Chapter 1 Introduction

1.1 Motivation

Micro-Electro-Mechanical System (MEMS) is a technology platform based on the planar fabrication processes in the IC industry. Because most of the materials and processes are similar to those used in IC fabrication, the goal of MEMS actuators, sensors, and micro systems development is the integration with circuits to form a smart module or system.

When micro systems become more mature, various smart networks employing micro sensors or transducers have been proposed, such as RFID and wireless sensor network [1]. In these applications, every node or tag may have the need of an independent power supply. In addition, portable 3C devices such as cell phones and PDA's also need stand-alone and stable energy source with long lifetime. Traditionally, batteries are used for such applications, though they have issues like limited lifetime, small energy density, large volume or weight, and potential of environmental pollution.

Fortunately, advances in the low power Very Large Scale Integration (VLSI) design along with the low duty cycles of wireless sensors have reduced power requirements to the range of tens to hundreds of microwatts [2]. Similar application is used on personal health monitoring [3], where remote or independent power supply is critical, to build more compact or longer-life-time modules. Such low power dissipation opens up the possibility of powering the sensor nodes by scavenging ambient energy from the environment. Therefore, the better alternative is to utilize and convert the energies in the environment into electricity, eliminating the needs for batteries and extending the lifetime indefinitely.

In particular, energy scavenge from ambient natural sources, such as vibration [4], radioisotope [5], ambient heat [6], is attracting much recent interests. Among various approaches, electrostatic vibration-to-electric energy conversion using the micro-electro-mechanical systems (MEMS) technology is chosen in this study due to its compatibility to CMOS processes and ubiquity of the energy source in nature.

1.2 Literature overview

1.2.1 Energy scavenging technologies

Many methods to harvest or scavenge energy from the environment for use by low power electronics have been studied. Perhaps the most widely used and most mature method to scavenge energy is the photovoltaic cell or the solar cell. Solar energy is abundant outdoors during the daytime. In direct sunlight at midday the power density of solar radiation on the earth surface is roughly 15mW/cm^2. Silicon solar cells are mature technology with efficiencies ranging from 12% to 25% for single crystal silicon cells. Thin film polycrystalline and amorphous silicon solar cells are also commercially available and cost less than single crystal silicon, but also have lower efficiency [7]. If the target application is outdoors and needs to operate primarily during the daytime, solar cells offer an excellent and technically mature solution. However, in normal office lighting, the same solar cell will only produce about 10 μW/cm^2, which is not nearly enough of most applications. Solar cells are very good when sufficiently intense light is available, but are inadequate in many other applications.

Naturally occurring temperature variations can also provide a means by which energy can be scavenged from the environment. A thermoelectric micro-device capable of converting 15μW/cm^3 from a 10℃ temperature gradient has been demonstrated [8]. For such a converter, the energy conversion mechanism is based on the electric potential difference between two materials with different temperatures (thermoelectric effect). Since the materials used to make up the thermocouples can be stacked films of polysilicon, aluminum, copper, etc., which have been used a lot in semiconductor industry, the fabrication process is compatible to the IC process. However, the temperature difference is the essential condition and the application is therefore limited. One possible application is to operate with energy consuming ICs like the CPU and recycle the waste heat into electricity.

Another source is the acoustic noise. However, there is far too little power available form acoustic noise to be of use in the scenario being investigated, except for very rare environments with extremely high noise levels [1]. Therefore, it is not a feasible energy source for most applications.

A significant amount of work has been done on the possibility of scavenging power off the human body for use by wearable electronic devices [9, 10]. The conclusion of studies undertaken at MIT suggests that the most energy rich and most easily exploitable source occurs at the foot during heel strike and in the bending of the ball of the foot. This research has led to the development of the piezoelectric shoe inserts and the power density available from the shoe inserts is 330μW/cm^3. However, the problem of how to get the energy from the foot to other places on the body has not been satisfactorily solved. For an RFID tag or other wireless device worn on the shoe, the piezoelectric shoe inserts offer a good solution. Similar to temperature variation method, the application space for such devices is limited.

Theory and experiments show that about 200 μW/cm^3 could be generated from vibrations that might be found in certain building environments [11]. Vibrations were measured on many surfaces inside buildings, and the resulting spectra were used to calculate the amount of power that could be generated. A more detailed discussion of this process is presented in Chapter 2. It is believed that conversion of vibrations to electricity can be sufficient for applications in certain indoor environments [11].

Batteries or fuel cells were the most commonly applied energy source. However, they have the issue of bulky device and limited lifetime. Not to mention the pollution issues of batteries. The energy densities are listed in Table 1.1 for comparison.

Comparison of power scavenging and energy sources are shown in Table 1.1[1,12] , The top part of the table contains energy source; the bottom part of the table contains energy storage devices. Based on the survey above, vibrations was chosen as the source of energy scavenging for it is ubiquitous and has more power density.

Table 1.1 Comparison of power scavenging and energy sources [1,12]

Energy source	**Power density**	**Energy density**
Solar (outdoors)	15 ,000μW/cm^2 -Direct sun 150μW/cm^2 -Cloudy day	
Solar (indoors)	6 μW/cm^2 -office desk	
Vibrations*	200 μW/cm^3	
Acoustic noise	0.003 μW/cm^2 at 75 dB 0.96 μW/cm^2 at 100 dB	
Temperature gradient	15μW/cm^3 at 10℃ gradient	
Shoe inserts	330 μW/cm^3	
Batteries (zinc-air)		1050 -1560 mWh/cm^3
Batteries (rechargeable lithium)		300 mWh/cm^3 (3 - 4 V)
Hydrocarbon fuel (micro heat engine)		333μW/cm^3
Fuel cells (methanol)		280μW/cm^3

*The converted power is from piezoelectric converter.

