of CMOS technology. The technology could therefore provide a readily tool for batch processing and miniaturization of devices and systems.

2.3.2.1 Fabrication of micro electromagnetic power generator devices

Electromagnetic power generator device usually composes of a number of complex structured components (magnet, coil, spring) fabricated out of different materials. An example is the power generator device shown in Figure 2.13 where the beam of power generator is made from metallic materials of beryllium copper that involves the photolithography and spray etching process. The beam is then clamped onto a Tecatron GF40 base using an M1 sized nut, bolt and a square washer arrangement. The coil is manually bonded to a semi-circular machined recess located at the base. To further compound the challenge, the dimensional tolerances need to be maintained at the appropriate sizes particularly for miniaturized devices. To fabricate micro electromagnetic power generator devices, various fabrication technologies have been developed to enable the micromachining of components, and the devices are fabricated using a combination of silicon micromachining in MEMS technology and electroplating. For example, permanent magnet films are produced by the sputtering process in MEMS and electroplating [98], and copper coils are to be fabricated also by electroplating [99-101]. Figure 2.28 shows a micro electromagnetic power generator device with 10 μm thick copper coils electroplated on a silicon paddle. The device is to resonate at 7.4kHz horizontally between the magnets. The paddle is to be etched by DRIE and batch fabricated onto a silicon wafer. Magnets are fabricated from $\text{Co}_{50}\text{Pt}_{50}$ phase hard magnets which are electroplated on separate silicon wafers. To increase the spring deflection for greater relative mass displacement, Pei-Hong Wang et.al [102] have chosen copper with lower young's modulus than silicon to fabricate the spring. The copper spring is electroplated on silicon wafer platform with dimension of $3\text{mm}\times 3\text{mm}\times 0.02\text{mm}$. The obtained resonant frequency is 121.25Hz. This too involves a dual type micromachining process.

Figure 2.28 Schematic of micro electromagnetic power generator with silicon paddle as spring and electroplated Cu coil [103]

Figure 2.29 Photo of the backside of the planar copper spring[102]

2.3.2.2 Fabrication of micro piezoelectric power generator devices

As mentioned in Section 2.3.1.2, most micro piezoelectric power generator devices are based on the cantilever or beam structure. This is to maximize the strain generated in piezoelectric material which translates to greater power generated. These cantilevers or beam structures can be easily fabricated from silicon micro machining in MEMS technology [104]. The challenging part of fabricating micro piezoelectric power generator devices is to integrate the piezoelectric thin film material into the mechanical structure. In integrating piezoelectric thin film into a cantilever structure, various deposition processes such as sputtering, photo-ablation, hydrothermal and chemical vapor deposition (CVD) techniques, and spin-on sol-gel processing are used

[75]. Of these, sol-gel processing, a wet chemical method for synthesizing and processing inorganic hybrid materials, is the most commonly employed techniques for PZT deposition due to various advantages such as cost effectiveness, texturing, and good control on stoichiometry [105].

Figure 2.30 Sol-gel process for PZT thin films[106]

The typical sol-gel process for PZT thin film is shown in Figure 2.30. Bottom electrode is to be deposited on the substrate first, and then PZT sol is spin-coated onto the substrate. After that, the PZT/silicon structure is subjected to the sintering process which involves annealing process at high temperature to make the PZT film dense as well as form into the desired perovskite crystalline phase. The annealing temperature ranges from 600°C to 700°C. The annealing time can last from 4 to 6 hours. Finally, top electrode is deposited onto the PZT film.

As the texture of PZT thin film can be affected by the piezoelectric properties, careful selection of the suitable substrate or electrode and control of the deposition conditions, and heating rate are needed. To obtain better texture of the PZT thin film, an insulating buffer layer such as silicon nitride and zirconium dioxide, could be used as it functions better than electrode buffer layer in preventing the reaction and inter diffusion between the PZT film and silicon substrate [107, 108].

The fabrication of PZT thin film faces a few challenges. The first is that thin PZT film produced by the sol-gel method tends to have inferior piezoelectric properties.

Typically, each coating of PZT sol ranges from 15nm to 100nm [109]. Cho et.al [110] reported that increasing the PZT thickness from 1 to 3 μ m could increase the coupling coefficient by a factor of about four. Their findings indicate that the charge accumulation associated with the material electric dipole is proportional to the film thickness. Therefore, multiple coating and annealing processes would be necessary to produce thickness of more than 1 μ m [106, 111]. The second challenge concerns high defective rate in thin films as cracks can easily be formed during the drying and annealing stage due to stress gradient in the material when the solvent evaporates [118, 112]. This can short-circuit the top and bottom electrodes thereby causing aging and fracture to the PZT film. The residual stress in the thin film after fabrication is found to reduce coupling coefficient [113, 114], and is an important consideration for producing cantilever structure based piezoelectric device [81, 114, 115]. Experiments performed have found that increasing the thickness of PZT thin film could reduce residual stress [116, 117].

2.3.2.3 Fabrication of micro electrostatic power generator devices

The energy conversion mechanism of micro electrostatic power generators is based on capacitance change with capacitors made of simple plate structures and spring-mass structure fabricated using standard silicon micromachining process based on MEMS technology. Hence, majority of the electrostatic power generators are silicon based [118, 119], as highlighted in Section 2.3.1.3. The integration of electret into the power generator devices has been a major focus of the design and fabrication activities. Inorganic electret, SiO₂ thin film is thermally grown on silicon wafer. Otherwise, Si₃N₄ thin film produced by Chemical Vapour Deposition (CVD) could be used [120, 121].

Figure 2.31 The fabrication process of the patterned electret plate: (a) Deposit and pattern base electrode (Cr/Au/Cr: 20/200/20 nm); (b) Spin-on and cure electret film;; (c) Deposit and pattern metal mask; (d) O₂ plasma etch and remove metal mask and; (e) Corona charging [122]

For organic electret, soluble fluoropolymer material, such as CYTOP, PTFE, and Teflon AF, are commonly chosen for the formation of electret because they can be coated, patterned and etched in the micromachining process [35]. Both types of electret material can be dry etched [123, 124]. An example of CYTOP etching process flow is shown in Figure 2.31. From the SEM image on the CYTOP in Figure 2.32, it can be seen that dry etching can produce micro sized electret material with very smooth etching profile.

Figure 2.32 SEM image of etched CYOP on the silicon surface [124]

2.3.3 Comparative review

From the above review, all three transduction mechanism power generators have shown potential to harvest vibration energy at low frequency ($<100\text{Hz}$), small acceleration amplitude ($<1g$) having a volume size of less than 1cm^3 . For micro electromagnetic power generators, the structural complexity which involves spring, coil and magnet makes it more difficult to miniaturise its overall volume. Another significant limitation is that its fabrication and assembly process is quite complex and thus not suited for large volume production as its design configuration usually composes a number of components fabricated out of different materials. For piezoelectric power generators, they are easier to be miniaturized than electromagnetic power generators due to the simpler structure and fewer types of material utilization. Although the non standard fabrication process of PZT thin films with high piezoelectric strain coefficient can be integrated into a MEMS fabrication process, the high temperature annealing process for crystallization of PZT is still of concern for integration with the low temperature CMOS process. In addition to fabricate thick PZT film with good texture, numerous multi-layer of different material deposition would be required. Coupled with the need to have a good residual stress control, the process is more complex to optimize than the electrostatic/electrets power generators. This is for electrostatic ones are easier to fabricate and miniaturise using MEMS technology because of its silicon based structure. Its micromachining process is also more compatible and can also be integrated with the silicon based microelectronics. By integrating low temperature and easy spin-coating process of electrets into the fabrication of power generator, the usage of charge pump in conventional electrostatic power generator is eliminated. In the ensuing section, various micro electret power generators will be reviewed in details.

2.4 Micro electret power generators

Current research on the micro electret power generator performance for harvesting of ambient vibration energy focuses on three main aspects namely modelling of micro electret power generator for optimal power generation, design of spring-mass mechanical structure for energy extraction at low resonant frequency and formation of electret with high and stable charge density

2.4.1 Modelling

In order to better design and predict the performance of micro electret power generators for optimization, attempts have been made to establish a theoretical model to characterise its parameter performances and relationships. P.D. Mitcheson [27], first proposed a generic model for electrostatic power generator and calculated the maximum power converted as a result of energy dissipated in the coulomb damper with the constant coulomb force F in the direction opposing the motion, shown in Figure 2.33. The generic model does not consider the type of materials and spring structures being used.

$$P_{coupled, max \text{ electrostatic}} = \frac{2Y_0^2 \omega^3 m \omega_c^4}{\pi \sqrt{(1 + U^2 \omega_c^2)(1 - \omega_c^2)^2}} \times \left[\frac{1}{(1 - \omega_c^2)^2} - \frac{\omega_c U}{\sqrt{(1 + U^2 \omega_c^2)(1 - \omega_c^2)^2}} \right]^{\frac{1}{2}} \quad \mathbf{2-21}$$

Where $U = \left(\frac{\sin(\pi / \omega_c)}{[1 + \cos(\pi / \omega_c)]} \right)$

Figure 2.33 Schematic diagram of coulomb-damped resonant generators

A more specific model for electret power generator, that is highly cited in the field of electret power generator was proposed by Boland [125]. In this generic electret power generator model, factors such as the electret material, electrostatic parameters of charge density σ on electrets, capacitive gap g , dielectric constant of the electret ε_2 , electret thickness d and the variable overlap area between the top and bottom electrode $A(t)$ are included in the analysis.

A first order ordinary differential equation for charge flow $q(t)$ in the power generator is as follows:

$$\frac{\partial q(t)}{\partial t} + \left(\frac{d}{\varepsilon_2 \varepsilon_0} + \frac{g}{\varepsilon_0} \right) \frac{1}{RA(t)} q(t) = \frac{1}{R} \frac{d}{\varepsilon_2 \varepsilon_0} \sigma \quad 2-22$$

Where R is the load resistance in outer circuit. This model does not consider the configuration of the mechanical structures which has a big effect on the dynamic behaviours, for instance $A(t)$ and the electromechanical coupling efficiency.

As the entire electret power generator system is too complex to model analytically as a whole, it is usually necessary to break the model into subsystems. In S Boisseau et.al's [126] work, the modelling was broken into two main sections: capacitance change based electrostatics modelling and displacement/velocity for mechanics modelling. FEM (finite element method) software (Comsol Multiphysics) and matlab

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software are used in the modelling to optimize the in-plane oscillation/rotary electret power generator. The optimization model highlights that electrets that are able to maintain a high surface voltage on small thicknesses are particularly well adapted for power generators.

2.4.2 Spring-mass structure

High-aspect-ratio Si springs micro machined on a Si or silicon-on-insulator (SOI) substrate are often used in MEMS generators [34, 87, 127, 128]. The advantage of Si springs is that a good quality factor can be obtained with a relatively simple fabrication process. Quality factor of 147 has been obtained from silicon spring-mass structure with resonant frequency of 250Hz [34]. A SEM image of one silicon based spring-mass structure in electret power generator is shown in Figure 2.34. During the same etch step, the mass is shaped and is connected by springs to the bulk of the wafer.

The silicon micromachining process enables the fabrication of spring structure with very fine features of varying shapes. Bartsch et al [128] developed a disk-shaped resonator of 4mm in diameter suspended by 15 μ m wide concentric circular springs for their electret generator, as shown in Figure 2.35. The width of the springs is decreased from 11 to 7 μ m from top to bottom. They obtained two closely spaced resonance frequencies of approximately 370Hz in two orthogonal horizontal directions and high quality factor of 1800 was obtained from both directions.

Figure 2.34 SEM photograph of the mass suspended by four silicon springs[129]

Figure 2.35 Scanning electron microscope (SEM) images of concentric circular springs: (a) Overview; (b) Magnified view of the circular springs[128]

To lower the resonant frequency of spring-mass structure, Suzuki and Tai [51] made use of soft polymer material and developed high-aspect-ratio parylene springs. Using parylene-C deposition onto a deep trench etched into a Si substrate as a mold, parylene springs with aspect ratios of up to 20 can be fabricated as shown in Figure 2.36. Since the Young's modulus and the yield strain of parylene are 4 GPa and 3%, respectively, soft but robust springs can be realized. This parylene spring has been incorporated into the design of electret power generator and able to operate at a resonant frequency of 63Hz but at a low quality factor of 8.6 [38].

Figure 2.36 SEM image of leaf springs anchored to a Si substrate [51]

Table 2.2 gives the measured mechanical Q -factors of micro electrostatic/electret power generators reported in literature. In Table 2.2, majority of micro electrostatic/electret power generators employ silicon as spring material and the quality factor achieved in silicon spring are significantly higher than that of parylene spring. To harvest energy from vibration sources with low frequency and low amplitude, the power generators needs to have a low resonant frequency f_r and high mechanical Q -factor which often conflicts each other, as generally manifested in the references.

Table 2.2 Comparison of measured mechanical Q -factor, resonant frequency, and spring material of micro electrostatic/electret power generators reported in literature

Reference	Mechanical Q -factor	Resonant frequency	Spring material
[128]	1800	370.5/373.9 [#]	Silicon
[38]	8.6	63	Parylene
[130]	5.23	51	Parylene
[131]	42	40	Silicon

[#] at two principal axes

2.4.3 Charging method

Currently, the most common way to form electrets is charge implantation via electron beam irradiation and corona charging. In electron beam irradiation, the electrets are charged by means of irradiation with low-energy electrons in vacuum. The depth level and the density of charges in the electrets can be controlled. However, this approach is technologically complex and difficult to implement for large-scale production.

Corona charging is widely used in the industry and research laboratories. The approach involves ionizing the surrounding gas resulting in a charge accumulation near the electret surface or region of interest [132]. Figure 2.37 shows a schematic diagram of a simple triode corona. A metallic pointed needle, having a small radius of curvature, is connected to a high voltage supply. In the region close to the needle, the electric field is very high that exceeds the breakdown field of the gas. This results in an electrical discharge at a voltage below the breakdown of air around the limited needle region. This corona discharge can be either negative or positive depending on the type of ions produced.

In negative corona charging with negative high voltage, CO_3^- ions are mainly generated in the air at atmospheric pressure, whereas in positive corona charging with positive high voltage, H^+ , NO^+ and NO_2^+ ions are produced. These ions travel towards the electret surface in the electric field built between the needle and the electret surface. A grid, biased by a voltage supply, is inserted into the gap between the metallic needle and the electret surface. A strong electrical field is formed in the gap between the grid charging voltage V_c and the surface of material. The surface potential V_s on material will be increased due to the charge accumulation. When V_s reaches to V_c , the electric field in the gap is equal to zero and the ion injection then ceases and the charging system maintains at an equilibrium state.

Figure 2.37 Schematic diagram of a simple triode corona charging system[132]

Recently, two new charging technologies have been reported at laboratory scale. They are X-ray charging [133] and vacuum UV irradiation[134, 135]. In X-ray charging, in-situ ionization of air molecules inside narrow gaps is occurred, as shown in Figure 2.38. However, due to the small collision diameters of the air molecules to soft X-rays, long charging time is required. For instance, irradiation time required for charging electrets through a few μm -wide can be as long as 30 minutes.

Figure 2.38 Conceptual diagram of charging method with soft X-ray irradiation for a silicon-condenser microphone [133]

Figure 2.39 schematically shows the vacuum UV charging system, where electrons are extracted from nitrogen through a multi-photon ionization process. The maximum ionization current is 300 times that of the soft X-ray irradiation

method, which enables a charging rate that is two orders of magnitudes faster compared with the corona/soft-X-ray charging method.

Figure 2.39 A conceptual diagram of charging method using vacuum UV irradiation[135]

However, the complexity of both X-ray and UV irradiation charging system currently limits their applications for large-scale production of power generators. Due to the easy implementation and high effectiveness, corona charging is used commonly in the formation of electrets.

A review into the formation of micro sized electret array on dielectric thin film material for the variable capacitors in micro electret power generator has also been made. The conventional method is to cut the sheet of dielectric film into small pieces by etching, followed by charge implantation [136, 137]. Experimental results from published work show that this gives rise to low charging efficiency and fast charge decay present in micro sized electrets formed by charge implantation [36, 37]. Leonov and Schaijk [36], reported that for electret strips of 500 μm , they can only obtain a charging efficiency of less than 10%. For strips that are less than 400 μm , it is even possible to implant charges in them. They had also found that even if charges could be successfully implanted in electret strips of less than 1mm, these charges would completely disappear after two days.

Another way to form micro sized electret array is to charge selected area over polymer sheet. By doing this, micro sized charged areas are formed without patterning the material. In Naruse's work [138], charging is aided by guard aluminium electrodes patterned on top of certain areas of SiO₂ thin film. During charge implantation, it was observed that charges on areas with aluminium electrodes tend to leak, and charges in areas without electrodes remain. The comparison of this stripe masked method and conventional method is illustrated in Figure 2.40. It has been proven that higher surface potential can be obtained by this charging method than the conventional method. However, the report of stability of charge is of concern. Because SiO₂ thin film has a relative low volume resistivity of $10^{16} \Omega\text{cm}$ which might result in a fast decay of the stored charges [89].

Figure 2.40 (a) Conventional electrets patterns for power generators, (b) Stripe masked electret patterns for power generators [138]

Another way to guide charges into selected area can be found in [131] where silicon mass is used as charging grids, as shown in Figure 2.41. The local charging on a whole piece of CYTOP is conducted after the device is assembled. However, this charging process sacrifices the mass which is a crucial factor for power generation of inertial power generators, as the mechanical power available to be converted into electrical energy is proportional to its mass [139]. Etching away a portion of mass material via creating slits not only decreases the weight of the mass, but also increases the air damping.

Figure 3: Electret charging by using Si grid electrode.

Figure 2.41 Electret charging by using Si grid electrode [131]

2.5 Conclusion

It is found that the low level ambient vibration is typically of frequency less than 100Hz and acceleration less than 0.1g and characterised by periodic and sinusoidal profiles. Energy from those vibration sources can be harvested by inertial power generator based on spring-mass structure at resonance to extract maximum mechanical energy available.

All three conversion mechanisms; piezoelectric, electromagnetic and electrostatic have the potential to harvest low frequency and small acceleration vibration energy. Compared with micro power generators based on piezoelectric and electromagnetic conversion mechanism, micro electrostatic power generators can be more easily fabricated by using MEMS technology which is compatible with CMOS technology. If the micro electrostatic power generators are integrated with electrets, the use of precharge voltage sources for charge pump is eliminated and the power generators are more fully independent and self-sustaining. As such, further work would focus on the design and development of micro electrostret power generator.

The field of micro electret power generators is still young that lacks models in accurately predicting and characterising the parameter behaviour and performance. Different type of spring-mass structures for micro electret power generators have been reported in literature, however, silicon spring-mass structures aim at generate resonant

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frequency less than 100Hz, giving relatively high quality factor to facilitate energy conversion have not been discussed. In order to produce high and stable surface potential on micro sized electret array, efficient methods of charging dielectric material are still lacking.

Chapter 3 Design, modelling and analysis of micro electret power generators

This chapter looks into the modelling and analysis of parallel-plate micro electret power generators for harvesting ambient vibration energy characterized by low frequencies and small acceleration amplitudes. The vibration-mechanical structure interface is first examined along with its key design parameters. This is then followed by looking into the electromechanical interface. The effect of fringing field in micro electrets power generators has also been incorporated into the modelling of electromechanical interface. A proposed sandwich structured micro electret power generator for more effective energy conversion along with its theoretical modelling is also discussed.

3.1 Theoretical modelling of parallel-plate micro electret power generators

Figure 3.1 shows a two-plate architecture commonly adopted in research work being carried out on in-plane vibrating micro electret power generators. The generator design composes of a bottom substrate plate which contains fixed electret cells on the electrodes. The surface potential on these electret cells is denoted by V_s . The top plate contains a spring-mass structure, in which the spring acts to transpose the vibration characteristics onto the mass. This spring-mass structure is deemed as the vibration-mechanical interface. Optimal energy harvesting can be derived when the main vibration direction of the mass is made to align with the principal direction of vibration source, assumed to be x axis in this work. When the mass is subject to vibration, the displacement $x(t)$ of the electrode cells relative to the electret cells leads to a capacitance change $C_{var} [x(t)]$, resulting in charge $q(t)$ being generated. When the

device is connected to the external resistive load R_L , a charge flow forms a current and generate power.

$$q(t) = V_s C_{vac} [x(t)]$$

3-1

Figure 3.1 Architecture of generic parallel-plate electret power generator

Figure 3.2 Forces in parallel-plate power generator

In the dynamic analysis, the displacement $x(t)$ and velocity $\partial x(t) / \partial t$ would first need to be derived from the mechanical interface. Figure 3.2 shows forces comprising the vibration-mechanical forces and electromechanical forces acting on the mass. The equation that governs the equilibrium of these forces is expressed as follows:

$$m \frac{\partial^2 x(t)}{\partial t^2} + F_e + F_m + F_k = -m \frac{\partial^2 x_i(t)}{\partial t^2} \quad 3-2$$

Where $x_i(t)$ is the vibration source displacement, F_k is the elastic spring force that equals to $kx(t)$. F_m is the mechanical damping force induced in the structure during motion, F_e is the electrostatic force.

