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PIEZOELECTRIC SENSING APPLICATION FOCUSED ON ACCELERATOR DESIGN

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ABSTRACT

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(*Keywords: Piezoelectric, vibration, cantilever, signal amplifier*)

Accelerometer is an electronic device used to measure the activity of vibration and shock which present in all areas of our daily lives. They may be generated and transmitted by motors, turbines, machine-tools etc. In this project, a low cost accelerometer device is developed for the use of measuring vibration level from vibration sources such as motor engine, machineries with a simple set-up using piezoelectric cantilever. The accelerometer is developed using easily available piezoelectric materials with physical area about a few cm^2 (3cm x 5cm) which can easily mounted in the form of a cantilever. The piezoelectric cantilever was obtained off-the-shelf and tailor made to suit to the application as an accelerometer. The accelerometer was designed to operate at frequency higher than its resonant frequency so that a linear response would be produced. At this said frequency, the voltage output is proportional to the magnitude of the acceleration level (g-level), therefore the level of the vibration from any sources with excitation frequency higher than the piezoelectric cantilever structure natural frequency can be measured. However, at frequency range outside from resonant, the voltage output produced by the piezoelectric accelerometer is small and very difficult to measure accurately due to measurement noise. Therefore, amplifier circuit was developed to amplifier the small signal from the accelerometer before being measured and analyzed.

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Chapter 1 Introduction

1.1 Introduction

Vibration and shock are present in all areas of our daily lives. They may be generated and transmitted by motors, turbines, machine-tools, bridges, towers, and even by the human body. Piezoelectricity occurs when an electric surface charge develops on a crystalline material by mechanical stress. It was discovered by Jacques and Pierre Curie in 1880, and the inverse phenomenon, named the converse piezoelectric effect (Park, 2010)therefore, piezoceramic accelerometers are the better choice at low frequencies and low acceleration. Piezoelectric accelerometers are widely accepted as the best choice for measuring absolute vibration (Zeng, 2008). Compared to the other types of sensors, piezoelectric accelerometers have important advantages such as: Extremely wide dynamic range, almost free of noise suitable for shock measurement as well as for almost imperceptible vibration, excellent linearity over their dynamic range, wide frequency range - very high frequencies can be measured, compact yet highly sensitive, self-generating - no external power required , great variety of models available for nearly any purpose and the Integration of the output signal provides velocity and displacement (Umeda, et al., 2006).

Table 1.1 shows advantages and disadvantages of other common types of vibration sensors compared to piezoelectric accelerometers. Piezoelectric materials used for the purpose of accelerometers can also fall into two categories. The first, and more widely used, is single-crystal materials (usually quartz). Though these materials do offer a long life span in terms of sensitivity. In addition to having a higher piezoelectric constant (sensitivity) than single-crystal materials, ceramics are more inexpensive to produce. The other category is ceramic material. That uses barium titanate, lead-zirconate-lead-titanate, lead metaniobate, and other materials whose composition is considered proprietary by the company responsible for their development (Weber & Burgemeister, 2010).

Table 1.1: Advantages and disadvantages of piezoelectric accelerometers.

Sensor Type	**Advantage**	**Disadvantage**
Piezoresistive	• Measures static acceleration	• Limited resolution because of resistive noise • Only for low and medium frequencies • Supply voltage required
Electrodynamic / Geophone	• Low cost for manufacturing	• Only for low frequencies
Capacitive	• Measures static acceleration • Cheap manufacturing with semiconductor technology	• Low resolution • Fragile

An accelerometer is an electromechanical device that measures acceleration forces. These forces may be static, like the constant force of gravity pulling at our feet, or they could be dynamic caused by moving or vibrating the accelerometer (Kan, 2009). Accelerometers are available that can measure acceleration in one, two, or three orthogonal axes. They are typically used in one of three modes: As an inertial measurement of velocity and position; As a sensor of inclination, tilt, or orientation in 2 or 3 dimensions, with magnitude of acceleration refers to a factor of gravity (1 g = 9.8m/s^2). The accelerometer can also be used as a vibration or impact (shock) sensor (Garcia, et al., 2007).

Another important specification of an accelerometer for a given application is its type of output. There are two different types of accelerometer; analogue and digital. For an analogue accelerometer, the output is a level of voltage depends on the amount of acceleration applied. For a digital accelerometer, the output is in a form of frequency square wave as a result of a modulation (Boser & Howe, 1996). There are considerable advantages to using an analogue accelerometer as opposed to an inclinometer such as a liquid tilt sensor, this is because an inclinometer giving an output in the form of binary information (indicating a state of on or off), thus it is only possible to detect when the tilt has exceeded some threshold angle (Leea, et al., 2004).