Vibration-to-electricity conversion

Vibration-to-electricity conversion offers the potential for wireless sensor nodes to be self-sustaining in various environments. Low level vibrations occur in environments such as automobiles, aircraft, ships, trains, large commercial buildings, industrial environments, and residential households.

A few groups have devoted research effort toward the development of vibration-to-electricity converters. An electromagnetic vibration-to-electricity micro-generator was first developed [13-15]. The generator had a footprint of roughly 4mm×4mm and generated a maximum of 0.3 μW from a vibration source of displacement magnitude 500 nm at 4.4 kHz. A generic second order linear model for power conversion was developed and close agreement between the model and experimental results were demonstrated. The electromagnetic generator was only 1mm thick, and thus the power density of the system was about 10 - 15μW /cm^3.

The calculated AC output voltage of the 0.3μW generator was 8 mV, which was too small to be rectified by a bridge rectifier that required a turn-on voltage of about 0.5 V. Therefore, this power source would need a large linear transformer to first convert the AC voltage up by at least a factor of 100 and preferably a factor of 500 to 1000.

A second issue is that the vibrations used to drive the device are of magnitude 500 nm, or 380 m/s^2, at 4.4 kHz. It is exceedingly difficult to find vibrations of this magnitude and frequency in many environments. These vibrations are far more energetic than those measured in common building environments. Nevertheless, it represented the first effort to develop micro or meso scale devices that converted vibrations to electricity

More recently, another group has developed an electromagnetic converter [2, 16, 17]. The electromagnetic converter was quite large and designed for vibrations with magnitude of about 2 cm at about 2 Hz generated by a walking person. Their simulations showed a maximum of 400 μW from this source under idealized circumstances (no mechanical damping or losses). The maximum measured output voltage was reported as 180 mV, necessitating a 10 to 1 transformer in order to be rectified. The device size was 4cm×4cm×10cm, and therefore the maximum power density according to the simulation would be 2.5μW/cm^3.

The energy output produced by the electromagnetic converter is proportional to the magnetic field and coil number. Therefore, the need of an external permanent magnet to provide the fixed magnetic field makes it difficult to be integrated with a micro system. Another issue is that it is difficult to fabricate large number of high quality coils with planer thin film processes. Thus the energy density of electromagnet converter using MEMS technology is lower than other types of devices.

Optimal power circuitry design for piezoelectric generators driven by vibrations has been studied [18, 19]. The maximum power output reported was 18 mW. The footprint area of the piezoelectric converter was 19 cm^2. The height of the device was not given. Assuming a height of about 5 mm gave a power density of 1.86 mW/cm^3. The frequency of the driving vibrations was reported as 53.8 Hz, but the magnitude is not reported. Prototypes of piezoelectric converters were also designed by another group [11, 12]. The piezoelectric converter generated a power density of 200μW/cm^3 for the vibration input 2.25m/s^2 at 120 Hz.

In the piezoelectric converter, high-piezoelectric-constant materials such as PZT are difficult to deposit and incompatible to the IC process. Most researches so far still utilize bulk materials, which is not suitable for the integrated microsystems.

The electrostatic converter demonstrated in [2, 16, 17] used a MEMS process with Silicon on Insulator (SOI) substrates. The generator was a standard comb drive [20] except that it was used as a generator instead of an actuator. Published simulation results for their system predicted a power output of 8.6 μW for a device size of 1.5cm× 0.5cm×1mm from a vibration source at 2.52 kHz (amplitude not specified). However, no actual test results published to date. Another optimal design for electrostatic converter was proposed [4] with an output power density of 110 $\mu W/cm^3$ under vibration input $2.25 m/s^2$ at 120 Hz predicted.

In general, the fabrication techniques for electrostatic converter are very mature in MEMS system, and the materials and process are compatible with IC process. Therefore, it is suitable to serve as a power supply for integrating in the microsystem. The drawback of the electrostatic converter is that it needs an auxiliary voltage source V_{in} to initiate the conversion periods. However, it is expected that besides powering the loaded microsystem or sensor nodes, the output power can be feedback to the external voltage source and recharge it. If the output power from the energy converter exceeds the need of load terminals, the external supply voltage source has no energy loss, and the system becomes self-sustained.

1.3 Thesis objective and organization

From the above literatures survey, electrostatic vibration-to-electricity converters are studied in this thesis in consideration of IC process compatibility and ease of integration with microsystems.

The objectives includes

(a) Construct a dynamic system simulation model and design an electrostatic vibration-to-electricity converter.

(b) Fabricate the device based on optimal design form the simulation and measure the mechanical and electrical characteristics.

In order to design the vibration to electricity converter, the nature of vibrations from potential sources must first be studied. Chapter 2 presents the characterization of several common occurring low level vibrations. A general conversion model and complete converter design are also presented in Chapter 2. The fabrication process, process issues and process results are described in Chapter 3. The measurement results and discussions are presented in Chapter 4. Future works will be discussed in Chapter 5.