The current output can be calculated by differentiating the charge q with respect to time:

$$i(t) = \frac{\partial q(t)}{\partial t} \quad 3-3$$

By combining with Equation 3-1, the current can be evaluated as follows:

$$i(t) = V_s \frac{\partial C_{\text{var}}(x)}{\partial x} \frac{\partial x(t)}{\partial t} \quad 3-4$$

3.1.1 Modelling and analysis of the vibration-mechanical interface

As mentioned in Chapter 2, the resonance of inertial power generator could be derived by making the resonant frequency of spring-mass structure in the power generator equal to or close to the frequency of the vibration source. Such frequency matching with the vibration source can be utilized in two main ways namely: (a) a direct match with the fundamental frequency f of the vibration source (b) a match with one of the harmonic components of the vibration source. For the latter, one could possibly harvest vibration energy when the fundamental frequency f of vibration sources is in the extremely low frequency range but the resonant frequency f_r of the power generator is in a relatively high frequency range and equal to the frequency of n harmonic component, i.e. $f_r = n \times f$.

The resonant frequency of a spring-mass structure along target direction in power generator is given by:

$$f_r = \frac{1}{2\pi} \sqrt{\frac{k}{m}} \quad 3-5$$

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where k is the spring constant in the vibration direction and m is the mass. From Equation 3-5, a large mass and low spring constant in the vibration direction would result in a low resonant frequency.

When the spring-mass structure moves, mechanical energy is lost owing to damping. Viscous damping arising in moving parts of spring-mass structure was found to be most dominant amongst other forms of damping which include clamping, vibration energy dissipated by transmission through support structure [140], thermoelastic damping of spring, and energy dissipated due to irreversible heat conduction [141]. To maintain viscous damping at low level and ensure effective electromechanical coupling when the capacitive cells overlap each other, parasitic motion of spring-mass structure, including rotation around and vibration along other directions must be minimized. This requires that the resonant frequencies of spring-mass structure along other directions(y,z) should be distinct from the resonant frequency of x to avoid triggering resonance in the unwanted directions. Key considerations of the spring design would be as follows:

(a) Small spring constant in x direction (to reduce resonant frequency). Together with a mass, the resonant frequency of spring-mass structure vibrating along x direction should be less than 100Hz.

(b) High spring constant in y and z direction (to reduce parasitic viscous damping).

The resonant frequency of vibration along other directions and rotation around any direction should be distinct from and higher than the vibration resonant frequency along x direction. The ratios between spring constants, k_y/k_x and k_z/k_x as a performance measure, are set to be larger than 4, to enable the magnitude of the vibration frequency distinct by at least twice, referring to Equation 3-5.

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- (c) The spring needs to be robust so as to increase the reliability of power generator during vibration

3.1.2 Spring-mass material

Table 3.1 lists properties of five types of spring material that have been reported to be used to fabricate small spring structure. Although polymer, such as parylene and polyimide, has a low Young's modulus, for the construction of a compliant structure, it has a low fracture limit and cannot withstand sudden shocks owing to the harsh vibration conditions. For silicon, it is selected in this work because it is robust, easy to fabricate, and its machining parameters of silicon are well established. For integration and assembly, compared with metal spring using aluminium or copper which needs additional material and process step for fabrication, silicon spring along with the silicon mass can be easily micro machined out from the same silicon wafer simultaneously. The complexity involved in assembly and using different materials for the mass and spring can therefore be eliminated.

Table 3.1 Properties of possible spring materials for spring structure

Material	Density (kg/m³)	Young's modulus(GPa)	Yield Strength(MPa)	Poisson's ratio
Aluminium[142]	2.7	68.4	94.4	0.33
Copper[142]	8.62	117	382	0.375
Parylene [142]	1.289	3.2	55.2	/
Polyimide[142]	1.3	7.54	118	/
Silicon[143]	2.33	165	/	0.22

3.1.3 Spring design

Figure 3.3 Long beam with thickness t , width w_b , and length l_b

To enable flexibility and compliance, the silicon spring configuration would make use of long beams with short ones acting as links. The long beam has a thickness t (dimension in z -direction), width w_b (dimension in x -direction) and length l_b (dimension in y -direction). By using the boundary condition of the clamped beam, the spring constants of beam along directions can be evaluated as follows:

$$\begin{aligned}
 k_{beam,x} &= \frac{Et}{4} \frac{w_b^3}{l_b^3}; \\
 k_{beam,y} &= \frac{Et}{4} \frac{l_b^3}{w_b^3}; \\
 k_{beam,z} &= \frac{Ew_b}{4} \frac{t^3}{l_b^3}; \tag{3-6}
 \end{aligned}$$

The ratios of spring constants can be computed as:

$$\frac{k_{beam,y}}{k_{beam,x}} = \frac{l_b^6}{w_b^6} \tag{3-7}$$

$$\frac{k_{beam,z}}{k_{beam,x}} = \frac{t^2}{w_b^2} \tag{3-8}$$

From Equations 3-7 and 3-8, it can be deduced that for a high ratio of spring constant, the long beam would need to have a high aspect ratio. To derive the appropriate spring constant and resonance frequency, proper selection relating to the beam dimension and configuration would need to be made.

In this work, three S-spring configurations; two outward type I and II and one inward type are examined as shown in Figure 3.4. An outward type S-spring is one where the spring has one clamped end with a few S-shape turns extending outwards of it. Inward spring is one where the clamped end is located within the S-shape turns. For compactness and sufficient compliance, each of the outward type I and type II S-springs and inward S-spring is designed to have five long beams.

For ease of comparison, the three types of springs have the same length, l_b in y axis, beam width w_b and spacing s_b between the two long beams. The overall width in x axis for three types of springs is $5w_b+4s_b$. For micro power generators [34, 144], the mass displacement is expected to be in the 100 μm range. As such, s_b between two long beams is fixed at 200 μm to allow for adequate deflection between them. For outward type II S-spring and inward S-spring, the vertical spacing s_a between the short beams is at 150 μm so that the overall length of the long beam is comparable to that of outward type I S-spring.

Figure 3.4 Three types of S-springs design: (left) outward type I S-spring, (middle) outward type II S-spring and (right) inward S-spring

3.1.4 Spring-mass structure modelling

The modelling will be carried out on spring structure at first to define dimension range, followed by the modelling of whole spring-mass structure. The spring configuration is to be modelled using finite element analysis. ANSYS, commercially available software, is used to perform static linear analysis on the three spring configurations. A three-dimensional beam element BEAM4 is selected for the finite element model of silicon spring which has a high aspect ratio. BEAM4 is a uniaxial element with tension, compression, torsion, and bending capabilities. The element has six degrees of freedom at each node: translations in the nodal x , y , and z directions and rotations about the nodal x , y , and z directions. Material properties of single crystal silicon having a density ρ of 2330 kg/m^3 , Young's modulus Y of 165 GPa , and Poisson's ratio γ 0.22 [143] are used.

**Figure 3.5 Simulated beam deflection in ANSYS when force F_x of 5×10^{-6} N is imposed in x axis.
Beam dimension: $l_b=1000\mu\text{m}$, $w_b=40\mu\text{m}$, $t=350\mu\text{m}$**

The modelling stiffness, $k_{beam,x}$ for a single beam in Figure 3.5 is first validated and found to be 924N/m which is also consistent with the analytical result of 924N/m using Equation 3-5.

Simulation is then performed on the spring model having a mass of thickness t . The spring material property is that of a silicon wafer. The mass surface area is set as $1\text{cm} \times 1\text{cm}$ which would be adopted throughout this chapter. The mass is evaluated to be 0.08g ($m=v\rho$, $v=1\text{cm} \times 1\text{cm} \times 350\mu\text{m}$). The spring width w_b and length l_b of the long beam are then made to vary having a fixed thickness t . The relationship between beam width, spring constant and its ratio can then be determined.

Figure 3.6 Modelled spring properties at three different long beam lengths and as a function of beam width w_b : (a) k_x ; (b) f_r ; (c) k_y ; (d) k_z

The modelling is first carried out on the outward type I S-spring. As seen in Figure 3.6(a), (c), and (d), a shorter beam length has a more pronounced effect in increasing the spring constant in all three directions especially when the width, w_b is sizeable. According to Equation 3-5, a higher k_x would also lead to a higher resonant frequency as in Figure 3.6(b). The result of finite element analysis suggests that for a resonant frequency of less than 100Hz, the length of long beam in S-spring structure with five turns should be designed in the range of between 3000μm and 5000μm having a beam width of less than 80μm.

Figure 3.7 (a) Spring constant k_x of three types of springs as a function of beam width w_b ; (b) Resonant frequency f_r of three types of springs with respect to beam width w_b

Assuming the length of long beam, l_b , is fixed at 5000 μm , k_x and f_r of three types of S-springs are then investigated and compared as in Figure 3.7. Figure 3.7(a) plots the k_x of three types of S-springs with respect to beam width w_b . It is observed that bigger w_b results in bigger k_x , thus leading to a higher resonant frequency in Figure 3.7(b) in all types of springs.

Figure 3.8 (a) Spring constant ratio k_y/k_x of three types of springs as a function of beam width w_b ; (b) Spring constant ratio k_z/k_x of three types of springs as a function of beam width w_b

Figure 3.8 highlights the spring constant ratios k_y/k_x and k_z/k_x for the three types of S-springs with respect to w_b . They all meet the requirements of spring design to achieve resonant frequency less than 100Hz and spring constant ratio larger than 4. The results show that the inward S-spring has the largest spring constant ratio k_y/k_x among all the spring design. The outward type II presents a smaller spring constant ratio while outward type I have the smallest spring constant ratio. Compared with the other two types, inward type S-spring with the aforementioned dimension ratios is more difficult to be implemented in the spring-mass structure when applied in an uni-axial in-plane vibration mode. Therefore, in this work, outward type I and II S-spring will be considered to employed in micro eletret power generators.

After investigating spring types, modal analysis using finite element method in ANSYS is then carried out on the spring-mass structures to determine the natural modal shapes and its corresponding frequency. To have parallel motion, the mass

needs to be suspended by at least two springs. Figure 3.9 shows the dimension of outward type I S-spring-mass structure in the mode analysis. Consider the balance, two outward type I S-spring are designed along the center line. Table 3.2 lists the frequency and the shape for each mode. It is found that the modes include vibration along three principal axes(x , y , and z) and rotation around axes(x , y , and z). The frequencies of other modes are more than twice of the resonant frequency along x axis.

Figure 3.9 Schematic drawing of spring-mass structure with two outward type I S-springs

Table 3.2 Frequency and shape of modes of spring-mass structure with two outward type I S-spring-mass structure

Mode	Frequency (Hz)	Characteristic
1	65	Vibration along x axis
2	171	Vibration along z axis
3	223.4	Vibration along y axis
4	183.8	Rotation around x axis
5	376.57	Rotation around y axis
6	323.3	Rotation around z axis

Figure 3.10 shows the schematic drawing of outward type II S-spring-mass structure in the mode analysis, with similar dimension with outward type I S-spring-mass structure in Figure 3.9. Table 3.3 lists the frequency and the shape for each mode. The resonant frequency along x axis of outward type II S-spring-mass structure is similar to that of outward type I S-spring-mass structure, but the resonant frequencies along other two vibration axes are much larger than those of outward type I S-spring-mass structure. However, the frequency of rotation around y axis is smaller than and close to the x resonant vibration frequency due to the long length of mass and short total length of spring perpendicular to y axis. This will expose spring-mass to low-frequency parasitic rotation motion and hinder the energy harvesting of harmonic of vibration with frequency less than x resonant vibration frequency. By adding two more outward type II S-springs, total four springs in Figure 3.11, the rotation risk has been largely reduced due to significantly increased rotation frequency as manifested in Table 3.4.

Table 3.3 Frequency and shape of modes of spring-mass structure with two outward type II S-spring-mass structure

Mode	Frequency(Hz)	Characteristic
1	68.6	Vibration along x axis
2	292	Vibration along y axis
3	194.2	Vibration along z axis
4	47.16	Rotation around x axis
5	45.3	Rotation around y axis
6	141.6	Rotation around z axis

Figure 3.10 Schematic drawing of spring-mss structure with two outward type II S-springs

Figure 3.11 Model analysis of spring-mss structure with four outward type II S-springs

Table 3.4 Frequency and shape of modes of spring-mass structure with four outward type II S-spring-mass structure

Mode	Frequency(Hz)	Characteristic
1	98.4	Vibration along x axis
2	405.7	Vibration along y axis
3	273.7	Vibration along z axis
4	652.8	Rotation around x axis
5	398.6	Rotation around y axis
6	442.7	Rotation around z axis

3.2 Modelling and analysis of the electromechanical interface

(a)

(b)

Figure 3.12 (a) Overlapping length $l [x(t)]$ between a electrode cell and electret cells as a function of the mass relative displacement $x(t)$; (b) Schematic drawing of a variable capacitor composed of a electrode cell and a electret cell

When subjected to in-plane vibration in x axis, each electrode cell of length L_0 and width W_0 is made to move back and forth passing a line of fixed electret cells. Each electret cell is of the same size and geometry and separated by a distance of L_0 . $l(t)$ is the overlapping length between the electrode cell and one electret cell with respect to time. The relationship between the profile $l(t)$ and the mass relative displacement of $x(t)$ is shown in Figure 3.12(a). The starting position $x(t) = 0$, the equilibrium position for resonant system, is at the mass centre and that the alignment between the electrode cells and electret cells are 100 % overlapping.

From Figure 3.12(a), the profile of $l[x(t)]$ with period of T_0 ($T_0 = 2L_0$) is observed to exhibit a trace of triangle wave which can be expressed using an infinite Fourier series (please refer to Appendix D) as stated below:

$$l[x(t)] = \frac{L_0}{2} + \frac{4L_0}{\pi^2} \sum_{i=1}^{\infty} \frac{1}{(2i-1)^2} \cos\left[\frac{(2i-1)\pi}{L_0} x(t)\right] \quad 3-9$$

To derive the overlapping area, this can be evaluated based on

$$A[x(t)] = nl[x(t)]W_0 \quad 3-10$$

Where $A[x(t)]$ is the total overlapping area of N number of electrode cells and N number of electret cells. From Figure 3.12(b), the variable capacitance of power generator without considering any non-linearity in the electromechanical interface can be expressed as:

$$C_{var}[x(t)] = \frac{\varepsilon_0 W_0 A[x(t)]}{\frac{d}{\varepsilon_2} + \frac{g}{\varepsilon_1}} \quad 3-11$$

Where ε_2 is dielectric constant of the electret material, ε_1 dielectric constant of air, ε_0 vacuum permittivity, g the gap between the electret and the metal electrode cell, and d , the thickness of electret material. When electrode cells and electret cells are 100% overlapping, C_{var} is at its maximum C_{max} ; whereas when the electrode cells and electret cells are 0% overlapping, C_{var} is at the minimum C_{min} .

From Equation 3-11, for a given cycle period, a larger offset area would result in a higher capacitance with a bigger amount of charges. As $A(t)$ relies on the geometry of the electrode cell and the mass relative displacement, it is crucial that the value of L_0 should be as close to the expected mass relative displacement which is about $100\mu\text{m}$ in this work. The electrode and electret cells for micro electret power generator are designed in an array format with spacing between two cells, W_0 , along y axis as shown in Figure 3.13. In this work, W_0 is also assumed to be $100\mu\text{m}$. This is to take into account the possible area offset along y axis in the case that vibration is not operating in an uni-axial direction due to misalignment between the power generator and vibration source. For an area size of $0.8\text{cm} \times 0.8\text{cm}$, this would have an array of 3200 cells.

Figure 3.13 Schematic drawing of the offset between fixed electret array and movable electrode array

To facilitate a large capacitance change, thinner electret with high surface potential is desired as highlighted in Equation 3-11. However, given the same initial surface potential subject to the same charging conditions, it was noted that the charges in a thinner electret are not so stable compared to a thicker electret [145]. This is owing to the presence of a larger internal electric field in the thinner electret which assists in

accelerating the diffusion of charges in the material recombining them with the intrinsic carriers thereby resulting in faster charge decay. Therefore, in this chapter, the thickness of electret is confined to 50 μ m.

3.2.1 Effect of fringing field

The presence of fringing electric fields in micro electrostatic device can be considerable and affect the capacitance change $\Delta C(C_{max}-C_{min})$, as the electric field extends some distance away, as shown in Figure 3.14. Hence, such field effects must be accounted for in the analysis and design of power generator.

Figure 3.14 Capacitance variation in a parallel-plate electret capacitor considering fringing field effect

Commonly used finite element methods used to model capacitance that incorporate fringing field effect in their analysis tended to be two dimensional in which the length along vibration direction and the gap between two electrodes are investigated [146]. This method is only valid when the relationship between the width that is perpendicular to the length is infinite long. In practice, the dimension of the electrodes in micro power generator is finite. The fringing field effect at all the edges of variable capacitors can therefore be sizeable and need to be taken into account.

In this work, a three-dimension FE (finite element) model based on the 3DTrefftz method characterized by boundary elements in ANSYS is used to formulate and establish H-method solid123 (3-dimensional tetrahedral electrostatic solid) elements. The major steps of Trefftz modelling are outlined in Figure 3.15.

(a)

(b)

(c)

Figure 3.15 Major steps of modelling a 3D parallel-plate capacitor containing electrets by using Trefftz finite element method: (a) create solid model; (b) mesh volumes and create a finite element model; (c) generate Trefftz nodes and domain

Figure 3.16 Capacitance variation ratio ($\Delta C/C_{max}$) as a function of the width W_0 of capacitor containing electret 50μm thick when two gaps ($g=20\mu\text{m}$, $g=50\mu\text{m}$) are assumed and L_0 is fixed at 100μm

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Figure 3.16 shows the capacitance variation ratio ($\Delta C/C_{max}$) as a function of the width of a capacitor for gaps of 20 μm and 50 μm . The electret is assumed to be 50 μm thick. Both capacitance variation ratios decrease as the width decreases. However, by neglecting the dimension of width, the relationships between capacitance variation ratio and dimensions exhibit a gross overestimation of the capacitance variation between the two electrodes in a two-dimension model. As the power conversion is intrinsically associated with the capacitance variation ratio when the upper electrode moves, assuming the width is infinite long would also mean that the output current would also be overestimated. With the use of Trefftz FEM method, it is better able to consider the fringing effects at all its edges.

3.2.2 Effect of out-of-plane pull-in

To derive optimal output from the electret power generator, the gap between electret and counter electrode cell should be kept to a minimum possible. The surface potential V_s on the electret should however be made as large as possible to obtain large amount of induced charges. This aspect is however challenged as in actual application, the spring-mass structure bears out a large out-of-plane vertical electrostatic force $F_e(z)$ between the electret and the counter electrodes owing to the large surface potential between the small gap, as shown in Figure 3.17. When a gap g_0 is fixed in the power generator, if V_s exceeds the so-called pull-in surface potential V_{s-pull} , at a certain point z_0 , the vertical electrostatic force would be able to overcome the vertical spring force and pull the mass plate downwards to the bottom substrate plate leading to “electrostatic sticking”. This unstable point and associated V_{s-pull} needs to be accurately predicted to facilitate the optimal design of the power generator. At fully overlapping, the vertical electrostatic force is at its maximum, and the set of pull-in parameters should be determined at this position.

Figure 3.17 Vertical displacement of mass caused by vertical electrostatic force $F_e(z)$

Adopting the potential energy method for pull-in analysis, the total potential energy in the capacitive configuration is given as:

$$U = -\frac{1}{2}C_{\max}(g_0 - z)V_s^2 + \frac{1}{2}k_z z^2 \quad 3-12$$

The vertical electrostatic force acting on the movable mass plate is obtained by deriving Equation 3-12:

$$F_e(z) = -\frac{\partial U}{\partial z} = \frac{1}{2} \frac{\partial C_{\max}(g_0 - z)}{\partial z} V_s^2 - k_z z \quad 3-13$$

At equilibrium, the electrostatic force and spring force would cancel each other out. If the initial gap is known, the unstable pull-in position z_0 of mass can be obtained by solving simultaneous equations:

$$\begin{aligned} F_e(z) &= 0 \\ \partial F_e(z) / \partial z &= 0 \end{aligned} \quad 3-14$$

In order to solve the above simultaneous equations, the capacitance variation $C_{\max}(g_0 - z)$ needs to be expressed first.