One of the first micro machined accelerometers was designed in 1979 at Stanford University, but it took over 15 years before such devices became accepted as mainstream products for large volume applications (Chollet & Liu, 2011). In the 1990s MEMS accelerometers revolutionized the automotive- air bag system industry. Since they have enabled unique features and applications ranging from hard-disk protection on laptops to game controllers. More recently, the same sensor-core technology has become available in fully integrated, full-featured devices suitable for industrial applications (Setuamalingam & Vimalajuliet, 2010). There are many different ways to make an accelerometer. Some accelerometers use the piezoelectric effect they contain microscopic crystal structures that get stressed by accelerative forces, which cause a voltage to be generated. Another way to do it is by sensing changes in capacitance (Zeng, 2008).

Accelerometers can be used to measure vibration on cars, machines, buildings, process control systems and safety installations. They can also be used to measure seismic activity, inclination, machine vibration, dynamic distance and speed with or without the influence of gravity.

In an attempt to make piezoelectric cantilever work as an accelerometer by low cost and easily available piezoelectric materials (Physical size > MEMS devices about (3cm x 5cm). Piezoelectric cantilevers has to be operated in a specific frequency between (100Hz to 180 Hz) to measure the g-level and get a linear output with an error of around 5%. The power produced by the piezoelectric cantilever under vibration excitation at lower frequency is very small, for that reason need to design the operational amplifier circuit to amplify the value of voltage and detect the signal.

1.2 Problem Statement

Piezoelectric cantilevers during conversion of the mechanical motion into an electrical signal produces a small current and voltage value.

- Another important characteristic of piezoelectric cantilever based on accelerometer is the frequency response of the vibration .A good accelerometer has to be linear in response to the frequency of the vibration sources. The normal response of an accelerometer is however nonlinear.
- Improve the linearity of the sensor; a lower frequency will be examined. However, the power produced by the piezoelectric cantilever under vibration excitation at lower frequency is very small, with electrical current usually in the range of few micro-amps or mile-volt; therefore, a charge amplifier is needed to detect the signal.
- The piezoelectric cantilever has very high output impedance.

1.3 Objectives and Scope of Work

The objective of this work are:

- To study the characteristic of a piezoelectric cantilever.
- To analyze the signal of the piezoelectric cantilever as an accelerometer to be operated higher than resonant frequency ≥ 180Hz.
- Design and simulate a charge amplifier for the piezoelectric device.
- Analyze the signal of the piezoelectric cantilever as an accelerometer.

The very important point is to get a piezoelectric cantilever work an accelerometer by:

- Using low cost and easily available piezoelectric materials (Physical size > MEMS devices about (3cm x 5cm). to be mounted as a cantilever based sensor.
- Piezoelectric cantilevers has to be operated as low frequency <= 180Hz (normal operating frequency is usually 50 cycles or less).

- Identify the range of signal and amplifier the signal in order to get a linear output with an error of around 5%.
- Multisim8 software to simulate the op-amplifier circuits.
- Function generator to get the frequency and the g-level (vibration level).
- Vibration generator to vibrate the piezoelectric cantilever.

1.4 Report Outlines

Chapter 2 of this report presents the background, theories and methods of analysis and synthesis that had been used for piezoelectric cantilever and accelerometer, as well as show different types of piezoelectric cantilever and its applications, this chapter also presents the review of accelerometer and its applications. Chapter 3 presents the methodology that is used in this project and also the equipment's that's used in the laboratory. Chapter 4 shows the results have been collected from simulations and testing and will be discussed. Chapter 5 presents the conclusion, recommendations also the suggestions of future work.

Chapter 2 Literature Review

2.1 Introduction

This chapter reviews resources on Piezoelectricity and accelerometer. Of particular focus in this chapter is the design of a low cost accelerometer using piezoelectric cantilever. In that regard, scholarly and engineering literature was used to establish what was already known regarding the topic. This was important in identifying the knowledge gaps that the study was supposed to fill.