For the model with no fringing field, $C_{\max}$ would be

$$C_{\max} = \frac{\epsilon_0 n W_0 L_0}{\left(\frac{g_0}{\epsilon_1} + \frac{d}{\epsilon_2} \right)} \quad 3-15$$

The pull-in position z_0 , the unstable point, where electrostatic sticking occurs can be derived as (see Appendix E for detail derivation)

$$z_0 = \frac{\frac{\varepsilon_1}{\varepsilon_2} d + g_0}{3} \quad 3-16$$

Substituting z_0 into $F_e(z)=0$ in Equation 3-14 gives the pull-in surface potential:

$$V_{s-pull} = \sqrt{\frac{\frac{8}{27} \left(g_0 + \frac{\varepsilon_1}{\varepsilon_2} d \right) k_z}{\varepsilon_0 \varepsilon_1 A_0}} \quad 3-17$$

Where A_0 is the full overlapping area.

Taking the fringing field effect as discussed in section 3.2.1 into consideration, a numerical model is established that involves evaluating the capacitance at discrete positions computed based on the Trefftz method in ANSYS. From the set of discrete positions, a relationship between the capacitance and vertical displacement can be closely approximated based on LAB FIT, a curve fitting software.

Figure 3.18 Curve fitting of the maximum capacitance of power generator ($W_0=L_0=100\mu m$, $g=50\mu m$, and $d=50\mu m$) versus gap (g_0-z) during the vertical displacement (z) of mass

When W_0 and L_0 are set as $100\mu m$ and d is set as $50\mu m$, the capacitance of power generator as a function of the gap, g_0-z , between electrode cells and electret cells can

be numerically computed as found in Figure 3.18. The constructed function has the following relationship with a correlation coefficient value equals to nearly 1, indicating a good fit.

$$C_{\max}(g_0 - z) = \frac{1}{A + B(g_0 - z) + \frac{C}{(g_0 - z)}} + D \quad 3-18$$

Hence, capacitance formula in Equation 3-18 is used to numerically compute z_0 in MATLAB. Table 3.5 compares the pull-in position in situations with fringing field and without fringing field. The results in the table reveal that for a fixed g_0 , the existence of fringing field causes the pull-in to occur at narrower gap, $g_0 - z_0$.

Table 3.5 Comparison of pull- in position in situations with fringing field and without fringing field

Initial gap $g_0(\mu\text{m})$	Unstable point $z_0(\mu\text{m})$	
	With fringing field	Without fringing field
50	26	24.2
100	46	40.9
150	66	57.6

After applying z_0 in $F_e(z)=0$, the relationship between the vertical spring constant k_z and pull-in surface potential V_{s-pull} over a fixed initial gap g_0 as shown in Figure 3.19 in which the two situations with and without fringing field effect are compared at different g_0 (50 μm , 100 μm and 150 μm). From Figure 3.19, for a fixed k_z value, the V_{s-pull} which represents the maximum surface potential that can be applied in micro power generator to prevent electrostatic sticking is found to be lower when taking fringing field effect into consideration in all the g_0 . Since most of micro electret power generators are operating with gap in the range of 50-100 μm , neglecting the fringing field effect would lead to overestimation of the maximum power generation. For

instance, if k is 100N/m and gap is 100 μm and V_{s-pull} is considered the maximum surface potential, the maximum current output will be estimated 12.5% higher in the condition without considering fringing field effect. This leads to the overestimation of power output by 26.5%.

Figure 3.19 Pull-in surface potential versus vertical spring constant k_z in two situations with and without fringing field effect. Three different initial gaps, 50 μm , 100 μm and 150 μm are considered

3.2.3 Effect of in-plane overlapping

The electromechanical coupling horizontal electrostatic force $F_e(x)$ induced in a variable capacitor can be expressed as follows:

$$F_e(x) = \frac{1}{2} V_s^2 \frac{\partial C_{\text{var}}(x)}{\partial x} \quad 3-19$$

The nonlinear characteristic of electromechanical interface due to the fringing field effect makes it very difficult to analytically derive $C_{\text{var}}(x)$. Therefore, numerical computation of capacitance at discrete position and curving fitting would be applied to construct the function.

$$C_{\text{var}}(x) = \left(1 / (A + Bx^2)^C \right) + D \quad 3-20$$

To illustrate, Figure 3.20 shows the curve relationship between capacitance change and mass relative displacement x for the power generator with $W_0=L_0=100\mu\text{m}$, $g=50\mu\text{m}$, and $d=50\mu\text{m}$. It has a correlation coefficient value, r^2 equals 0.9997.

Figure 3.20 Curve fitting of capacitance change against mass relative displacement x in power generation ($W_0=L_0=100\mu\text{m}$, $g=50\mu\text{m}$, and $d=50\mu\text{m}$)

Consequently, the horizontal electrostatic force between overlapping electret cells and electrode cells can be derived as follows:

$$F_{e0}(x) = \frac{-BCV_s^2 x}{(A+Bx^2)^{C+1}} \quad 3-21$$

Figure 3.21 The diagram of variable capacitances of a movable electrode cell and electret cells

During motion, as the electrode cells move back and forth, this gives rise to a set of variable capacitors $C_{var}(x+L_0)$ and $C_{var}(x-L_0)$ with the electret cells in the near region.

The superimposed electrostatic force on the mass would therefore be:

$$F_e(x) = F_{e0}(x) + F_{e0}(x-L_0) + F_{e0}(x+L_0) \quad 3-22$$

The horizontal electrostatic force on the mass versus the mass relative displacement in power generator with $W_0=L_0=100\mu\text{m}$ and $d=50\mu\text{m}$, but of varying gaps are depicted in Figure 3.22(a). The basic model without fringing field can be found in Figure 3.22(b). For the basic model without fringing field, the horizontal electrostatic force (combining Equations 3-9 and 3-10, 3-11 and 3-19) can be derived as follows:

$$F_e(x) = -\frac{2}{\pi} n V_s^2 \frac{\epsilon_0 W_0}{\frac{d}{\epsilon_2} + \frac{g}{\epsilon_1}} \sum_{i=1}^{\infty} \frac{1}{2i-1} \sin \frac{(2i-1)\pi}{L_0} x \quad 3-23$$

Figure 3.22 The horizontal electrostatic force imposed on the mass with respect to the relative displacement of mass of power generator ($W_0=L_0=100\mu\text{m}$, $d=50\mu\text{m}$ and g varies) the surface potential is 500V (a) with fringing field effect; (b) without fringing field effect;

From the simulated results, it can be seen that when the inherent fringing field effect in the micro power generator is considered, the magnitude of the horizontal electrostatic force is observed to be smaller than the one without fringing field effect. Under such conditions, the electrostatic force acts locally either as a restoring or repulsive force during the relative motion of the mass. A restoring force is one that acts in the opposite direction of the relative displacement attempting to pull the mass back to the equilibrium position. The repulsive force, on the other hand, acts in the same direction to the relative displacement thus pulling the mass away from the equilibrium position. The local maximum magnitude of the two forces appears at period of $100\mu\text{m}$, equal to $T_0/2$, where $T_0=2L_0$. In other words, the phase difference is π . In Figure 3.22(a), it is also observed that the further the mass is pulled away from the equilibrium position, the bigger the magnitude of the restoring force is being generated. The horizontal electrostatic force generally presents a characteristic of restoring force to pull the mass back to the equilibrium position. This hinders the relative motion of mass which in turn affects the amount of energy that can be

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converted. This problem is further compounded when harvesting energy from low amplitude vibration where the driving force couldn't overcome the restoring force to move the mass. Therefore, appropriate method should be employed to tackle this problem.

3.3 Proposed Sandwich Structured Power Generators (SSPG)

To reduce the restoring characteristics of the horizontal electrostatic force on the mass while maintaining its electromechanical coupling in the capacitive configuration, a sandwich structure power generator is proposed, denoted by SSPG. This sandwich structured power generator has a three layered parallel plate configuration with a spring coupled to a mass having electrodes sandwiched in between the top and bottom plates of electrets. For the sandwich mass structure, it consists of two main configurations containing a capacitive configuration in each of them. This mass structure seeks to neutralise the electrostatic forces present in the capacitance configuration as highlighted in section 3.2.3 by one acting as the restorer and the other to repel having a phase difference of π . This is as shown in Figure 3.23. When the mass equilibrium position of Configuration I is at 0% overlapping between electrode and electret cells, the mass equilibrium for Configuration II would be at the 100% overlap position between the electrode and electret cells. The periods of overlapping length for the two configurations would be both at $T_0=2L_0$.

Figure 3.23 Sandwich structured power generator consists of two configurations 180° out-of-phase

For the sandwich structured power generator, although the two configurations share the same mass plate, each configuration has its own individual current output port. The outputs from the two configurations can be connected either in parallel or series to provide power for the outer circuit. In the ensuing section, an investigation would be made to one of the configurations in sandwich structure power generator, as the other configuration would theoretically produce similar output with the same capacitive parameters, as listed in Table 3.6.

The framework of a theoretical model formulation to determine current output from one configuration is presented in Figure 3.24. The framework consists of two main steps; one is the dynamic analysis of mass relative motion; the other is for determination of current generation.

Figure 3.24 Block diagram of modelling flow of current generation

To derive $F_{eII}(x)$ in Configuration II, the newly established modelling steps which take into consideration the fringing field effect of capacitance change in section 3.2.3 would be used. The capacitive parameters in Configuration I are set to be the same as those in Configuration II. Because the electrode arrangement in Configuration I has phase different of π , as illustrated in Figure 3.23. The electrostatic force equation between the two configurations would therefore be:

$$F_{eI}(x) = F_{eII}\left(x + \frac{T_0}{2}\right) \quad 3-24$$

The superimposed electrostatic force on mass would be:

$$F_e(x) = F_{eI}(x) + F_{eII}(x) \quad 3-25$$

F_m , the mechanical damping force induced in the structure during motion, is modelled as a viscous damping force that is linearly related to the velocity of mass, $c_m \partial x(t) / \partial t$, where c_m is the mechanical damping coefficient. The spring-mass structure is not

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expected to exhibit any parasitic motion. On viscous film damping, the mechanical energy loss would also take into account the sliding film damping resulting from two parallel plates that are in relative tangential motion as well as the squeezing film damping due to viscous loss associated with squeezing the air out from between moving surfaces. Viscous damping coefficient, c_m , based on the parallel-plate model [147], can be derived from Equation 3-26 where the first expression represents the sliding damping owing to the relative motion of the mass with the bottom substrate plate and the second expression representing the squeeze film damping arising in the gap between beams of the spring:

$$c_m = \frac{2\mu S}{g} + N_b \frac{3\mu s^2}{2\pi s_b^3} \quad 3-26$$

Where μ is the gas's viscosity (1.8×10^{-5} kg/m·s for air at 20°C), s is the lateral area of squeezing gaps and N_b is the number of squeezing gaps.

After substituting the above forces into Equation 3-2, numerical solutions of displacement and velocity to the ordinary differential equation are obtained in the dynamic analysis. Upon determining the velocity and displacement, these values along with the earlier formulations developed to derive the surface potential and capacitance variation based on the fringing field effect are then used to determine the amount of current required.

The power generator makes use of two outward type I S-springs which gives a stiffness of k_x at 5N/m and k_z at 150N/m. The resonant frequency, f_r is at 40Hz based on spring modelling performed as highlighted in Figure 3.7 and 3.9. Employing Equation 3-26, the corresponding c_m is calculated to be 1×10^{-4} Ns/m. Referring to the pull-in analysis discussed in Figure 3.19, the pull-in surface potential is evaluated to

be 240V having a gap of 50 μm . Taking fringing field effect into consideration, the corresponding surface potential V_s would be at 200V for the two configuration layout.

Table 3.6 Parameters for modelling of power generator with two configurations in sandwich structured power generator

Parameters(assumed)	Symbol	Value
Resonant frequency	f_r	40
mass	m	0.08g
Gap	$g_I=g_{II}$	50 μm
Thickness of electrets	$d_I=d_{II}$	50 μm
Length of plate	L_0	100 μm
Width of plate	W_0	100 μm
Dielectric constant of air	ϵ_1	1
Dielectric constant of electret	ϵ_2	2.2
The surface potential on electret	$V_{SI}=V_{SII}$	200 V

Figure 3.25 Simulated electrostatic forces, F_{eI} and F_{eII} in configurations and net electrostatic force, F_e on mass

Figure 3.25 shows the electrostatic forces of Configuration I and II along with the net electrostatic force acting on the mass. F_{eI} and F_{eII} are forces acting in the opposite

direction of each other owing to the phase difference of π . It is observed that after the superimposition of these two forces, the net electrostatic force F_e on mass is found not to be at zero or cancelled out each other. Instead, the net electrostatic force has a residual magnitude that is smaller than F_{eI} and F_{eII} . This indicates that the non-linear fringing field effect does affect the cancel-out effect between F_{eI} and F_{eII} .

Figure 3.26 (a) shows the modelled results of the relative velocity of mass in SSPG and a commonly adopted two plate power generator with a single configuration. The magnitude of relative velocity of the mass for the sandwich structured arrangement is significantly higher than the two plate one. This is owing to cancelling out effect that significantly reduces the magnitude of electrostatic forces imposed on mass. Figure 3.26 (b) also compares the modelled amplitude of relative velocity of mass in SSPG with and without considering fringing field effect. Without considering fringing field effect, the modelled velocity results will lead to overestimation of the performance of power generator by up to 10 times.

Figure 3.26 Simulated amplitude of relative velocity of mass as a function of acceleration

By substituting the results obtained from dynamic analysis into current output function, its corresponding output value can be computed. Figure 3.27 compares the maximum current extracted from current output in one configuration for a sandwich structured power generator and that of a two-plate power generator. In a single configuration, sandwich structured power generator has the potential to provide more current output than conventional two-plate power generator particularly at higher acceleration values.

Figure 3.27 Comparison of simulated maximum current output from configuration in sandwich structured power generator and from conventional two-plate power generator

3.4 Conclusions

Modelling and characterization of micro electret power generators for harvesting low frequency and small acceleration were discussed in this chapter. Three different S-spring design configurations with folded beams were examined. Finite element analysis performed on the spring configuration reveals that to design for a low resonant frequency of less than 100Hz, the length of the long beam in a S-spring structure with five turns should be designed between 3000μm and 5000μm having a beam width of less than 80 μm. Both outward type I and outward type II S-spring configurations could provide spring stiffness constant ratios (k_y/k_x and k_z/k_x) larger than 4. Such ratios are adequate to differentiate the resonant frequencies between the principal axis and the other two directions as well as minimising parasitic motion along its axis. It was also found that two outward type I S-spring mounted along the center line of mass plate could reduce the rotating parasitic motion by having in-plane principal vibration frequency of less than 100 Hz as well as a rotation frequency more than 200Hz. With relatively larger spring constant ratios to filter out parasitic motion,

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outward type II S-springs would be more suitable for harvesting the harmonic component with much smaller amplitude than the fundamental component of vibration.

A new model formulation making use of three-dimension finite element model incorporating fringing field effect at all edges of micro capacitors is established. Through the model analysis, the fringing field was found to have a pronounced effect on the electromechanical interface of power generator by reducing the capacitance change, reducing the pull-in surface potential, and reducing the electromechanical coupling horizontal electrostatic force.

To reduce the horizontal electrostatic force restoring characteristic which hinders the motion of mass while maintaining its electromechanical coupling in capacitive configuration, sandwich structured power generators with two capacitive configurations having phase difference of π are proposed. By reducing horizontal electrostatic force by twice, the current output has been increased more than twice.

Chapter 4 Study and characterization of micro sized electret array

The design of electret cell array in micro size has been found to offer large offset area which facilitates large capacitance change when power generator with parallel-plate configuration is driven by low frequency and small acceleration amplitude vibration energy. This chapter presents a proposed method to form micro sized electret array via corona charging for power generators and address the challenges when producing high and stable surface potential on micro sized electrets.

4.1 Charge implantation by corona charging

Electret charge may consist of surface charges, space charges trapped in electret material and dipolar through polarization[148]. Figure 4.1 shows the schematic cross section of an electret having deposited surface charges, injected space charges, aligned dipolar charges and compensation charges as well. In the application of electret in power generator, surface and space charges, generating surface potential are exploited because they have a longer lifetime and larger electric dipole moment than that of dipoles through polarization[149], giving rise to larger electric field to be formed.

Figure 4.1 Schematic cross section of an electret, adapted from[148]

As micro sized electret areas are needed in the micro electret power generator to generate electrical power from motion in micro meters range, the selection of polymer material for the formation of electrets in power generator is limited to soluble fluoropolymer materials, as indicated in literature, such as CYTOP, PTFE, and Teflon AF. This is because they can be coated, patterned and etched using microfabrication processes and integrated into electret power generators [35]. Polymer material is first patterned into micro sized areas and then implanted with charges. However, experimental results have found that this has two main inherent limitations namely low charging efficiency during charge implantation and fast charge decay in the short period after charging. To better understand the mechanism of low charging efficiency and associated fast charge decay in micro sized electret, the electric field during is being modelled since it has direct relation with charge motion.

Figure 4.2(a) shows a corona charging system which an ANSYS model is based on. The charging voltage V_c applied on the grid is 600V. Two dimensional 8-node element of Plane 121 which depicts the cross section of dielectric material with length and thickness are used in the electrostatic simulation and meshed by a mapping scheme. The thickness d of the dielectric material is set at 50 μ m. Since the dielectric constant of polymer commonly used for power generator is around 2 (2.2 for parylene HT®, 2.1 for CYTOP, 1.9 for Teflon AF and 2.1 for PTFE) [41], the dielectric constant ϵ_2 is set as 2 in the modelling. The length L_0 of the material is allowed to vary with the gap between the grid and the surface material set at 200 μ m. Among the electric fields generated, E_c denotes the central surface electric field inside the material whereas E_f refers to the fringing field near the edges of the material as shown in Figure 4.2(a).

Two charging conditions are investigated with regards to the electric field near the surface of material. The first charging status is at the initial stage where the surface potential on electret, $V_s=0$. The central surface electric field is E_{c_0} , and the fringing field is E_{f_0} . In the second charging condition, small amount of charges are implanted into the shallow surface of the material. The surface potential is assumed only at $V_s=30\text{V}$, when the electric field inside the material is affected by the charging voltage V_c , the surface potential V_s , and the grounding of the sample. The central surface electric field and the fringing field change to $E_{c_{30}}$, and $E_{f_{30}}$, respectively. Figure 4.2(b) shows the electric field distribution in and out of electret material when its length is $100\mu\text{m}$.

Figure 4.2 (a)Corona charging parameters in modelling; (b) Modelling of the electric field in and out of electret material with $L_0=100\mu\text{m}$ in corona charging

The trend of the change of central surface electric field at a given length is denoted by percentage change of central surface electric field, ρ , represented by $(E_{c\_30}-E_{c\_0})/E_{c\_0}$. Negative ρ indicates a drop of central surface electric field, whereas positive ρ indicates an increase of central surface electric field. From the Figure 4.2(b), it can be observed when L_0 is greater than 400 μm , ρ has a positive value. This indicates an increase in the central surface electric field owing to the accumulated charges. If L_0 is reduced to a size that is less than 400 μm , it was found that ρ registers a negative value, and the central surface electric field inside the material recorded a drop owing to charge accumulation on the surface. This charge accumulation on the surface increases the electric field gradient across material, ΔE . The field gradient can be determined by $\Delta E = E_f - E_c$, a difference between the central surface electric field inside the material and the fringing field near the edges of the material.

Figure 4.3 The trend change of central surface electric field in electret material during charging as a function of the length of dielectric material

Figure 4.4 shows the relationship between the electret field gradient, ΔE , and the length of electret. The electric field gradient was observed to decrease with the length of micro sized electret in both material conditions; uncharged and slightly charged. Smaller electric field gradient is desired during charging, as large electric field

gradient generates fringing field that is stronger than central electric field. This limits the charge implantation as the stronger fringing field would either divert the majority of the incoming charges to the material edges or to the surrounding air. This restricts the charges from penetrating deeply into the depth of the material. This therefore accounts for the low charging efficiency when charging of micro sized dielectric material of 100 μm or less. In addition, the close proximity of the charges at the edges to the surrounding air in smaller sized material would cause neutralization with the atmospheric ions, leading to charge leakage from the material during storage

Figure 4.4 The electric field gradient in electret material during charging as a function of the length of dielectric material

From the above analysis, it can be seen that ρ and ΔE are size dependent. Macro sized (>1000 μm) dielectric material performs better than micro sized material (<100 μm) in capturing and holding charges in the charging process. The findings meant that to avoid charge decay it is appropriate that micro sized electret be formed on macro sized dielectric material. Figure 4.5 compares the field gradient in an isolated dielectric material pit with length of 100 μm and the field gradient in an isolated area with length of 100 μm on a dielectric thin film with length of 940 μm during charging. For the isolated pit, the fringing electric field is much larger than the central surface

field in the material, leading to digression of incoming charges and therefore low charge efficiency. However, in the case of localized charging, the fringing field is almost equal to the central surface field, resulting in a uniform charge injection on the surface.

Figure 4.5 Modelling of the electric field in an isolated dielectric material pit with length of $100 \mu\text{m}$ and the field gradient in an isolated area with length of $100 \mu\text{m}$ on a dielectric thin film with length of $940 \mu\text{m}$ during charging

4.2 Localized charging method

This section looks into a new method in charging of micro sized electrets with the view of producing high and stable surface potential on micro sized electret array for the application of micro electret power generator. The proposed approach is to locally charge micro sized areas onto macro sized material in the formation of electret.

4.2.1 Electret material consideration

Material selection for the formation of electret in power generator is a significant factor as the amount of charge density or surface potential on electret relates to the

power output that can be derived from the device. Two key parameters that affect the charge density are the density of the trap levels and dielectric strength of the material.

Figure 4.6 Energy band of dielectric material with trap levels, adapted from [150]

- Density of the trap levels.

Surface potential is generated through net charges implanted and trapped in the trap levels, as shown in Figure 4.6. Traps levels refer to local energy levels placed in a forbidden gap in the band model. The depth of trap level is the energy barrier needed to overcome the transfer of an electron from a trap level back to the conduction band or a hole back to valence band. This is expressed as eV.

In polymer materials, localized trap levels exist for three main reasons. The primary one being the impurities present in the polymers, such as catalyst molecules, monomers and oxygen vacancies. Another reason is owing to the structural defects in the monomer units. The trap levels appear mainly in the vicinity of the areas of irregularity of molecular chain conformation, i.e. in the vicinity of bending and chain ends. Finally, the imperfections of the crystalline order, especially those on the interfaces with amorphous areas give rise to trap levels. These amorphous areas act as traps where implanted charges are caught and remained there over a prolonged

period of time. A high density of trap level is one where they are significant number of traps per unit area. This material would have a high capacity to trap more charges thereby providing a higher charge density or surface potential. According to Table 4.1, LDPE (low density polyethylene) is found to have a significant high surface trap level density than other electret polymer materials. It is about five times that of polypropylene and twice that of polytetrafluoroethylene.

Table 4.1 Surface trap density of electron and hole traps in different polymer materials[151]

Polymers	Electron trap density $N_{et}(\times 10^{18} \text{ m}^{-3})$	Hole trap density $N_{ht}(\times 10^{18} \text{ m}^{-3})$
LDPE(Low density polyethylene)	1.2992	1.1900
PP(polypropylene)	0.3441	0.2262
PTFE(Polytetrafluoroethylene)	0.6797	0.5768

- Dielectric strength

Dielectric strength of the material is another important selection parameter as it relates to the amount of surface potential charge that a material can hold before breakdown occurs. A material with high dielectric strength E_m is one where high surface potential charge is achieved without electrical breakdown. If an electric field breakdown is to occur, the dielectric insulating material will become conductive and loses its capacity to store these charges. Another consideration is the dielectric constant. This relates to the concentration of electrostatic lines of the flux. A high-dielectric-constant material is suitable for manufacture of high-value capacitors with small physical volume. Table 4.2 lists the dielectric strength and dielectric constant of four different polymer materials used in the design and development of electret power generator. From Table 4.2, LDPE has the highest dielectric strength with a dielectric constant that is comparable with the others.

Table 4.2 Properties of polymer materials

Polymers	Dielectric strength E_m (MV/m)	Dielectric constant
CYTOP	110 [93]	2.1 [89]
PTFE	18 [93]	2.1 [89]
Teflon AF	21 [93]	1.9 [89]
LDPE	600-800 [152]	2.4 [153]

From the above findings, LDPE has the highest density traps and dielectric strength amongst the commonly used polymer electret materials. It is also readily available and more environmentally friendly, compared with soluble fluoropolymers (CYTOP, PTFE and Teflon AF) which emit toxic substances when heated up during production cycle[154]. Based on these factors, LDPE, in thin film form as purchased from Goodfellow Cambridge Limited, is chosen as the electret material for this project.

4.2.2 Localized corona charging system

For this project, charging is performed on the shadow masks used to form locally charged micro sized electret areas on macro sized LDPE thin film without introducing any chemical processing of the material. With the purpose of using SF₆ gas with high dielectric strength as insulation gas in electrostatic power generator, positive corona charging providing positive ions is employed to produce positively charged electrets in this work. This is because SF₆ has high electron affinity [155], and it will attract negative charges from negatively charged electrets and reduces surface potential on electrets.

Figure 4.7 shows the schematic configuration of the proposed locally positive corona charging system using shadow mask. The details of corona charging system set up in this work are presented in Appendix F. The LDPE thin films are sandwiched between a shadow mask (top) and a silicon substrate (bottom). Each gold electrode on the bottom silicon substrate is mapped to a shadow mask opening. A variable DC voltage supply is connected to a beryllium copper needle and shadow mask. For this project,

the DC voltage supply is set at 10 kV which is connected to the Beryllium copper needle of high electrical conductivity and low resistivity of $6\mu\Omega/\text{cm}$. During charging, the distance between the needle tip and the shadow mask is set at 5mm. The shadow mask is biased by a positive voltage, V_c , which is the charging voltage, equal to the targeted surface potential on electrets. The holes under openings have vertical sidewalls and are conductive. This is to facilitate positive ion movements that are generated from the needle as they arrive at the shadow mask and move through the holes in the mask. Owing to the repelling force caused by the positive voltage, these charges are accelerated and implanted into the thin film below the charging mask. The back side of the thin film is designed to be biased by a negative voltage V_e . This is to facilitate the charge movement inside thin film. The design of localized corona charging system will be analysed in the following subsections.

Figure 4.7 Localized positive corona charging using shadow mask

4.2.2.1 Shadow mask consideration

For localised charging, the shadow mask will be made of silicon. This is for the shadow mask formed from silicon wafers can be micro machined to a good degree of accuracy as it is rigid and flat. The silicon shadow mask composes of an array of etched micro sized through-holes etched using MEMS technology. To ensure that charges are implanted into the targeted micro sized areas on the thin film, the

thickness of silicon shadow mask is kept thin and yet has adequate strength to deal with handling and fragility problems. In this project, 200 μm thick silicon wafers are used to fabricate the shadow mask. The process flow for the fabrication of the shadow mask is shown in Figure 4.8

Figure 4.8 Fabrication process of silicon shadow mask

The silicon wafer is first prepared with a vapour priming of HMDS (Hexamethyldisilazane) coating process. This is to improve the photoresist adhesion (Figure 4.8(a)). After that, a 10 μm thick AZ9260 photoresist is spun onto the substrate and cured for 4 minutes at 90 $^{\circ}\text{C}$ (Figure 4.8 (b)). Photolithography is performed on the silicon wafer to form patterns of openings in it (Figure 4.8 (c)). The patterned photo-resist on the wafer works as a mask subject to the DRIE etching process (Figure 4.8(d)) forming through-holes in the silicon wafer of 100 μm width with 200 μm etching depth.

After the DRIE process, the photoresist is removed by Acetone. A sputtering process is then applied to deposit a metallic layer on the surface of mask facing the needle and sidewalls of through-holes (Figure 4.8(e)). Compared with the evaporation process, sputtering is preferred as it has a better step coverage of 20~50% (the ratio of film thickness on sidewall of to film thickness on the top horizontal surface), faster deposition rate, better uniformity, and better adhesion to the substrate [156]. A 20 nm thick Cr layer is first deposited by sputtering to form an adhesive layer, followed by an Au (300 nm) thin layer. The set of process parameters is listed in Table 4.3.

Table 4.3 Process parameters for sputtering

Parameters	
Sputtered material	Cr - 25nm/Au - 300nm
DC power	200W
Process pressure	3mTorr
Process gas	Argon (20 ppm)
Sputtering temperature	Room temperature

Figure 4.9 (a) SEM images of top view of square holes; (b) Cross section of micro sized square holes sputtered with gold in shadow mask with thickness of 200 μm

Figure 4.9 shows the SEM images of the cross section of different size square holes for a 200μm thick shadow mask after sputtering. When the hole opening is 114.84μm

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$\times 114.8\mu\text{m}$ in size for forming $100\mu\text{m} \times 100\mu\text{m}$ electret array, the metallic layer is shown to cover all the areas of the side wall. The deposited metallic layer is the brighter areas found in some parts of the hole structure in the SEM images.

4.2.2.2 Voltage-biased charging configuration

Another feature of the localized charging system is the voltage-biased charging configuration designed to facilitate charge trapping in the targeted charging areas of the material. After charges are injected into the material, it was observed that the charges are either captured or subsequently released from traps. This charge motion, μ , is dependent on the electric field which can be computed as follows:

$$\mu = \mu_0 (E(x,t) / E_0)^n \quad 4-1$$

Where μ_0 is the free charge mobility in the field E_0 at the surface and $t=0$, n a positive exponent and $E(x,t)$ the field strength at depth x in the bulk of material and time t . According to Equation 4-1, theoretically, charges move fast inside the bulk of material due to the strong electric field. With a fixed charging voltage, the electric field inside the electret material can be adjusted by changing the bias voltage V_e at the backside of electret material. The influence of an electric field on the electret property will be examined alongside that of a globally charged macro sized electret, as surface potential used to derive electric field can be directly measured from the surface of electret. The shadow mask has been substituted by steel grid to conduct the global charging.

The repeatability of corona charging system is examined by charging two test samples sets at charging voltage $V_c=1000\text{V}$ and $V_e=0$. Each test sample of $1\text{cm} \times 1\text{cm} \times 15\mu\text{m}$ is charged for 10 minutes and observed for surface potential decay over a 30 minutes period. The samples are stored in an environment with a constant temperature of $25^\circ\text{C} \pm 2^\circ\text{C}$ and a humidity of 48%-51% Rh. The surface potential is measured using a

noncontact electrostatic voltmeter (Model 542, Trek). The test results are then recorded and repeated for another four times. Figure 4.10 (b) showed the results of the surface potential decay plots for the two sets of test samples with thickness of 15 μm . Both plots show a decaying trend in its surface charge potential with minimal variation. Good reproducibility of the surface charge potential can therefore be achieved.

Figure 4.10 Observation of surface potential decay of five samples charged under same condition

Figure 4.11. Schematic diagram of positively charging double-layer.

The charge space storage in the bulk of electret material after charging determines the charge density and surface potential. As it is difficult to do space characterization of single layer electret, double-layer LDPE thin films have been utilized to examine the charge penetration caused by charge motion, as shown in Figure 4.11. The whole

double-layer sample is to be charged. After the charging, the top layer will be peeled off and the surface potential on the bottom layer is measured. During the charging, the electric field E_d across the double-layer sample can be computed as follows (Appendix G):

$$E_d = \frac{V_g - V_e}{d + \frac{\epsilon_2}{\epsilon_1} g_1} \quad 4-2$$

Where g_1 is gap between electret material surface and the grid with charging voltage, setting at 1mm. In experiments, each sample is a double-layer with thickness d of 65 μm , composed of: a piece of LDPE film with thickness d_1 of 50 μm , and LDPE film with thickness d_2 of 15 μm in Figure 4.11. A charging voltage $V_c = 2.5 \text{ kV}$ is used and varied $V_e(0 \sim -4.5\text{kV})$ applied on the backside of the LDPE double-layer. The charging duration is 1 minute.

Figure 4.12 Surface potential on the bottom layer of a doubly-layer LDPE thin film as a function of charging electric field E_d

Fig. 4.12 highlights the relationship between V_{15} and E_d based on four samples for each E_d . It can be observed that V_{15} increases as E_d gets stronger and then stabilises at around 490V after E_d reaches 2.1 kV/ mm, where $V_e = -V_c$ was applied. A possible

reason for the increase of V_{15} with E_d is that as the charged electric field gets stronger because of the imposition of V_e , this facilitates the motion of charges and draws the charges deeper into the LDPE film. The charges are then able to reach trap levels at deeper locations resulting in a higher surface potential at the deeper bulk of the material.

Another experiment is to examine the effect of the larger electric field on the trap level occupation. Two charging voltages are used: 1kV and 2kV. Samples of $20\text{ mm} \times 20\text{mm} \times 15\mu\text{m}$ samples are charged for 30 minutes under different conditions (S1-S4). The initial surface potential V_0 of samples are then measured immediately after charging and presented in Table 4.4.

Table 4.4 Initial surface potential V_0 on samples charged under varied conditions

Charing conditions				
S1: $V_c=1\text{ kV}$, $V_e=0\text{ kV}$				
S2: $V_c=1\text{ kV}$, $V_e=-1\text{ kV}$				
S3: $V_c=2\text{ kV}$, $V_e=0\text{ kV}$				
S4: $V_c=2\text{ kV}$, $V_e=-2\text{ kV}$				
	S1	S2	S3	S4
V_0	630V	800V	1300V	1700V
V_0/V_c	0.63	0.8	0.65	0.85

In Table 4.4, it shows that charging conditions S3 and S4, applying $V_c=2\text{kV}$, result in higher surface potentials on sample than S1 and S2 ($V_c=1\text{kV}$), because of the higher charging voltage V_c . Sample (S2) and sample (S4) charged with a strengthened electric field have higher charging efficiency V_0/V_c than the other samples (S1 and S3). The initial charge stability of the various samples is plotted in Figure 4.13. To facilitate easy comparison, the surface potential has been normalized against the initial value of each of the samples and is expressed as a ratio of r .

Figure 4.13 Normalized surface potential decay in the first 600s

A model based on isothermal relaxation current theory in reference [157] permits the direct determination of the trap distribution is used to study the distribution of trapped charges at different energy levels, which can be applied numerically in the initial charge decay stay. Because at constant temperature, the decreasing current $I_e(t)$ inside the electret caused by charge detrapping has the relation with the decay of surface potential: $I_e(t) = C dV_s(t)$, where C is the capacitance of electrets. The current density therefore is can be written as follows:

$$J = \frac{\varepsilon_0 \varepsilon_2}{d} \frac{\partial V_s(t)}{\partial t} \quad 4-3$$

The energy level, the density of the energy trapping levels and current density can be derived from the following [151]:

$$E_t = kT \ln(\eta) \quad 4-4$$

$$J = \frac{qdkT}{2t} f_0(E_t) N_t(E_t) \quad 4-5$$

Where E_t is the trap energy level, $N_t(E_t)$ the density of trap levels, $f_0(E_t)$ the initial occupancy of trapping levels, assuming as 1/2, q the electron charge, d the thickness

of sample, k the Boltzmann's constant, γ the attempt-to-escape frequency, usually of the order 10^{11} to 10^{12} sec^{-1} , is assumed as 10^{11} [157], T the temperature, and t the time.

Based on the measurement of surface potential in Figure 4.13, the density of trap levels can be plotted against the energy level based on the above three Equations 4-3, 4-4 and 4-5. Graphs in Figure 4.14(a) and (b) show that the distribution of trap density in samples operates over a range from 0.8eV to 0.9eV, where energy trap levels of LDPE are located [158]. By performing the integral of the density of trap energy level, the number of traps occupied by charges can be determined as listed in the column graph of Figure 4.14(c), in which S3 and S4 charged with 2kV have nearly twice as many trap levels occupied as S2 and S1 charged with 1kV. S2 and S4 charged with a larger charging electric field, are also found to trap more charges than S1 and sample S3, respectively which results in higher surface potential.

Figure 4.14: (a) Density of trapping energy level as a function of energy level of trap of different samples in samples charged under S1 and S2 conditions; (b) Density of trapping energy level as a function of energy level of trap of different samples charged under S3 and S4 conditions; (c) Number of occupied trap levels in different samples

4.3 Characterization of micro sized electret array

4.3.1 Surface potential on micro sized electret area

Surface potential is an important parameter for electret characterisation particularly for micro sized electret area. Commonly, non contact electrostatic voltmeter using probes are used to determine the surface potential of micro sized electret areas. The reading accuracies are however compromised owing to the spatial resolution of non-contact voltmeter technology. As such, smaller aperture size of probe provides finer spatial resolution. Currently, the minimum aperture size for probed based non contact surface potential measurement is 790 μ m from Trek, Inc, a world leading supplier of electrostatic measurement equipment (Appendix H). For a spot electret area of diameter 100 μ m, it would not be able to provide good characteristic measurement of the actual surface potential of the small electret area. This is for the surface potential reading recorded by the electrostatic voltmeter provides average values of the surface potential of the charged and uncharged area that the probe makes with. This means the measurement for a locally charged sample which is smaller than the probe size,

the value of surface potential registered in the voltmeter is the averaged value of surface potential on the charged area and on the uncharged area. It does not determine what the actual surface potential in the charged area is. The smaller the localised area, the greater the error would be.

Figure 4.15 Schematic of charge patterns on locally charged sample

To overcome this shortcoming, a novel approach is proposed that could more accurately to characterize the surface potential of micro sized electret area without making contact with the material. This proposed approach involves making use of the average surface potential measured and the dimension of micro-size local electret area having an evenly distributed array arrangement.

Figure 4.15 shows the charge patterns on samples locally charged. Area A denotes a unit area where the voltmeter averages the surface potentials on charged areas A_s and on non-charged areas.

The actual surface potential on a charged micro sized area A_s is [148]:

$$V_s = \frac{\sigma_s d}{\epsilon_0 \epsilon_2} \quad 4-6$$

Where σ_s is the surface charge density on the charged area A_s . The average potential value V_{as} of area A displayed on the voltmeter could be determined by σ_{as} the average surface density on unit area A using the following Equation

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$$V_{as} = \frac{\sigma_{as}d}{\epsilon_0\epsilon_2} \quad 4-7$$

σ_{as} is calculated by surface charge density σ_s on charged areas and charged area factor equivalent, named as *CAF* in this project, which is equal to the charged areas divided by the unit area.

$$\sigma_{as} = \sigma_s \times CAF \quad 4-8$$

Hence, the relation between surface potential on the locally charged micro sized charged area V_s and the registered average surface potential in voltmeter V_{as} on the whole piece of thin film is derived by substituting Equation 4-8 into Equation 4-7:

$$V_s = \frac{1}{CAF} V_{as} \quad 4-9$$

To verify this derived relationship, samples globally charged via applying charging voltage on grid are used as references. Compared with locally charged samples by using shadow mask, globally charged samples will have the whole surface areas exposed for charge implantation. If the same charging voltage is applied on samples with the same size, the surface potential measured on a globally charged sample is equal to the surface potential on the micro sized area on a locally charged sample owing to the similar charging implantation in exposed areas driven by the same charging voltage. The verification of Equation 4-10 is carried out by using voltmeter to measure V_s from the newly globally charged sample, and V_{as} from newly locally charged sample, and extract *CAF* from shadow mask design.

For the shadow mask of $A_s=100\mu\text{m}\times100\mu\text{m}$ and $A=260\mu\text{m}\times260\mu\text{m}$, *CAF*, equal to $A/2A_s$, is computed to be 3.38. Two sets of experiments are then conducted with the same charging voltages, $V_c = 2\text{kV}$ for both local and global charging. The surface potential V_{as} on samples locally charged is found to be at 580V. For the globalised

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samples, the non-contact probe from voltmeter gives a surface potential reading of 1880V. This is quite similar to the derived value 1960V by using the area factor, CAF and V_{as} formulation taking into account the measurement errors of the equipment and actual localised electret areas. The results highlight that the viability of CAF , to derive the actual local surface potential from the average surface potential for samples with evenly distributed micro sized charge patterns.

4.3.2 Mapping of surface charge distribution

Another important electret characteristic concerns the charge distribution and movement. Such measurements are not possible using the conventional approach by means of a voltmeter with probe. Only discrete point readings can be obtained. Besides, the probe could only perform 1D line scans on the charged surface. Any charge movement not on the scan line could not be detected and determined which thereby poses difficulty in characterizing the charge distribution in a 2D electret array.