2.2 Piezoelectric cantilever and accelerometer

Shocks and vibrations generated by machine tools, human body, towers, motors, bridges and even towers are very common in day to day life. Some of them can be overlooked as they are not disturbing (Shen, et al., 2006). However, some vibrations are very destructive and cannot be overlooked. For that reason, it is imperative that accurate and safe to use methods of measuring these vibrations and shocks is developed. Such electronic equipment that accurately measures these vibrations is a low cost piezoelectric cantilever accelerometer (Galchev, et al., 2010). Piezoelectric Cantilever accelerometer utilizes piezoelectricity in measuring dynamic changes in various mechanical variables. The main mechanical variables measured by the piezoelectric accelerometer includes shock, vibration, and acceleration (Boser & Howe, 1996). In that regard, piezoelectric accelerometer is a transducer: it converts energy from one form to another. Specifically, piezoelectric cantilever responds to the quantity, condition, or property that is being measured by producing a measurable electric signal of similar magnitude (Sari, et al, 2008). It utilizes a standard sensing method in which acceleration acts on a spring restrained seismic mass suspended on a cantilever beam (Shen, et al., 2006): the general setup responsible for converting a physical quantity to an equal or respective electrical signal. This implies that acceleration is not measured directly using the piezoelectric accelerometer: it is first converted into a displacement or a force before it is converted into an electric quantity (Boser & Howe, 1996).

2.3 Piezoelectricity

Piezoelectricity comes from “piezein”: a Greek word that refers to press or squeeze (Holler, 2007). When a stress is applied on a piezoelectric crystal, it induces an electric polarization in the material that is directly proportional to the sign and the magnitude of the strain: direct piezoelectric effect. Where an elastic strain is produced by the polarizing electric field within the piezoelectric material, then a converse piezoelectric effect occurs.

The human impact with the piezo has been there for ages. This is evidenced by the primitive use of piezoelectric effects by humans such as flint in producing fire through exerting pressure on the crystal. During Stone Age, the main material that was used to produce fire, cut other materials, and in the making of tools was flint (Andres, 2001). The use of flint as a lighter was however accidental. While the ancient man was manufacturing tools, he knocked it with iron and the resultant was fire. As days progressed, more and more uses of the crystal were discovered (Zhu & Worthington, 2009). In 1880, a more serious experimental work conducted by Jacques Curie and Pierre resulted to the discovery of piezoelectricity. Through study of single crystals like quartz, tourmaline, and Rochelle salt by subjecting them to mechanical stress, Curie and Pierre noted direct piezoelectric effect (Ajitsaria, et al., 2006). Further discoveries were made during the World War 1 and the World War II. Further research on the piezoelectric crystal led to the discovery of the lead Zirconate titanate (PZT). This was a solid solution that had superior piezoelectric properties that the predecessor. From its phase diagram, PZT was established to have a morphotropic phase boundary (MPB) that lay between the rhombohedral and tetragonal phase: a property that has been harnessed in varied applications (Shen, et al., 2006).

Apart from PZT, other materials have since then, been identified regarding piezoelectric effect. For instance, in 1969, polivinylidene fluoride (PVDF) a strong uniaxial drawn strong piezoelectricity. Additionally, it also came to known that piezoelectric effect could be derived from other plastics such as nylon and polyvinyl chloride (PVC) (Garcia, et al., 2007): though of lower intensity. Currently, studies on grain-oriented glass-ceramic, a glassy and a more crystalline phase composite, is still being studied for its latent promise for a bright future in the piezoelectricity. Piezoelectric Effect Electromechanical coupling dictates that stress (T), electric field (E), strain (S), polarization (P), and flux density mechanical properties are all interrelated in piezoelectric crystals (Zhang, et al., 2006).

When a force of significant magnitude is applied to a piezoelectric material, it induces a surface charge through the dielectric displacement. Such a phenomenon leads to a build-up of electric current in the piezoelectric crystal (Galchev, et al., 2010). Identifying the electrodes and subsequently connecting probes, an electric voltage can be tapped. Shorting the electrodes results to a balance between the surface charge and the current: an effect called direct piezoelectric effect. Figure 2.1 and Figure 2.2 illustrate direct piezoelectric effect in a shorted and open circuit (Shen, et al., 2006).

Conversely, an electric field is usually sistorted whenever it acts on a piezoelectric body. When such a distortion partially or totally blocks the material, an elastic tension (T) occurs within the material (Weber & Burgemeister, 2010). In the event, a force (F) is then applied to the piezoelectric device. This prevents any distortion that could have occurred on the piezoelectric body during the process. This pghenomenon where direct piezoelectric effect is reversed is called converse or indirect piezoelectric effect. Figure 2.3 and Figure 2.4 converse effect in a piezoelectric body (Zhang, et al., 2006).

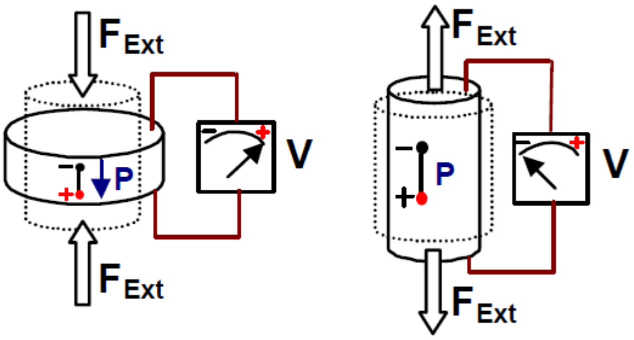


Figure 2.1: Pezoelectric direct effect in an open circuit configuration.