A SEM (scanning electron microscope) is one of the commonly used metrology methods to image micro-machined parts for visualization of surface structure and finer details. In our experiment, it is used to map the charge distribution on the surface of LDPE electret. Secondary electrons which used to create image of surface are used to map the charge distribution on the surface of LDPE electret. The electron beam with energy in 0-50 keV range generated from the emitter in SEM radiates the sample surface, and secondary electrons are emitted, detected and counted in the detector, and used to create an image of the sample. Figure 4.16 shows the schematic diagram of electron beam in SEM radiating the locally positive-charged sample to map charge distribution

Figure 4.16 Schematic diagram of a scanning electron microscope(SEM) applied to map charge distribution on positively locally charged sample

Electret samples are devoid of sample preparation (e.g. metal coating) for the SEM imaging process. The existing charges in pre-charged sample will interact with the incident electrons and affect the produced secondary charges, and change the image. If the sample is negatively charged, incoming incident electrons with energy will activate trapped negative charges in sample and induce more secondary electrons. However, if the sample is positively charged, incoming incident electrons are partially neutralized on the charged electret area, and therefore the induced secondary electrons are diminished, this will increase the brightness on the generated image. Figure 4.17 presents the SEM images of $1\text{cm} \times 1\text{cm} \times 50\mu\text{m}$ LDPE samples either negatively (Figure 4.17 (a) and (b)) or positively charged (Figure 4.17 (c) and (d)) by a voltage of 900V, using different shadow masks.

Figure 4.17 SEM images of charge patterns (a) negatively charged array of $200\mu\text{m} \times 200\mu\text{m}$, $V_{acc} = 5\text{kV}$; (b) negatively charged array of $50\mu\text{m} \times 100\mu\text{m}$, $V_{acc} = 1\text{kV}$; (c) positively charged array of $200\mu\text{m} \times 200\mu\text{m}$, $V_{acc} = 5\text{kV}$; (d) positively charged array of $100\mu\text{m} \times 100\mu\text{m}$, $V_{acc} = 1\text{kV}$;

The images are taken immediately after charging. Acceleration voltage of $V_{acc} = 5\text{kV}$ is applied in the imaging process of samples of figures on the left side, while $V_{acc} = 1\text{kV}$ is applied in figures on the right side. In SEM imaging process, a bigger difference of the amount of secondary electrons induced from charged areas and non charged areas can create a higher contrast. It can be seen that SEM images taken under small acceleration voltage of $V_{acc} = 1\text{kV}$ (Figure 4.17(b) and (d)) have higher contrast between charged and non-charged area than images taken under relatively higher acceleration voltage $V_{acc} = 5\text{kV}$ (Figure 4.17(a) and (c)). Fast disappearance of patterns is also observed when $V_{acc} = 5\text{kV}$ is applied. This is because strong electron beam under high V_{acc} reduces the difference of amount of secondary electrons and makes it difficult to enhance the contrast of the fine boundary of charged and non charged

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areas, and the quick electron charge-up can easily destroy the original charge pattern on the sample. Moreover, we also found acceleration voltage lower than 0.5kV makes it difficult to capture image due to insufficient difference of secondary electrons. Therefore, for characterization of charge pattern on micro sized electret with surface potential around several hundred volts which is often applied in micro electret power generators, acceleration voltage approximately around 0.5~1kV is suggested. Moreover, SEM images of positively charged samples have clearer images than negatively charged samples. The possible reason could be that reducing the production of secondary electrons on charged areas can further increase the difference of the amount of secondary electrons induced from charged areas and non charged areas. It should be noted that the image must be taken right after the focus of electron beam. Because the focused area will get charged up by the incoming electron beam within a few minutes and becomes fully negative charged and charge patterns are destroyed. Figure 4.18 shows the SEM image of sample after focus is applied. The rectangular area was focused before and the charged patterns are destroyed.

Figure 4.18 SEM image of sample with charge patterns destroyed by the focus of electron beam

4.3.3 Charge stability on micro sized electret area

Surface potential measurement and mapping of charging distribution are combined to characterize charge stability on micro sized electret area. Samples with 1cmx1cm

x50 μm are charged by charging voltage 900V by using shadow mask with array of openings with size of 100 μm ×100 μm . The measured V_{as} right after charging is 250 V, and based on $CAF=3.38$ indicated by Figure 4.19. The derived V_s on area of 100 μm ×100 μm is 845 V. Charging efficiency of 94% (V_s/V_c) is achieved. After 20 days of storage, Figure 4.19(a) shows that the shape of the charge patterns remain intact but with a reduced length (95 μm). The surface potential on the charged areas drops to 800V, according to $V_{as}=210\text{V}$ for $CAF=3.8$. Figure 4.19 (b) shows the sample SEM image taken after 240 days. The charges remain concentrated in the locally charged areas but with a side length of 50 μm . The surface potential on the charged area is 730 V, computed by multiplying measured V_{as} of 60V and CAF of 12.1, representing 87% of its initial surface potential of 840 V.

Figure 4.19 SEM images of locally charged samples: (a) 20 days after charging; (b) 240 days after charging

Unlike charges in globally charged electrets where they migrate laterally due to the self-field [159], charges in locally charged samples are not found to have such movement. This could be owing to the distance separation in micro meters between the charged regions; and the electric field distributed within these charged regions prohibits charge migration and leakage at the surface. It is also found that charges retain more at the centre than at the edges of the locally charged areas. This could be

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explained by the fact that, during charging, moving charges in the centre of the through-holes of the shadow mask have higher acceleration energy than moving charges close to the through-holes' sidewall, which exerts a repelling force on charges and results in a loss of the acceleration energy of charges. Therefore, those charges close to the sidewall tend to reside at the shallow parts of the material surface. As such, they are more easily displaced, released and neutralized by atmospheric ions.

4.4 Optimal charging parameters

For high current output, thinner electret with high surface potential is desired, as indicated by Equation 3-8 and 3-26. The charge stability of thin electret with high surface potential is important as it affects reliability of a power generator. But electrets suffer from charge instability, because of two main factors namely the recombination of charges with ions in the air and the recombination of charges with intrinsic carriers of opposite polarity present in dielectric material [160, 161]. These above two processes take place simultaneously and the decay behavior is determined by the dominant one. With the same initial surface potential, the thinner electret has worse charge stability than the thicker electret charged under the same condition [162]. This is caused by a stronger internal electric field due to the smaller thickness. And the stronger internal electric field accelerates the diffusion of charges in the material to recombine with intrinsic carrier, resulting in faster charge decay. Charge stability study has been more focused on thick electrets ($>50\mu\text{m}$) for their piezoelectric characteristics resulted from polarization [163, 164]. The charge stability of thin electrets ($<30\mu\text{m}$) receive more attention nowadays because of their application in emerging electret power generator. Hence, in this section, charge stability of LDPE thin film with thickness of $15\mu\text{m}$ will be studied and methods to improve charge stability are investigated.

The highest surface potential V_{sm} can be obtained without electric breakdown of material is determined by the dielectric strength E_m of 200MV/m of purchased LDPE thin film and the thickness of 15um of thin film via $V_{sm}=E_md$. Therefore, high charging voltages in the range of kilo volts but less than 3kV are applied. Besides the thickness and charging voltage, the other two charging parameters, charging temperature (annealing) and charging time, can be varied to find the optimal charging parameters for the improvement on charge stability.

4.4.1 Charing duration

The influence of charging time on surface potential decay has received less attention over the years [165]. The majority study of charge decay on LDPE or PE(polyethylene) electrets has been applying charging duration up to minutes [166-168]. Longer charging duration and long-term charge decay observation are therefore presented in this section. Surface potential decay is observed on samples charged under conditions listed in Table 4.5.

Table 4.5 Charging conditions with varying charging duration

Parameters	
V_c	1.5kV
V_e	0
Sample size	20mm×20mm×15μm
Temperature	Room temperature(25°C)

Figure 4.20 Surface potential decay of samples charged by varied charging duration

Although the initial surface potential on all samples are similar, the surface potential after a decay of 85 hours for samples charged for more than 1 hour is found to be higher than others samples charged for less than 1 hour. The surface potential of sample charged by 2 hours is as twice as the surface potential on sample charged by 30 minutes. From charge penetration experiment carried out in Figure 4.12, it is observed that charges are able to inject into the bulk of material within 1 minute. Therefore, for all samples, charges not only occupy traps in shallow surface but also traps in the bulk of material. It is believed that charges in samples charged over longer duration have more charges being contained or captured in deeper trap levels. Such charges are less prone to neutralisation by the atmospheric or intrinsic material carriers. As 2 hours of charging duration gives the similar charge stability performance with the other two samples charged with longer time, 4 hours and 6 hours, 2 hours would be suggested as the optimal charging duration for LDPE thin film considering the operation effectiveness.

4.4.2 Annealing

Deep traps at crystalline amorphous interface play a major role in charge stability. It has been observed that charge stability of polymer can be greatly improved by annealing, as the increase of crystallinity caused by annealing creates interface between crystalline and amorphous areas and give rise to more deep traps [169]. Therefore, annealing has been commonly used as a method to stabilize charges in polymer material[170] [171, 172]. The change of crystallinity can be characterized by DSC (differential scanning calorimetry) method.

Samples are first annealed at different temperature for 2.5hour and then analyzed by DSC method. DSC measures the temperatures and heat flows associated with transitions in materials as a function of time and temperature in a controlled atmosphere. Through DSC, the degree of crystallinity of a polymer can be determined through analysis of its melting endotherm. As the crystalline portions of a polymer melt, the sample possesses latent heat of fusion as it changes phase from solid to liquid phase. The degree of crystallinity can be determined as such:

$$X_c = \frac{\Delta H_f}{\Delta H_f^0} \quad 4-10$$

Where ΔH_f is the enthalpy of fusion of the analyzed sample, and it is the heat energy required for melting or released upon crystallization. This is calculated by integrating the area of the DSC peak from T_1 (the onset temperature of melting) to T_2 (the end of melting), as shown in Figure 4.21; while ΔH_f^0 is the heat of fusion of 100% crystalline polyethylene which is 293J/g [173]. The average X_c obtained from non-annealed sample, sample annealed at 60°C, and sample annealed at 90°C is listed in Table 4.6. The temperature of the melting peaks is all at 113°C. It can be seen that the degree of crystallinity increase slightly with the increase of the annealing temperature

and annealing at 90°C has introduced approximately 1% of increase of crystallinity which indicates a slow recrystallization character in thin film LDPE.

Table 4.6 Degree of crystallinity of samples annealed at different temperature

Sample	Average X_c
Non-annealed	35.5%
Annealed at 60°C for 2.5 h	36%
Annealed at 90°C for 2.5h	36.4%

Figure 4.21 Overlaid DSC plot of samples annealed at different temperatures

Charge stability of samples annealed at different temperatures, from room temperature to 100 °C, lower than melting temperature, is characterized by the surface potential decay observed over 75 hours. All samples are charged under conditions in Table 4.7. From the plot in Figure 4.22, the final surface potential obtained from samples is quite similar because of similar charge storage capability resulted from close degree of crystallinity. Therefore, such as stretching polymer thin film to create new boundaries and defect traps will be considered in future [169, 174].

Table 4.7 Charging conditions with varying annealing temperatures

Parameters	
V_c	2.5kV
V_e	0
Sample size	20mm×20mm×15μm
Charging duration	20mininutes

Figure 4.22 Surface potential decay of samples charged by varied annealing temperature

4.5 Conclusion

This chapter has described the work on formation and characterization of micro sized electret array. Aided by modelling, fast charge decay and low charging efficiency in corona charging have been found to be caused by the size-dependent electric field gradient which generates fringing field that is stronger than central electric field in dielectric material. This limits the charge implantation as the stronger fringing field would either divert the majority of the incoming charges to the material edges or to the surrounding air. Therefore, localized charging method to form micro sized electret areas on macro sized dielectric material is proposed. Shadow mask was used to transfer charge patterns using the localized charging method and voltage-based charging configuration to facilitate charge transportation in the formation of 100μm×100μm electret array on 1cm×1cm electret material. The method was found able to reduce the electric field gradient in the material sample. A charging efficiency

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of 93% with 87% of its initial surface potential remained on the localized areas of $50\mu\text{m} \times 50\mu\text{m}$ after 240 days could be achieved.

For the characterization of micro sized electret array, SEM surface topography combined with non-contact measurement of average surface potential is employed for the first time to map the charge distribution on locally charged dielectric thin film and charge migration in long-term period and measure the surface potential on the micro sized area by incorporating the layout characteristic of electret array, denoted by *CAF* (charged area factor equivalent) is able to be observed by this technique. By combining this topography technique and non contact measurement of average surface potential on electrets, the surface potential on micro sized area in evenly distributed array can be measured indirectly.

In the investigation on two charging parameters, i.e. annealing temperature and charging duration, to enhance the charge stability in thinner LDPE, commonly used annealing method is found not to be critical to the optimal charging, and other methods such as stretching polymer thin film to create new boundaries and defect traps will be considered in future to create more deep traps. Longer charge duration of 2 hours which enables charges to be captured by deeper traps is suggested for thin film charging.

Two charging parameters namely charging duration and annealing temperature were investigated as to its effect on charge stability for very thin LDPE of $15\mu\text{m}$. It is observed that the surface potential decay becomes slower as the charging time increases and when the charging duration reaches a certain length, the performance of charge stability maintains at similar level. By prolonging the charging duration from minutes to hours, the stable surface potential could be increased twofold. Annealing LDPE thin film for around 2 hours results in 1% increase of crystallinity due to the

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slow recrystallization character of LDPE. And no significant improvement of charge stability has been observed from the annealed sample.

Chapter 5   Fabrication of micro electret power generators

5.1   Introduction

This chapter looks into the fabrication of a proposed three-plate Sandwich Structured Power Generator (SSPG) silicon based micro electret power generators using MEMS technology. This has necessitated the development of approaches to align the electrode patterns, plate assembly as well as precise fabrication of the spring-mass structure so as to minimise fabrication error and resonant frequency deviation. These aspects will be discussed in the ensuing sections.

5.2   Fabrication of power generator features

5.2.1   Fabrication design for electrode patterns

To fabricate the three plates of SSPG, two key aspects namely the alignment of the plate features during fabrication and aligning the features during plate assembly are to be examined. This is for the electrode patterns on each of the three plates are fabricated out individually. To facilitate maximum capacitance change, this would require maximum displacement overlap between the two sets of electrode configurations.

5.2.1.1   Electrode patterns alignment design

One approach is the overlay method that involves photomask design which requires the electrode pattern structures in each of the plates to overlay on top of each other forming two paired electrode configurations. This is highlighted in Figure 5.1 in which Configuration I highlights the electrode arrangements on the bottom substrate plate(B_electrode) and electrodes on the bottom side of the mass(M_B_electrode) as in Figure 5.1(a); and for Configuration II, electrodes on the top substrate plate

(T_electrode) and that of the electrodes on the top side of the mass (M_T_electrode) in Figure 5.1(b). In this work, the design size of an electrode cell is $100\mu\text{m}\times 100\mu\text{m}$ and the distance between the two electrode cells is $160\mu\text{m}$. It must be said that the M_B_electrode and T_electrode photomasks seek to be mirror patterns of each other, as highlighted in Table 5.1.

Figure 5.1 (a) the overlay of electrode patterns of M_B_electrode photomask and B_electrode photomask for Configuration I; (b) the overlay of electrode pattern of M_T_electrode photomask and T_electrode photomask for Configuration II

Table 5.1 Pattern appearance of electrode photomasks

Mask name	Pattern Appearance	
	Normal	Mirror
M_T_electrode	√	
M_B_electrode		√
T_electrode		√
B_electrode	√	

5.2.1.2 Feature alignment for plate assembly design

This section highlights the development of an accurate feature alignment method for plate assembly. Conventional wafer-bonding techniques, such as anodic bonding and silicon-direct bonding with semi-automation alignment process are considered not suitable for use in micro electret power generators as these processes tend to operate at temperatures that are more than hundreds of degrees. This results in charges from the locally charged electret being released by the high heat energy. Another approach relates to employing adhesive materials at room temperature [38, 91] [39] to stick the set of plates together. Some have attempted to make use of transparent glass plates with alignment patterns to assist in performing this task via visualization through a microscope during the manual assembly[38] . Another work [38] makes use of micro grooves that are created on the surfaces of silicon substrates in which micro ball bearings are used to assist in the alignment. Nevertheless, to achieve high and consistent alignment accuracy in μm for non-transparent silicon plates involving several layers or plates would be a challenge.

In this work, pins and alignment holes are used to align the three silicon plates. The approach is to incorporate micron size alignment holes at designated locations on all the three plates for assembly. This is done during the silicon micromachining of the plates which can produce high dimensional accuracy to facilitate the integration. The alignment process will also be assisted by using an alignment fixture which would be discussed later in this chapter. Figure 5.2 illustrates a set of alignment holes that has been designed on the shadow mask for etching the plate arrangement of the bottom substrate plate, top substrate plate and middle plate containing the spring-mass structure. These alignment holes of diameters $295\mu\text{m}$ (or slightly larger to cater for manufacturing tolerance) are to be fabricated and located on the edge of substrate

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plates and on the frame of the middle plates. After the holes are fabricated, alignment pins of diameter $295\mu\text{m}$ are then used to assemble the set of plates.

(a)

(b)

(c)

Figure 5.2 Alignment holes designed on (a) Bottom substrate plate; (b) Top substrate plate; (c) Middle plate containing spring-mass structure. Dark areas correspond to parts that will be removed from silicon wafer in etching process

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5.2.2 Fabrication design for spring-mass structure

Another fabrication consideration relates to the silicon manufacturing of small springs with a large mass structure for the proposed power generator device. For the spring-mass structure design, the effect of the isotropic etching is significant because the resonant frequency highly relies on the geometries of spring-mass structure. Local heat accumulation will result in isotropic etching, leading to deviated structural geometries, and a low fabrication yield owing to over etching [175]. To achieve low resonant frequency, a large mass with a small narrow spring is desired. This however gives rise to local heat accumulation with a rapid rise in temperature experienced on the narrow spring. This is highlighted in Fujii's work [131] where the fabrication error can be -40% (at the bottom) to -20% (at the top) for the spring width designed at a resonant frequency of 71Hz. Attempts are therefore made in this section to increase fabrication yield and reduce fabrication error.

To fabricate the spring structure as in Figure 5.3, the DRIE process is carried out using the Surface Technology System (STS) multiplex inductively coupled plasma (ICP) system which normally operates at ambient temperature. In this system, the oscillating RF powered electric field would ionize the gas molecules by stripping them of electrons by means of a plasma. Heat energy is usually generated in the DRIE process which could be caused by ion bombardment, exothermic reactions and eddy currents [176]. In the STS-ICP etch system, helium gas is to be applied at the back side of wafer for cooling as well as to maintain its temperature at 20°C or less, as illustrated in Figure 5.3.

Figure 5.3 The schematic drawing of STS-ICP etch system [177]

Figure 5.4 Mechanism of Deep Ion Reactive Etching [178]

The mechanism of DRIE is shown in Figure 5.4. The etching proceeds in a SF_6 plasma for etching the silicon whereas a C_4F_8 plasma is used to create the passivation polymer layer protecting the entire substrate from further etching.

During the passivation cycle:

Oxygen plasma is then used to enhance the etching properties of the plasma. The ionized O_2 creates the O^* radicals which also forms a passivation layer (SiO_xF_y). During the etching process, the polymer at the bottom of the trench is rapidly removed but those on the sidewalls would remain, protecting the silicon from the SF_6

narrow spring structure needs to be dissipated to the frame and mass block to avoid heat build-up. As in Figure 5.6(c), the connection between the frame and mass block is however broken due to the fast etch rate in those wide trenches. Consequently, the heat accumulates in spring beams and the rise of local temperature destroys the protecting passivation polymer layer on the sidewall of trenches and lead to isotropic etching. The thermal impact is aggravated with the use of a carrier wafer. It was found that stacking two pieces of silicon wafers together using adhesive bonding layer will further increase the wafer temperature as the heat dissipation paths are being blocked thereby affecting the etching process.

Figure 5.6 Schematic illustration of the etching of spring-mass structure influenced by RIE lag and of the heat flow path in the etching process

To overcome present shortcomings, the approach undertaken in this work is to incorporate adequate heat blocks to the fabrication of plates containing the spring-mass structure as well as the wide trenches around spring-mass structures. This is to facilitate heat dissipation around microstructures during the DRIE process. To manage the heat accumulated on springs, a heat management model based on the equivalent thermal circuit formulation has been developed to analyse the heat flow mechanism in DRIE process. In the circuit model, thermal resistances are represented by resistors in which a large resistance indicates that the heat dissipates and flows slowly. Figure 5.7 presents the schematic diagram of the equivalent thermal circuit that highlights the heat flow in a die from a single spring to its surrounding structures and ambient environment during etching.

Figure 5.7 Equivalent thermal circuit of heat flow in a die during DRIE etching

In this analysis, heat flow is represented by a combination of thermal conduction across different structural material and thermal convection at the interface between material and ambient. Heat generated on the spring is conducted to the mass (the

corresponding thermal resistor is $R_{cond,M}$, to frame ($R_{cond,F}$), bonding layer 1 ($R_{cond,S}$), bonding layer 2 ($R_{cond,B}$) and then to the carrier wafer ($R_{cond,W}$).

Each conductive thermal resistance is calculated by:

$$R_{cond, \theta} = \frac{x_{\theta}}{A_{\theta} k_{\theta}} \quad 5-3$$

Where x_{θ} is length of heat path, A_{θ} is the cross section area, perpendicular to the path of heat flow, and k_{θ} is thermal conductivity of the material.

The total conductive thermal resistance can be computed as follows:

$$R_{cond} = \frac{1}{\frac{1}{R_{cond,M}} + \frac{1}{R_{cond,S}} + \frac{1}{R_{cond,F}}} + R_{cond,B} \quad 5-4$$

As the silicon die has a planar and thin structure, the thermal convection at the edges is assumed to be negligible compared to the thermal convection at the top and bottom surfaces. Equivalent thermal resistances for thermal convection taking place on the top surface of mass, spring and frame are denoted by $R_{conv,M}$, $R_{conv,S}$, and $R_{conv,F}$, respectively.

Each convective thermal resistance can be expressed as:

$$R_{conv, \theta} = \frac{1}{h_{\theta} A_{\theta}} \quad 5-5$$

Where h_{θ} is the heat transfer coefficient, A_{θ} is the area exposed to ambient.

The total convection thermal resistance on top surface is $R_{conv,top}$:

$$R_{conv,top} = \frac{1}{\frac{1}{R_{conv,M}} + \frac{1}{R_{conv,S}} + \frac{1}{R_{conv,F}}} \quad 5-6$$

The heat on the bottom surface dissipated on the carrier wafer through convection thermal resistance on bottom surface $R_{conv,bottom}$ is

$$R_{conv,bottom} = R_{conv,W} \quad 5-7$$

The total thermal resistance R_θ of circuit is therefore calculated as:

$$R_\theta = R_{conv,top} + R_{conv,bottom} + R_{cond} \quad 5-8$$

Thermal conductivity of materials and heat transfer coefficient for convection are listed in Table 5.2. It must be said that precise estimation of the heat transfer coefficient for convection is difficult during the etching process as it depends on the fluid velocities, fluid viscosity, and the condition of the heating surfaces. In this work, non-silicon thermal grease with good thermal conductivity is used for bonding. In the modelling, air natural convection of $10\text{W}/(\text{m}^2\text{K})$ is assumed as the heat transfer coefficient of ambient convection [182].

Table 5.2 Thermal properties of materials and air

Material	Thermal conductivity W/(mK)/heat transfer coefficient W/(m ² K)
non-silicon thermal grease-COOL-GREASE® CGR7016 (Appendix I), k_θ	4 W/(mK)
Silicon [183], k_θ	140 W/(mK)
Air, h_θ	10W/(m ² K)

For the dimensions of the etched materials, they are listed in Table 5.3. By applying Equations 5-3 and 5-5, the equivalent thermal resistances in the heat flow paths are evaluated. Based on the data in Table 5.3, the total convective and conductive thermal resistances can be derived from Equations 5-4, 5-6, 5-7 and 5-8.

Table 5.3 Dimensions of material used in the thermal modelling

Dimensions	Dies with outward type I S-spring-mass structure
The surface area of the spring structure, A_S	$1.56 \times 10^{-6} \text{ m}^2$
The surface area of the frame, A_F	$1.2 \times 10^{-4} \text{ m}^2$
The surface area of the mass, A_M	$1 \times 10^{-4} \text{ m}^2$
The area of the bonding layer A_B	$7.9 \times 10^{-3} \text{ m}^2$
Thickness of bonding layer $x_{\theta,B}$	$5 \times 10^{-6} \text{ m}$
The area of the carrier wafer A_W	$7.9 \times 10^{-3} \text{ m}^2$
Thickness of carrier wafer $x_{\theta,W}$	$300 \times 10^{-6} \text{ m}$

Table 5.4 Modelled equivalent thermal resistances in the path of heat flow

Thermal resistance(K/W)	Die with outward type I S-spring
$R_{conv,M}$	1000
$R_{conv,S}$	6.4×10^4
$R_{conv,F}$	827.8
$R_{conv,W}$	12.7
$R_{cond,M}$	0.0125
$R_{cond,F}$	0.01
$R_{cond,S}$	0.8
$R_{cond,B}$	2.7×10^{-4}

Table 5.5 Modelled total convective and conductive thermal resistances

Thermal resistance(K/W)	Die with outward type I S-spring
$R_{conv,top}$	449.7
$R_{conv,bottom}$	12.7
R_{cond}	0.006
R_{θ}	462.4

From Table 5.5, the modelled results show that the convective thermal resistances are significantly larger than the conductive thermal resistance. This indicates that heat convection plays the dominant role in the heat transfer in etching. It was also observed that $R_{conv,top}$ is bigger than $R_{conv,bottom}$ indicating that the thermal convection at the top surface is more significant than the bottom surface. Attempts are therefore made to examine the heat convection on the top surface so as to facilitate heat dissipation and quicken the heat flow thereby decreasing the convective thermal resistance and maintain the surface temperature on the spring structure to less than ambient temperature (293K). Otherwise, the polymer thin layer would be greatly when the wafer warmed up to the ambient temperature [184].

In an ICP system, the ion power density P_i (in watts per square) can be expressed as [185]

$$P_i = n_i q_0 V_b \sqrt{\frac{q_0 T_e}{M}} \quad 5-9$$

Where n_i is the ion density, q_0 is electron charge ($1.6 \times 10^{-16} \text{C}$), T_e is the electron temperature measured in electron-volts (2-5eV for a typical ICP system), V_b the DC bias on the sheath voltage for etching (normally 200-350V) [186], and M is the mass of the reactive ions. The mass of ions generated from SF_6 and O_2 plasma ranges 80-90 amu ($1 \text{amu} = 1.66 \times 10^{-27} \text{kg}$) [184].

The thermal current on the spring can be obtained by differentiating the thermal power Q with respect to time. This is equal to $P_i A_s$ where A_s is the surface area of spring structure:

$$\frac{dQ}{dt} = P_i A_s = \frac{d}{dt} \left(\frac{T_{top,S}(t) - T_{bottom}}{R_\theta} t \right) \quad 5-10$$

Assuming that the etch rate and ion density are constant during the etching, the steady state temperature of the spring is therefore

$$T_{top,S} = P_i A_S R_\theta + T_{bottom} \quad 5-11$$

Where T_{top} is the temperature of spring and T_{bottom} is the cooling helium gas temperature at the bottom side of the carrier wafer. The surface area of heat blocks is assumed to be A_H . Hence,

$$R_\theta \approx R_{conv,top}^* + R_{conv,bottom} = \frac{1}{(A_S + A_F + A_M + A_H)h} + R_{conv,bottom} \quad 5-12$$

$$R_{conv,top}^* = \frac{T_{top,S} - T_{bottom}}{P_i A_S} - R_{conv,bottom} \quad 5-13$$

After substituting Equation 5-12 into equation 5-13, the area of heat block required for minimizing anisotropic etching for certain spring-mass structure is shown below:

$$A_H = \left(\frac{P_i A_S}{(T_{top,S} - T_{bottom})} - R_{conv,bottom} \right) / h - A_S - A_F - A_M \quad 5-14$$

Based on a standard set of etching parameters with an etch rate of around 2.4μm/min in a STS-ICP etch system [187], as listed in Table 5.6, the corresponding ion density can be computed to be $150 \times 10^{10} \text{ cm}^{-3}$ [188]. The substrate temperature is 283K.

Table 5.7 lists the least area of heat block required and the corresponding top convective thermal resistance needed for $T_{top,S}$, to be less than 293K.

Table 5.6 Stand etching parameters for DRIE process

DRIE process parameters	Standard parameters
SF ₆ flow rate (sccm)	130
O ₂ flow rate (sccm)	13
C ₄ F ₈ flow rate (sccm)	100
Coil power(W)	600

Table 5.7 Modelled result of the area of heat blocks and the corresponding convective thermal resistance required to maintain $T_{top,S}$

$T_{top,S}(\text{K})$	The area of heat blocks, $A_H (\text{m}^2)$	The top convective thermal resistance
		$R_{conv,top}^* (\text{K/W})$
288	0.003	31.8
293	0.001	76.4

Figure 5.8 Schematic drawing of the top view of plates containing outward type I S-spring-mass structure after adding heat blocks. Dark areas are the trenches

From equation 5-3, it can be seen that to reduce the convective thermal resistance without affecting the plasmas on the surface, the available top surface area for heat convection during etching would need to be increased. Hence heat blocks are to be either placed around springs, near other blocks with big surface areas, such as mass and frame, and in trenches around each die in Figure 5.8. This is to enable heat to be transferred from spring, through heat blocks, to mass and frame and to other dies during etching. Heat dissipation can therefore now be channelled from the die-level to wafer-level. This means that the whole surface area of wafer, representing 18 times that of the die area, could be used for heat dissipation of fine structures which have small surface areas. The thermal convective area for the top surface area would be

$R_{conv,top} = R_{conv,W}$. Consider the aforementioned RIE lag, the width of trenches around

the heat block is designed to be equalled to the trenches between the two long beams in spring having the same etching rate.

Incorporating these changes, the simulated results of the total thermal resistance after adding heat blocks in mask design can be found in Table 5.8. It can be seen that the thermal resistances have been largely reduced to the desired levels.

Table 5.8 Modelled total convective and conductive thermal resistances

Thermal resistance(K/W)	Die with outward type I S-spring
$R_{conv,top}^*$	12.7
$R_{conv,bottom}$	12.7
R_{θ}	25.4

Based on the aforementioned, the enhanced etching process incorporating with heat blocks is illustrated in Figure 5.9. It can be observed that the heat in the spring structure is now able to transfer to the heat blocks, frame block and mass block throughout the etching process as illustrated in Figure 5.9(a). Heat blocks remain after the completion of etching in Figure 5.9(b). They will only be removed when the etched silicon wafer and the carrier wafer are to be separated while the spring remained attached to the frame and mass. This will be explained in details later in the fabrication process flow section.

Figure 5.9 Schematic illustration of the etching of spring-mass structure after adding heat block; the trenches are designed with the same dimension: (a) During etching; (b) After etching

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5.3 Fabrication validation and discussion of results

5.3.1 Fabrication process flow

This section discusses the results derived in fabrication of the sandwiched three plate incorporating the findings as highlighted in the preceding sections. The test samples of electrode cells, interconnections, and electrode pads of the power generator configuration and spring-mass structure are fabricated out from a 4-inch size diameter (10.16cm) silicon wafer of 320 μ m thickness.

In this work, gold is chosen as the metallic material for fabrication of the electrodes owing to its good conductivity and chemical stability. To pattern the micro sized electrodes on the silicon wafer, a lift-off technique is adopted that involves the use of a sacrificial photoresist layer to remove unwanted gold material on the top of it. This technique is chosen over chemical etching as the size of patterned photo resist can be better controlled during the photolithography process. Besides, chemical etch also involves using toxic enchansts.

To fabricate the substrate plates, a 1 μ m oxide layer is to be thermally formed on the wafer (Figure 5.10(a)). The thermally grown silicon oxide layer on the surface of silicon wafer is to function as an insulating layer in the electrostatic power generator to prevent charge leakage when contact is made with the electret material. Prior to lithography, silicon wafer is prepared with vapour priming of HMDS (Hexamethyldisilazane) coating process. Good adhesion of the photoresist is important to ensure the integrity of pattern characteristic transfer. Photoresist will not adhere to a hydrated silicon surface, so the silicon surface of the wafer must be dehydrated. This process will enable the molecular water of the hydrated wafer surface to be contained as well as increase the liquid contact angle of the wafer surface making it more hydrophobic. After that, a 5 μ m thick AZ 9260 photoresist is

spun on the substrate and cured for 4 minutes at 90°C and patterns are then defined on the silicon wafer by photolithography.

Figure 5.10 Fabrication process flow of substrate plate

The metallic layer is then blanket-deposited on the substrate (Figure 5.10(b)). To ensure the layer on top of photoresist can be easily lifted-off, an e-beam evaporation of coarse step coverage is used to deposit the metallic layer. This involves first

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depositing an adhesive film of reactive metal Cr of 20nm followed by a 300nm metallic film of non-reactive metal Au. The thin metallic layers allow solvents to seep underneath. When the whole wafer is immersed in Acetone solution, the unexposed photoresist under the metallic layers is removed together with the metallic layer on it. This leaves only the part which was deposited directly on the wafer (Figure 5.10 (c)). Prior to the DRIE process, wafer is bonded with carrier wafer by a 5 μ m thick thermal grease. Trenches are created around the substrate dies in DRIE (Figure 5.10 (d)). DRIE is carried out using the STS-ICP system.

Substrate dies are released from the whole wafer after acetone solution is used to remove the photoresist layer and ready for bonding with LDPE thin film. In this work, 1cm $\times$ 1cm LDPE thin films are manually cut from the LDPE sheet. This is to ensure charges are uniformly implanted into the micro sized areas, the LDPE thin film should be bonded fully flat on the substrate plate. A 5 μ m thick spun-on SU-8 is then used as a bonding adhesive layer between the LDPE thin film and substrate plate (Figure 5.10 (e)). After LDPE thin film is placed on the SU-8 layer, the substrate plates bonded with LDPE thin film are ready for corona localized charging.

In the fabrication process flow of plate containing spring-mass structure, photo mask designed with heat block taking into account the RIE lag is used as the etching step. Lift-off process described in the fabrication of substrate plate is used to fabricate electrodes on top side of silicon wafer with 1 μ m thick thermally grown silicon dioxide layer (Figure 5.11 (b)). The wafer is then flipped over to be sputtered with 300nm thick aluminium layer which acts as an etch stop layer (Figure 5.11 (c)). For fabrication of the plate containing spring-mass in SSPG, electrodes are also patterned on the bottom side of silicon wafer prior to the sputtering of aluminium layer. After that, wafer is bonded with carrier wafer by thermal grease (Figure 5.11 (d)).The

patterned photoresist on wafer works as a mask for the following etching steps (Figure 5.11 (e)). In the last step (Figure 5.11 (f)), in order to release silicon dies from the carrier wafer, the bonded wafers are immersed in Acetone to remove photoresist and grease, followed by using AZ 9620 photoresist developer solution to dissolve the aluminium. Figure 5.12 presents the successfully fabricated substrate plates as well as plates containing outward type I S-spring.

Figure 5.11 Fabrication process flow of plate containing spring-mass structure

Figure 5.12 The fabricated top substrate plate, bottom substrate plate and middle plate with outward type I S-springs

5.3.2 Discussion on heat block in etch process

In the first set of results, twelve plates containing spring-mass structures are designed on one wafer with eight of them containing plates with outward type I spring. It was found that the etch yield rate for fabricating the spring-mass structure has been improved significantly from 30% using photo mask without heat blocks to 100% using photo mask designed with heat blocks.

Besides an improved yield rate, the dimensions of trenches across wafer are also examined. Like the photoresist without heat blocks, it was found that the dimensions of trenches still vary across the wafer for those designed with heat blocks. This is probably owing to the isotropic etch effect which vary with respect to the location on the wafers resulting in a varied spring dimension which leads to a deviated resonant frequency. As the etch rate is non uniformed, an over-etch time is also required to release all dies in the wafer.

Table 5.9 shows the set of designed and fabricated dimensions of the various spring widths. Due to isotropic etching, the top width is slightly bigger than the bottom width of the spring. The weight of mass detached from the mass block of the plate is

also measured. The fabrication errors of spring width are better controlled at -10% (bottom) and -6% (top).

Table 5.9 Comparison between designed dimension and fabricated dimension of spring-mass spring

Structure	Designed	Measured	deviation
Width of spring beam	50 μ m	45 μ m ~47 μ m (top) 43 μ m~45 μ m (bottom)	6~10% 10~15%
Resonant frequency	65Hz	44.2-48Hz across the wafer	26-32%
Mass	73.6mg	74mg	

5.3.3 Discussion of results for feature alignment and assembly

In this section, two sets of results are examined namely the accuracy of the feature locations, alignment of plate assembly and gap size as such alignment affects the effective performance of the electromechanical coupling.

For feature accuracy, Table 5.10 compares the designed and measured dimensions for the electrode cell and alignment hole. Maximum deviation from the designed sizes of 3% is found for the electrode cell, and 1% for alignment hole based on SEM images captured as shown in Figure 5.13.

Table 5.10 Comparison between designed and fabricated dimensions of spring-mass spring

Structure	Designed dimension	Measured dimension	Deviation
Side length of electrode cell	100 μ m	100~103 μ m	3%
Alignment hole	295 μ m	298 μ m	1%

Figure 5.13 SEM images of electrode cells and alignment hole

Figure 5.14 The validation mechanism of double-sided alignment

These readings are derived using a double-sided alignment that has been developed to facilitate the measurement as illustrated in Figure 5.14. The distances from the electrode edge to the mass plate edge on one surface are first measured and then flipped. The distance measurements are then repeated on the designated edge and compared along two axes as in Table 5.11. Offset caused by isotropic etch along the vertical profile of mass plate is also accounted for as in Figure 5.16 where the alignment error of $0.6\mu\text{m}$ along x axis, and $0.7\mu\text{m}$ along y axis are registered as in Table 5.11. From the results, one could infer that the proposed approach is able to fabricate features with good feature alignment accuracy.

Table 5.11 Derived double-sided alignment error

Axis	d_B	d_T	offset	Alignment error (d_B -offset- d_T)
x	121.4 μm	119.1 μm	2.9 μm	-0.6 μm
y	244.2 μm	239.5 μm	5.4 μm	-0.7 μm

Figure 5.15 SEM images of electrodes in one corner of the mass plate (a) on bottom surface; (b) on top surface

Figure 5.16 SEM image of the side profile of the corner of the mass plate

In the alignment of plates, this involves the development of an alignment assembly design stage and a set of alignment pins as shown in Figure 5.17. Plates are placed on the step of alignment stage fabricated from a larger sized acrylic boards which are machined out using precision laser technology. After that, spacers are put in place and alignment pins are manually stuck through the alignment holes fabricated on the edges of plates. After the plates are firmly bonded, the alignment pins are then

removed. This alignment pins method has also been applied to the assembly of substrate plates and shadow masks for charging as shown in Figure 5.18.

Figure 5.17 Schematic drawing of assembly method

Figure 5.18 Schematic drawing of assembly of substrate plate and shadow mask for localized charging

For the spacer between plates of generator to create air gap, liquid crystal polymer (LCP) strips of different thickness are chosen as they are easy to handle and can provide consistent thickness along strip. LCP material can also perform very well in harsh environments due to their high heat resistance, and high chemical resistance [189]. For bonding, epoxy glue is chosen as the adhesive material between silicon

wafer and LCP strips. To control the thickness of the glue bonding layer, a needle is used to fetch glue balls. A small glue drop is absorbed on the needle because of liquid absorbability and placed on the frame. LDP strip is then pressed onto the glue drops. The thickness of glue bonding layer is found to be in the range of $7\mu\text{m}\sim 12\mu\text{m}$.

To validate the proposed alignment method by pins and holes, a magnified image of assembled middle plate and bottom substrate plate is captured along with the overlaid photomask layout as in Figure 5.19. In the overlaid photomask layout, M_T_electrode is found on top side of the mass of the middle plate whereas the B_T_electrode and B_wire electrode are located on the bottom substrate plate. From the magnified image, it can be observed that the B_T_electrode is covered by mass plate. There is little alignment error of less than $5\mu\text{m}$ found between the B_wire electrode and the M_T_electrode.

Figure 5.19 (a) Magnified image of assembled bottom substrate plate and plate containing spring-mass structure; (b) Overlaid photomask layout of M_T_electrode, B_T_electrode and M_spring (outward type II S-spring)

Figure 5.20 presents the successful assembly for both the two-plate and SSPG configuration hence validating the viability of the proposed assembly method.

(a)

(b)

Figure 5.20 (a) Assembled two-plate power generator (with outward type I S-spring design) is compared with a twenty cent coin; (b) Assembled SSPG (with outward type I S-spring design) is compared with a twenty cent coin

5.4 Conclusion

A heat management approach based on thermal circuit equivalent model has been developed that which can be used in the design and placement of heat blocks for plate fabrication using the etching process. Preliminary results based on the developed approach with the use of heat block show a substantial improvement in the etching yield from 30% to 100%. The fabrication errors of spring width are better controlled at -10% (bottom) and -6% (top). Smaller deviations from the designed resonant frequencies are also recorded as 26%, compared with a reported figure of 43.7%. This enables greater predictability in design though efforts can be made to refine the approach and reduce this further.

To facilitate better alignment, the double sided alignment approach and the pin and hole alignment approach have been established. The approaches have helped to

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minimise the feature and assembly alignment errors to an acceptable level. Alignment errors between electrodes on mass plate are found to be about $0.6\mu\text{m}$ whereas the alignment error for plate assembly is less than $5\mu\text{m}$.

Chapter 6 Characterization and analysis of power generators

This chapter looks into the characterization and testing of two energy harvesting power generators that have been developed for harvesting ambient vibration sources of low frequency and low amplitude. Discussion on the characterisation of the Sandwiched Structured Power Generator (SSPG) prototype with the outward type I spring as well as another with outward type II S-spring for harvesting the fundamental and harmonic components of the ambient vibration signals will be made.

6.1 Test setup

Figure 6.1(a) shows the experimental test setup for energy harvesting of vibration signals based on the micro electret prototypes that have been developed. To mimic the acceleration amplitude and frequency of ambient vibration signals, an Agilent 33120A 15MHz Function/Arbitrary waveform generator coupled to a power amplifier is used to generate as the desired sinusoid vibration characteristics, $x_i(t)=X_0\sin\omega t$. This is then fed to the shaker which intrinsically contains both the fundamental and harmonic components of the vibration signals [190, 191]. An L-shape device holder is used to house the power generator device and is attached to the shaker by means of a M4 screw as illustrated in Figure 6.1(b). The device housing seeks to align the planar direction of the device (x axis) with the vibration direction generated by the shaker. A Brüel & Kjær accelerometer is also attached to the device holder to monitor the acceleration. The motion of the mass and the shaker during vibration are monitored using a high speed camera. Images are captured at a high frame rate of 6000 (frame per second) which are then used to determine the absolute displacements of mass $x_o(t)$ and of shaker $x_i(t)$. The relative displacement of the mass $x(t)$ can be

computed by $x_0(t) - x_i(t)$ via extracting information from the set of frames. To derive the electrical current flow, the metal pads on the device are connected to a designed testing circuit. The electrical outputs of the testing circuit are then acquired by a data acquisition (DAQ) system NI USB-6289 M series and subsequently analysed using a Labview software.

Figure 6.1 (a) Schematic of testing setup; (b) Schematic drawing of device holder attached to the shaker

6.2 Energy harvesting from fundamental component of vibration

The first set of test characterisation relates to the energy harvesting of the fundamental component of vibration signal by the Sandwich Structured Power Generator (SSPG) having an outward type I S-spring configuration. The schematic configuration can be found in 6.2(a) and the outward type I S-spring-mass structure incorporated in the generator is shown in Figure 6.2(b). There are a total of four wiring pads with each connecting to a set of electrode cells on the plate. The wiring pads on the mass plate are for collecting charges, while the wiring pads on the top and bottom substrate plates allow one to apply bias voltage on the electrode cells during corona charging. The thicknesses of each of the structure layers are shown in Figure 6.2(c) with the wiring schemes for the two configurations found in Figure 6.2(d).

(a)

(b)

(c)

Figure 6.2(a) Schematic drawing of SSPG; (b) Outward type I S-spring-mass structure in SSPG; (c) Schematic drawing of cross section of SSPG; (d) Schematic drawing of top view of SSPG

The set of measured parameters of the Sandwich Structured Power Generator prototype are summarized in Table 6.1. The device has also an overall thickness of about 1.33mm inclusive of the three silicon plates ($3 \times 310\mu\text{m}$) and spacers between plates ($2 \times 200\mu\text{m}$). To prevent the electrostatic stacking between plates after corona charging on LDPE thin film, a pull-in test is conducted on Configuration II in which electrode cells and electret cells are made to fully overlap with each other to determine the proper gap size needed between the plates. As earlier noted in Chapter 4, charges having high surface potential of several hundreds of volts are found to be stable for a $50\mu\text{m}$ thick LDPE thin film. As such, the surface potential on the electret cells are charged to an average surface potential of 200V. By applying a *CAF* value of 3.38 for localized charging, the surface potential, V_s , on the micro sized electret cells would be equalled to 676V. A pull-in movement is observed when the gap between the electret surface and the bottom of mass plate is at $67\mu\text{m}$ or less. Based on pull-in

analysis in Table 3.5, fringing field effect, spring stiffness, k_z of 40N/m, as well as taking surface potential and fabrication tolerance into account, spacers having a 200 μ m thickness are used to establish a gap size of more than 120 μ m in each of the two configurations in the SSPG.

Table 6.1 Summary of measured SSPG parameters

Parameters	Values
Overall Enclosed Volume	0.35cm ³
Resonant frequency of spring-mass structure	44.2Hz
Surface potential on micro sized electret area, $V_{sl}=V_{sl}$, measured after charging	676V
Thickness of LDPE thin film d	50 μ m
Capacitive cell	100 μ m $\times$ 100 μ m
The number of capacitive cell on one plate	2965

6.2.1 Vibration-mechanical characterization

Mechanical quality factor Q is a critical factor used to evaluate the performance of resonant power generator in terms of the maximum amount of mechanical energy available to be converted as well as energy loss of the resonant system. The Q factor can be derived from the measured amplitude X_m of mass relative displacement at frequencies near to the expected resonant frequency based on the following:

$$Q = \frac{f_r}{f_2 - f_1} \quad \mathbf{6-1}$$

Where f_1 and f_2 are the lower and higher frequency at which the magnitude is 3 dB lower than the peak at the resonance frequency. It must be said that in deriving the

mechanical quality factor, the electrical aspects of the system needs to be decoupled during the test without charging the LDPE thin film so as not to introduce any bias voltage in the capacitor of the device.

Figure 6.3 Resonant response of power generator device with outward type I S-spring

Figure 6.3 shows the resonant response of a power generator device when subject to a small amount of acceleration of 0.03g (1g is about 10 ms^{-2}) so as to avoid or minimise any mechanical energy loss due to mechanical collision arising between the beams of spring, spring-mass, and spring-frame. The amplitude X_m of relative motion of mass can be observed at frequencies of between 44.5Hz and 44Hz that are close to the resonant frequency f_r of 44.2Hz. This gives a high quality factor, Q of 89. This value is 10 times higher than a current reported works of 8.6 based on a polymer spring structure operating at low level vibration of 63Hz [38]. The air damping coefficient c_m works out to be $2.3 \times 10^{-4} \text{ Ns/m}$ using Equation 2-9 and 2-10. This value would be used in the model to predict the electrical output in the next section.

6.2.2 Electromechanical interface characterization

Characterisation study is made on the electromechanical coupling for a single capacitive configuration of the SSPG. Capacitive configuration functions as a current source $i(t)$ due to induced charge flow. The current $i_0(t)$ flows through the optimal load R_L and the voltage across the load is denoted by $V_0(t)$. To facilitate maximum power transmission from the system to the load, the resistance of the optimal load needs to be matched with the internal impedance of the power generator. In this experiment, 10 resistive loads, ranging from $6\text{M}\Omega$ to $80\text{M}\Omega$ (6.5, 8, 10, 12, 20, 30, 40, 50, 68, $80\text{M}\Omega$) are employed to test the optimal load for a single configuration in the SSPG. The voltage output across the load is measured at a constant frequency of 44.2Hz having an acceleration amplitude of 0.01g. Peak power output is observed to be at a maximum when $R_L=10\text{M}\Omega$ as in Figure 6.4 which represents the optimal load for this capacitance configuration.

Figure 6.4 Power output versus various resistive load ($f=44.2\text{Hz}$, $a=0.01\text{g}$)

6.2.3 Power generation performance of SSPG

In SSPG, each capacitive configuration functions as an independent current source, together with an external load as a power output port. The equivalent circuit is as illustrated in Figure 6.5. Parasitic capacitance C_{par} , in parallel with external load, arises from the MEMS structure interconnection and wiring. The real-time AC voltage output voltage $V_o(t)$ across the load and current $i_o(t)$ flowing through the load is given as:

$$V_o(t) = i_o(t) R_L \quad 6-2$$

The real-time power output on the optimal load R_L can be computed as follows:

$$P(t) = \frac{V_o^2(t)}{R_L} \quad 6-3$$

Figure 6.5 Equivalent circuit of power output port in SSPG

Using Kirchhoff's circuit law, the current flow can be evaluated as follows:

$$i(t) = C_{par} R_L \frac{di_o(t)}{dt} + i_o(t) \quad 6-4$$

Parasitic capacitance in each capacitive configuration is derived by measuring the capacitance of the capacitive configuration using a HP (Hewlett Packard) 4284A precision LCR meter, as illustrated in Figure 6.6. This is in the order of picofarad

range. In Configuration I, the measured total capacitance, C_I , is composed of C_{min} and C_{par_I}

$$C_I = C_{min} + C_{par\_I} \quad \mathbf{6-5}$$

In Configuration II, C_{II} is composed of C_{max} and C_{par_II} :

$$C_{II} = C_{max} + C_{par\_II} \quad \mathbf{6-6}$$

The measured C_{II} and C_I are 10.5pF and 7.8pF respectively. The C_{max} , is estimated to be 3.39pF and C_{min} , equals to 2.96 pF using model discussed in Chapter 3. The C_{par_II} and C_{par_I} would therefore be 7.1pF and 4.84pF respectively.

Figure 6.6 Measurement of capacitance change by LCR meter

To better study the effect of the two proposed configurations with a phase difference of π on the power output in a given port, the results of Configuration I only is compared with the results of Configuration I having Configuration II placed on top of it as illustrated in Figure 6.7. Figure 6.8 presents the simulated and experimental voltage waveforms across the load of $10M\Omega$ when the device is excited by a sinusoidal vibration source of 0.01g at frequency of 44.2Hz. For the simulation, the waveform results are derived based on the proposed model that incorporates the fringing field effect, device parameters in Table 6.1, and derived parameters in Table 6.2.

Table 6.2 Parameters for the simulation of electrical output from Configuration I of micro power generator

Parameters	Values
Air damping coefficient, c_m	2.3×10^{-4} Ns/m
Spring constant, k_x	5.7N/m
Parasitic capacitance, C_{par}	4.84pF (Configuration I)
Resistive load, R_L	10M Ω
Air gap in two configurations, g	120 μ m

For the maximum voltage after the introduction of configuration II, its value was increase by twice when compared with to that of before. This behaviour could be explained by the increase in the relative displacement of mass as presented in Figure 6.8(c) resulting from a reduced electrostatic force being experienced by the configuration. This therefore enables greater amount of mechanical energy to be harvested.

Figure 6.7 Schematic drawing of measurement from Configuration I only (Two-plate structure) and Configuration added with Configuration II (Sandwich structure)

(a)

(b)

Figure 6.8 (a) Experimental voltage output and simulated voltage output in capacitive Configuration I only(Two-plate structure); (b) Experimental voltage output and simulated voltage output in Configuration I with Configuration II (Sandwich structure)

Figure 6.9 Estimated relative motion of mass in two-plate structure and in SSPG;

Figure 6.10 Comparison of measured peak power output generated from Configuration I only (Two-plate structure) and Configuration I added with Configuration II (Sandwich structure)

Figure 6.10 shows the peak power generated from Configuration I in SSPG and in a two-plate structure when the acceleration is made to vary from 0.01g to 0.05g. An increase of more than three times the amount of power output was observed in a single capacitive configuration of a SSPG when compared to a conventional two-plate power generator. It must however be said that the trends for the change in the measured peak power outputs as a function of acceleration in Configuration I of

power generator structures differ from those results obtained by theoretical modelling. This is probably owing to the internal impedance of the capacitive configuration which varies and functions dynamically. The ideal optimal load therefore changes with capacitance [126] making it difficult to match the varying internal impedance all the time in order to derive the maximum power conversion. The peak power outputs from two configurations are shown in Figure 6.11. Harvesting effectiveness E_H of configurations can be computed based on Equation 1-1 as highlighted in Chapter 1. The total effectiveness is calculated by using the total power from two configurations, vibration inputs and mass relative displacements. By summing the outputs from both configurations in SSPG, the total power from SSPG could reach 100nW at an acceleration of 0.03g. The average of total effectiveness obtained at acceleration of 0.01g, 0.02g and 0.03g is found to be about 7%.

Figure 6.11 Measured peak power outputs from Configuration I and Configuration I and the harvesting effectiveness in each configuration as a function of acceleration

The power generated from SSPG has also been used to charge a storage capacitor. Figure 6.12 shows the measured voltage output from Configuration I for a conventional two-plate configuration and SSPG at vibration with frequency of 35 Hz, acceleration of 0.8g. For the measurement, the peak-to-peak voltage, V_{p-p} , generated

from Configuration I in a two-plate configuration is 0.32V, and maximum power output on 10MΩ load is 2.56nW whereas for Configuration I in SSPG, this provides about V_{p-p} of 0.7V and maximum power 12.25nW.

Figure 6.12 Circuit for voltage output measurement and charging storage capacitor

To derive the energy generated, this could come from a storage capacitor C_L , which can be charged by a rectified output voltage from the generator. The storage energy ΔE in the capacitor can be evaluated as follows:

$$\Delta E = 0.5C_L \Delta V^2 \quad \mathbf{6-7}$$

Where ΔV is the instant voltage measured from the storage capacitor charged for a period time of Δt . The harvesting power is derived from ΔE :

$$P_C = \Delta E / \Delta t = 0.5C_L \Delta V^2 / \Delta t \quad \mathbf{6-8}$$

Electrical outputs are rectified and used to charge storage capacitor C_L of 100μF. The voltage ΔV across capacitor increases linearly with respect to the charging time and the harvesting power P_C at that instant can be shown in Figure 6.4. It is found that a higher energy harvesting power P_C can be achieved in Configuration I in SSPG than in a conventional two plate configuration. This is owing to the higher electrical output resulting in a faster charging time to reach a targeted charge level. It is however observed that when the rectified outputs from the two configurations in the SSPG are

connected to charge the storage capacitor simultaneously, a longer charging time is required compared to a single configuration. This is probably owing to the mismatch in the charging characteristics. As such, each configuration is to have its own separate power output port for electrical storage.

Figure 6.13 Measured voltage waveforms from Configuration I in two-plate structure(a) and sandwich structure of SSPG(b) excited by vibration at frequency of 35 Hz, acceleration of 0.8 g

Figure 6.14 DC Voltage on storage capacitor C_L rising over charging time

6.3 Energy harvesting from harmonic component of vibration

This section presents vibration energy harvesting of the resonant frequency excited by a harmonic component of the vibration that is generated by machineries as discussed in Chapter 2. A prototype of two-plate micro electret power generator with outward type II S-spring based on design in 6.2 will be characterized and tested for this purpose.

6.3.1 Device characterization

(a)

(b)

Figure 6.15 (a) Schematic drawing of micro electret power generator with outward type II S-spring (b) Outward type II S-spring-mass structure in power generator

Table 6.3 Summary of parameters of two-plate power generator with outward type II S-spring

Parameters	value
Volume	0.28cm^3
Resonant frequency	97Hz
Spring constant k	27.4 N/m
Initial surface potential on micro sized electret area	1014V
Capacitive cell	$100\mu\text{m} \times 100\mu\text{m}$
Gap	150 μm
Thickness of LDPE thin film	50 μm
Number of capacitive cells on one plate	2965

Figure 6.15 shows the schematic drawing of micro electret power generator with four outward type II S-springs for harvesting the harmonic component of vibration. The measured average surface potential is 300V after charging. By applying a CAF value = 3.38, the surface potential on micro sized area is computed to be $V_s=1014\text{V}$. A gap

of $150\mu\text{m}$ is set for the experimental two-plate micro eletret power generator to avoid the pull in effect. For the outward type II S-spring-mass resonant system, f_r , f_1 and f_2 are found to be 97, 96.4, and 97.2Hz respectively. The computed Q -factor is 121 as derived from Equation 6-1.

Figure 6.16 Resonant response of power generator device with outward-type II S-spring when acceleration of 0.08g is applied

Figure 6.17 Power output versus various resistive load ($f=97\text{Hz}$, $a=0.065\text{g}$)

For the optimal load for electrical power transfer from power generator, this works out to be about $10\text{M}\Omega$ similar to SSPG configuration based on the set of parameters as in Table 6.2.

6.3.2 Testing and results

Two sets of experimental tests were carried out with the view of harvesting the harmonic component of the vibration source. These frequencies of harmonic components are selected to match the resonant frequency of the power generator.

In the first set of experiments, the input vibration is set at a frequency f of 19.4Hz and acceleration of 0.7g. Fast Fourier Transform (FFT) analysis is then applied to the motion of the shaker. The frequency spectrums generated by the relative motion of mass can be found in Figure 6.18 which highlights the harmonic components characterized by $2f$, $3f$, $4f$, $5f$, $6f$ and $7f$. At frequency f_h of the fifth harmonic component, this equals to $5f$ matching the resonant frequency f_r of 97Hz of the power generator. This would however trigger a resonant response of the power generator as shown in Figure 6.18(b). The figures highlights that the vibration amplitude of the fifth harmonic ($5f$) is magnified approximately 27.5 times to around $55\text{ }\mu\text{m}$ in the device, resulting in appreciable voltage output in Figure 6.19. The electrical period T_e is 0.005s while the mechanical period is 0.52s. At resonance, the vibration amplitude matches that of the amplitude at 19.4Hz.

Figure 6.18(a) FFT frequency spectrum generated from shaker's motion at frequency of 19.4 Hz, acceleration of 0.7g; **(b)** FFT frequency spectrum generated from mass's relative motion

Figure 6.19 Measured relative displacement of mass and voltage output from power generator harvesting energy from the fifth harmonic component of shaker's vibration at frequency of 19.4 Hz and acceleration of 0.7g

In the second set of experiments, the shaker is tuned to have an input frequency of 2.02Hz and acceleration of 0.7g. Voltage output from the device can be found in 6.19(a), with the FFT analysis result generated from the relative motion of mass shown in Figure 6.20(b). At the 48th harmonic component of the shaker's frequency, this matches with the resonant frequency of the device. In this instance, the FFT vibration amplitude is magnified by about 4 times. This amplitude magnification could then be harvested and further exploited for other suitable applications where appropriate.

Figure 6.20 (a) Voltage output from power generator harvesting energy from the fifth harmonic component of shaker's vibration at frequency of 2.02 Hz and acceleration of 0.7g ; (b) FFT frequency spectrum generated from mass's relative motion

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6.4 Conclusion

Outward type I S-spring-mass structure has been employed in Sandwich Structured Power Generator (SSPG) with two capacitive configurations having a phase difference of π and a volume of 0.35cm^3 . The power generator device can resonate at low frequency of 44.2Hz having a mechanical quality factor of 89. Surface potential of 676V produced on $100\mu\text{m} \times 100\mu\text{m}$ charged areas of LDPE electret thin film have been incorporated into the SSPG. Total power output from both configurations in SSPG, could reach 100nW at an acceleration of 0.03g. The average of total effectiveness is found to be about 7%.

Power output from a single capacitive configuration in SSPG was found to increase by more than three that of in a conventional two-plate capacitive configuration structure. This is owing to the phase difference in the two configuration leading to a reduced electrostatic restoring effect and increase in the mass relative displacement.

An outward type II S-spring configuration for micro electret power generators has been developed and tested for harvesting of the harmonic component of vibration source. The spring configuration which has a high stiffness ratio is able to achieve a high mechanical quality factor Q of 121 at a resonant frequency of 97Hz. This high quality factor has enabled the power generator to harvest the 48th harmonic of a very low fundamental frequency at 2Hz having an acceleration of 0.7g. A voltage of 0.15V with a power output of 2.2 nW, can be obtained.

Chapter 7 Conclusions and future work

7.1 Conclusions

A novel highly effective parallel in plane micro Sandwich Structured Power Generator (SSPG) design having a volume of 0.35cm^3 has been successfully developed for harvesting ambient vibration energy of frequency less than 100Hz and acceleration less than 0.1g. The generator has two capacitive configurations having a phase difference of π and employing a newly modelled outward type I S-spring-mass structure. The generator is able to resonate at low frequency of 44.2Hz having a mechanical quality factor of 89. The average total harvesting effectiveness of the generator is found to be about 7% which is significantly higher than current ones. Total power output from both configurations in SSPG, could reach 100nW at an acceleration of 0.03g.

Various sizes of outward type I and outward type II folded S-spring configurations have been investigated. For low resonant frequency of less than 100Hz, a S-spring structure with a length of between $3000\mu\text{m}$ and $5000\mu\text{m}$ having five folds with a beam width of less than $80\mu\text{m}$ should be designed. To differentiate the resonant frequencies between the principal axes and the other two directions, the spring constant ratios (k_y/k_x and k_z/k_x) need to be larger than 4.

A new model formulation based on 3-D finite model that incorporates the fringing field effect experienced by the electromechanical coupling has been established. It was found that the fringing effect has a profound effect in reducing the capacitance change, pull-in surface potential and the horizontal electrostatic force. Based on the model, the two capacitive configurations having phase difference of π are found to reduce the restoring effect of the horizontal electrostatic force.

A localized corona charging method to form micro sized electret areas on macro sized dielectric material has been established. This method involves using shadow mask to transfer charge patterns and voltage-based charging configuration to facilitate charge transportation in the formation of $100\mu\text{m}\times 100\mu\text{m}$ electret array on $1\text{cm}\times 1\text{cm}$ electret material. It was found that charging efficiency of 93% with 87% of its initial surface potential remained on the localized areas of $50\mu\text{m}\times 50\mu\text{m}$ after 240 days.

To characterize the formed micro sized electret array, a technique based on SEM surface topography combined with non-contact measurement of average surface potential has been developed. The technique is able to map the charge distribution on locally charged dielectric thin film and measurement of the surface potential on the micro sized area by incorporating the layout characteristic of electret array, denoted by *CAF* (charged area factor equivalent).

A heat management involving the design and placement of heat blocks for spring-mass structure in the etching fabrication process has been developed. The developed approach has enabled the etching yield to be substantially improved from 30% to 100%. The fabrication errors of spring width are also better controlled at -10% (bottom) and -6% (top), resulting in smaller deviations of 26% from the designed resonant frequencies compared with a reported figure of 43.7%. To facilitate better alignment, a double sided alignment approach and the pin and hole alignment approach have been established. Alignment errors between electrodes on mass plate are found to be about $0.6\mu\text{m}$ whereas the alignment error for plate assembly is less than $5\mu\text{m}$.

A two-plate micro electret power generator with outward type II S-spring has been designed and tested for harvesting the harmonic component of vibration source. With a high quality factor of 121, the power generator is able to harvest the 48th harmonic

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of a very low fundamental frequency at 2Hz having an acceleration of 0.7g. A voltage of 0.15V with a power output of 2.2 nW, can also be obtained.

7.2 Recommendations for future work

The presented results in this work have demonstrated the enhanced performance of inertial micro electret power generators. Based on the results, future work for extended study is recommended as follows:

(a) Investigate broadband vibration energy harvesting using micro resonant electret power generators. With high quality factor, the current system has a sharp resonance, resulting in good performance in harvesting vibration energy at single frequency. In environment, some vibration sources have rich frequency contents. If micro electret power generators with different resonant frequencies can be stacked together to address major frequencies in the vibration source, the stacked power generator device would be more versatile in harvesting vibration energy with changing frequencies.

(b) Enhancement study on charge density and stability should be carried out on locally charged dielectric thin film. This includes: (i) employment of dielectric material which have higher trap density by doping micro particles or by stretching the material to create new boundaries and defect which create traps; (ii) studying charging parameters for localized charging, such as annealing temperature, charging time and charging voltage.

(c) To more accurately fabricate device with frequency in accordance with designed value, besides heat management, other etching factors including etching(SF₆)/passivation gas(C₄F₈) flow rate and cycle duration, chamber pressure, and coil power should be optimized in the study of etching profile of spring beam in future work.

(d) To study the power transfer interface between device and external circuit. This would require the investigation on the effect of circuit load to electrical system of

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micro electret power generator and internal impedance characterization based on capacitance change for designing real-time impedance matching circuit for maximum power transfer.

(e) To make micro electret power generators commercially viable, the reliability of devices need to be investigated. First of all, long term performance over extremely large operation cycles need to be studied and demonstrated. This aspect is closely related to reliability of mechanical structure, including the fatigue in the spring, the wear life of device assembled by sticking technique.

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Appendix A: Specifications of microcontroller

PIC10(L)F320/322

6/8-Pin Flash-Based, 8-Bit Microcontrollers

High-Performance RISC CPU:

- Only 35 Instructions to Learn:
  - All single-cycle instructions, except branches
- Operating Speed:
  - DC – 16 MHz clock input
  - DC – 250 ns instruction cycle
- Up to 512 Words of Flash Program Memory
- 64 Bytes Data Memory
- Eight-level Deep Hardware Stack
- Interrupt Capability
- Processor Self-Write/Read access to Program Memory
- Pinout Compatible to other 6-Pin PIC10FXXX Microcontrollers

Special Microcontroller Features:

- Low-Power 16 MHz Internal Oscillator:
  - Software selectable frequency range from 16 MHz to 31 kHz
  - Factory calibrated to $\pm 1\%$, typical
- Wide Operating Range:
  - 1.8V to 3.6V (PIC10LF320/322)
  - 2.3V to 5.5V (PIC10F320/322)
- Power-On Reset (POR)
- Power-up Timer (PWRT)
- Brown-Out Reset (BOR)
- Ultra Low-Power Sleep Regulator
- Extended Watchdog Timer (WDT)
- Programmable Code Protection
- Power-Saving Sleep mode
- Selectable Oscillator options (EC mode or Internal Oscillator)
- In-Circuit Serial Programming™ (ICSP™) (via Two Pins)
- In-Circuit Debugger Support
- Fixed Voltage Reference (FVR) with 1.024V, 2.048V and 4.096V ('F' variant only) Output Levels

Low-Power Features (PIC10LF320/322):

- Standby Current:
  - 20 nA @ 1.8V, typical
- Operating Current:
  - 25 μ A @ 1 MHz, 1.8V, typical
- Watchdog Timer Current:
  - 500 nA @ 1.8V, typical

Peripheral Features:

- Four I/O Pins:
  - One input-only pin
  - High current sink/source for LED drivers
  - Individually selectable weak pull-ups
  - Interrupt-on-Change
- Timer0: 8-Bit Timer/Counter with 8-Bit Programmable Prescaler
- Timer2: 8-Bit Timer/Counter with 8-Bit Period Register, Prescaler and Postscaler
- Two PWM modules:
  - 10-bit PWM, max. frequency 16 kHz
  - Combined to single 2-phase output
- A/D Converter:
  - 8-bit resolution with 3 channels
- Configurable Logic Cell (CLC):
  - 8 selectable input source signals
  - Two inputs per module
  - Software selectable logic functions including: AND/OR/XOR/D Flop/D Latch/SR/JK
  - External or internal inputs/outputs
  - Operation while in Sleep
- Numerically Controlled Oscillator (NCO):
  - 20-bit accumulator
  - 16-bit increment
  - Linear frequency control
  - High-speed clock input
  - Selectable Output modes
    - Fixed Duty Cycle (FDC)
    - Pulse Frequency (PF) mode

Appendix B: European and French Sensor Industry Technology, Market and Trends (April 2008)

End application Market	Definition
Aerospace/Defense	Embedded sensors in aerospace and military platforms (civil/military aircraft, weapons, etc.)
Automotive	Embedded sensors in passenger cars (engine, body, chassis)
Building	Embedded sensors in home, office and public buildings as well as real estate infrastructures (civil engineering)
Consumer	Embedded sensors in mass market products (mobile phones, TVs, media players, computers, etc.)
Energy	Sensors used in power plants as well as energy transportation networks
Environment	Sensors used to monitor environmental parameters (meteorological sensors, air/water monitoring, etc.), excluding those integrated to an equipment platform (e.g. gas sensors in cars)
Home Appliances	Embedded sensors in large and small appliances (coffee machine, washer and dryer, etc.)
Industrial	Sensors used in industrial process and manufacturing including petrochemical industries, equipment manufacturing and assembly plant, food industry, etc.
IT infrastructure	Embedded sensors in computer and telecom networks and infrastructure (e.g. data warehouse)

Laboratories/test	Sensors used in R&D, laboratories and for test purposes
Medical	Embedded sensors in medical equipment including medical imagery, drug delivery, implantable devices, homecare devices, etc.
Security	Sensors used for personal, goods, site and homeland security
Transport	Sensors used in railway and marine transportation equipment and networks

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Appendix C: Table of power equations

No.	Power equation	Power generators	Characteristic
2-3	$P_{mech,max,piezo,direct}$ $= \frac{\omega F^2 X}{2\pi AY}$	Direct force piezoelectric power generators	The maximum amount of mechanical power available for extraction
2-6	$P_{mech,max,iner}$ $= \frac{2}{\pi} X_0^2 Q \omega^3 m$	Spring-mass inertial power generators	The maximum amount of mechanical power available for extraction; input sinusoidal vibration wave
2-15	$P_{elec,max,iner}$ $= \frac{P_{mech,max,iner} \zeta_e \pi}{4(\zeta_e + \zeta_m)}$	Spring-mass inertial power generators	The maximum amount of electrical power can be generated; input sinusoidal vibration wave; both electrical and mechanical damping are linear
2-20	$P_{elec,max,electret}$ $= \frac{\sigma^2}{\frac{4\epsilon_0\epsilon_2}{d} \left(\frac{\epsilon_2 g}{\epsilon_1 d} + 1 \right)} \cdot \frac{dA(t)}{dt}$	Parallel-plate electret power generators	The maximum electrical power output for the in-plane micro electret power generator; not consider electric fringing field effect

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2-	$P_{coupled,max electrostatic}$	Electrostatic	The maximum power
21	$= \frac{2Y_0^2 \omega^3 m \omega_c^4}{\pi \sqrt{(1+U^2 \omega_c^2)(1-\omega_c^2)^2}}$ $\times \left[\frac{1}{(1-\omega_c^2)^2} - \frac{\omega_c U}{\sqrt{(1+U^2 \omega_c^2)(1-\omega_c^2)^2}} \right]^{\frac{1}{2}}$	power generators	coupled as a result of energy dissipated in the coulomb damper with the constant coulomb force F in the direction opposing the motion

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Appendix D: Fast Fourier Transform expression of overlapping length between one electrode cell and one electret cell

Figure D-1 shows the equilibrium position when electrode cells and electret cells are at the 100% overlapping status.

Figure D-1

When the electrode cells are moving along x axis, the overlapping length $l_{II}(x)$ between an electret cell and an electrode cell is:

$$l_{II}(x) = \begin{cases} -\frac{2L}{T_0}x + L_0 & \left(0 \leq x \leq \frac{T_0}{2}\right) \\ \frac{2L}{T_0}x + L_0 & \left(-\frac{T_0}{2} \leq x \leq 0\right) \end{cases} \quad \text{D-1}$$

where $T_0 = 2L_0$ is the period of the overlapping motion. This periodic overlapping motion can be represented by the Fourier Series:

$$l_{II}(x) = \frac{a_0}{2} + \sum_{n=1}^{\infty} a_n \cos \omega_n x + b_n \sin \omega_n x \quad \text{D-2}$$

where $\omega_n = n\omega_0$, $\omega_0 = \frac{2\pi}{T_0}$,

The coefficient a_0 , a_n , b_n in Equation D-2 are derived as follows:

$$a_0 = \frac{2}{T_0} \int_{-\frac{T_0}{2}}^{\frac{T_0}{2}} l_{II}(x) dx = L_0$$

$$a_n = \frac{2}{T_0} \int_{-\frac{T_0}{2}}^{\frac{T_0}{2}} l_{II}(x) \cos n\omega_0 x dx = \begin{cases} \frac{4L_0}{n^2 \pi^2} & (n = 1, 3, 5, \dots) \\ 0 & (n = 2, 4, 6, \dots) \end{cases}$$

$$b_n = \frac{2}{T_0} \int_{-\frac{T_0}{2}}^{\frac{T_0}{2}} l_{II}(x) \sin n\omega_0 x dx = 0 \quad \text{D-3}$$

By substituting a_0 , a_n , and b_n into Equation D-2:

$$l_{II}(x) = \frac{L_0}{2} + \sum_{n=1}^{\infty} \frac{4L_0}{n^2 \pi^2} \cos \frac{n\pi}{L_0} x \quad (n = 1, 3, 5, \dots)$$

$$l_{II}[x(t)] = \frac{L_0}{2} + \frac{4L_0}{\pi^2} \sum_{i=1}^{\infty} \frac{1}{(2i-1)^2} \cos \left[\frac{(2i-1)\pi}{L_0} x(t) \right] \quad \text{D-4}$$

Figure D-2

If the equilibrium position is at the 0% overlapping status, using the same method, l_I

$[x(t)]$ is obtained:

$$l_I[x(t)] = \frac{L}{2} - \frac{4L}{\pi^2} \sum_{i=1}^{\infty} \frac{1}{(2i-1)^2} \cos \left[\frac{(2i-1)\pi}{L} x(t) \right] \quad \text{D-5}$$

Appendix E: Pull-in study without considering fringing field effect

Figure E-1

Assume the vertical spring constant of spring is k_z . Mass with electrode cells experiences a vertical displacement of z due to attractive electrostatic force. Capacitance of capacitor composed of electrode plate and electret plate is:

$$C = \frac{n\epsilon_0 A}{\frac{d}{\epsilon_2} + \frac{g-z}{\epsilon_1}} \quad \text{E-1}$$

The total potential energy in the capacitive system:

$$U = -\frac{1}{2} \frac{n\epsilon_0 A}{\frac{d}{\epsilon_2} + \frac{g-z}{\epsilon_1}} V_s^2 + \frac{1}{2} k_z z^2 \quad \text{E-2}$$

Where the first term is the electrostatic potential of the deformable capacitor with biased voltage V_s provided by electrets and the second term is due to the mechanical energy stored in the spring. The force acting on the movable plate is obtained by deriving Equation E-2:

$$F_{ez} = -\frac{\partial U}{\partial z} = \frac{1}{2} \frac{n\epsilon_0 A}{\epsilon_1 \left(\frac{d}{\epsilon_2} + \frac{g-z}{\epsilon_1} \right)^2} V_s^2 - k_z z \quad \text{E-3}$$

At equilibrium, the electrostatic force and spring force cancels ($F_z=0$), and Equation E-3 gives:

$$\frac{1}{2} \frac{n\epsilon_0 A}{\epsilon_1 \left(\frac{d}{\epsilon_2} + \frac{g-z}{\epsilon_1} \right)^2} V_s^2 = k_z z \quad \text{E-4}$$

Equation E-3 can be solved for the equilibrium plate position z as a function of surface potential on electrets V_s . A simple expression for the pull-in point is obtained by deriving Equation E-3:

$$\frac{\partial F_z}{\partial z} = \frac{1}{2} \frac{2}{\epsilon_1} \frac{n\epsilon_0 A V_s^2}{\epsilon_1 \left(\frac{d}{\epsilon_2} + \frac{g-z}{\epsilon_1} \right)^3} - k_z \quad \text{E-5}$$

Substituting Equation E-4 into E-5 gives the stiffness around the equilibrium point:

$$\frac{\partial F_z}{\partial z} = \frac{2k_z z}{\left(\frac{\epsilon_1 d}{\epsilon_2} + g - z \right)} - k_z \quad \text{E-6}$$

The unstable point is given by $\frac{\partial F_z}{\partial z} = 0$, therefore the unstable position is at:

$$z = \frac{\frac{\epsilon_1}{\epsilon_2} d + g}{3} \quad \text{E-7}$$

Substituting Equation E-7 into E-4 gives the minimum gap we can have if the surface potential V_s is set at certain value:

$$\frac{1}{2} \frac{\epsilon_0 n A V_s^2}{\epsilon_1} = \frac{4}{9} k_z \frac{\frac{\epsilon_1}{\epsilon_2} d + g}{3} \left(\frac{d}{\epsilon_2} + \frac{g}{\epsilon_1} \right)^2 \quad \text{E-8}$$

Multiplying $\epsilon_1^2 \epsilon_2^3$ at both sides, gives:

$$\frac{1}{2} \epsilon_0 \epsilon_1 \epsilon_2^3 n A V_s^2 = \frac{4}{27} k_z (\epsilon_1 d + \epsilon_2 g)^3 \quad \text{E-9}$$

Therefore, to prevent pull-in occurrence, the minimum gap we can have in the capacitive system with certain spring design and surface potential on electrets is

$$g_{\min} = \frac{3}{2} \sqrt{\frac{\varepsilon_0 \varepsilon_1 n A V_s^2}{k_z}} - \frac{\varepsilon_1}{\varepsilon_2} d \quad \mathbf{E-10}$$

Appendix F: Schematic drawing of corona charging system

Figure F-1 Specification of BeCu needle used in corona charging system

Figure F-2 Schematic drawing of corona charging system

Figure F-3 Picture of corona charging system

Appendix G: Charging electric field across dielectric material

Figure G-1

During the corona charging, the electric field in the air gap and inside LDPE is denoted by E_{g1} and E_d , respectively. The potential difference V between the grid and the sample is:

$$V = V_g - V_e \quad \text{G-1}$$

D_1 and D_2 are normal component due to dipole polarization in the air medium and LDPE medium, respectively

$$D_1 = \epsilon_1 \epsilon_0 E_{g1}, D_2 = \epsilon_2 \epsilon_0 E_d \quad \text{G-2}$$

According to boundary conditions, the normal component of D is continuous across the boundary. This means that at the interface between air and LDPE

$$D_1 = D_2 = D \quad \text{G-3}$$

Implementing Gauss's law, the electrical charge Q contained in the interior of the closed surface S can be expressed by:

$$\oint_s D \cdot dS = Q \quad \text{G-4}$$

And the charging configuration can be described by a capacitor model with capacitance of C , and biased by potential difference of V :

$$D = \frac{Q}{S} = \frac{CV}{S} \quad \mathbf{G-5}$$

Therefore, D_2 is derived as:

$$D_2 = \frac{\varepsilon_0 V}{\frac{d}{\varepsilon_2} + \frac{g_1}{\varepsilon_1}} \quad \mathbf{G-6}$$

Hence, by combining Equation G-6 with G-2, E_d across LDPE is

$$E_d = \frac{V_g - V_e}{d + \frac{\varepsilon_2}{\varepsilon_1} g_1} \quad \mathbf{G-7}$$

Appendix H: Trek, Inc. Non-contacting electrostatic probe selection chart

Electrostatic Voltmeter Model	Aperture Size
Model 320C	6.35 mm dia.
Model 323C	1.32 mm dia.
Model 325	4.6 mm dia.
Model 341B	3.05 mm × 1.52 mm
Model 344; Model 347	0.79 mm dia.; 2.56 mm dia.; 1.17 mm dia.; 1.32 mm dia.
Model 368A; Model 370	1.85 mm dia. ; 2.35 mm dia. ; 1.6 mm dia.
Model 370TR	1.5 mm × 3.0 mm; 5.3 mm dia.

Appendix I: Properties of electrically insulating thermal grease

AIT Product	Thermal conductivity (watt/m-K)	Electrical resistivity (ohm-cm)	T _g (°C)
Cool-Grease ®CGR 7016	>4.0	> 1×10 ¹⁴	Grease

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3. **S.W. Liu**, Z.Y. Shen, S.W. Lye, and J.M. Miao, *Stable micro sized electret array produced by localized charging using silicon a silicon shadow mask*, Micro & Nano Letters, 2012, 7(11), pp.1094-1096
4. **S.W. Liu**, S.W. Lye, and J.M. Miao, *Sandwich structured electrostatic/electrets parallel-plate power generator for low acceleration and low frequency vibration energy harvesting*, Proceedings of the IEEE International Conference on Micro Electro Mechanical Systems(MEMS), 2012, art.no. 6170390, pp.1277-1280
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7. Z.Y. Shen, **S.W. Liu**, J.M. Miao, S.W. Lye and Z. Wang, *Proof mass effects on spiral electrode d33 mode piezoelectric diaphragm-based energy harvester*, Proceedings of the IEEE International Conference on Micro Electro Mechanical Systems(MEMS), 2013, art.no. 6474369, pp.821-824