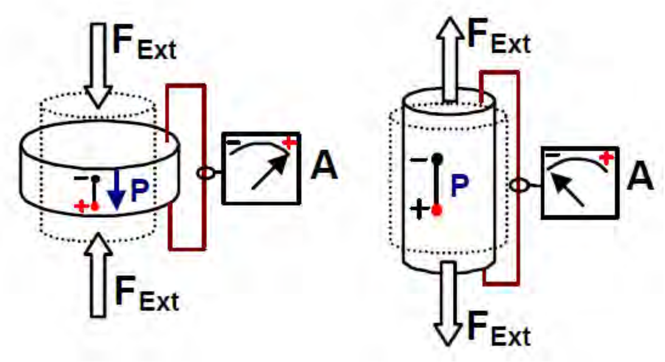


Figure 2.2: Piezoelectric direct effect in shorted circuit.

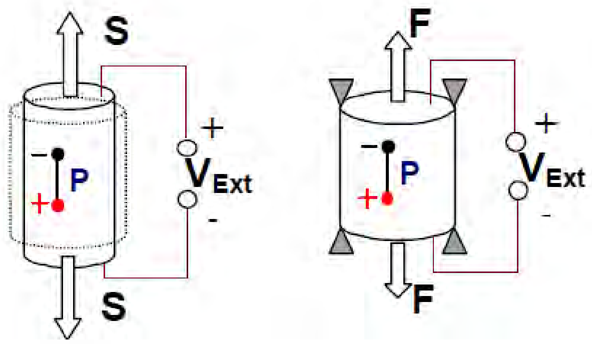


Figure 2.3: Free displacement and blocking force Converse effect.

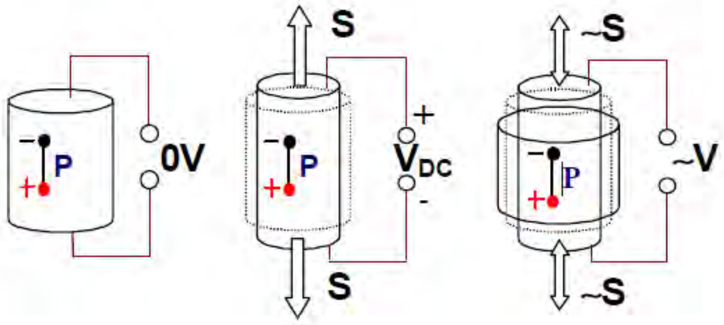


Figure 2.4: Static and dynamic operation converse effect.

2.4 Piezoelectric Materials

Piezoelectric materials are usually grouped into two: ceramics and crystals (Galchev, et al. 2010). However, quartz (SiO2 is the crystal that is widely used in the design of piezoelectricity. Apart from quartz, there are several other naturally occurring materials that exhibit piezoelectric properties. These materials include:

Berlite, sucrose, topaz, Rochelle salt, tourmaline-group of minerals. Berlinite is identical to quartz: but a very rare phosphate mineral. In topaz, the piezoelectricity action could be attributed to the effect of F,OH in its lattice. This is because of its anomalous optical properties that are caused by such ordering in the lattice.

Biological materials such as silk, wood, enamel, tendon, wood, and many viral proteins have piezoelectric properties. Additionally, a dry bone also has piezoelectric properties (Zhu & Worthington, 2009). Polymers such as Polyvinylidene fluoride (PVDF) have also been established to have piezoelectric properties.

2.5 Type of Piezoelectric Actuators/Sensors

This section will briefly review several common configurations of piezoelectric actuators or sensors that utilize the different poling configurations. For each case a description and example is given.

Piezoelectric devices generally cannot create large deformations. Also, it takes a relatively large electric field to produce a large strain. This fact, along with the material being extremely brittle makes it difficult to use as an actuation device (Leea, et al., 2004). However, if a large number of thin piezoelectric plates are glued together and wired in parallel, a large strain, or deflection, can be produced with a small electric field. This is known as a piezoelectric stack actuator. The device can also operate as an energy harvester if a force is applied in the same direction as poling. However, energy can only be generated if the force is applied longitudinally so the structure would not be very good to use in vibration applications where bending is usually used as a stress inducer (Ajitsaria, et al. 2006). Also, the volume of piezoelectric stack actuators is usually large. Both a piezoelectric stack actuator and energy harvester are shown in Figure 2.5

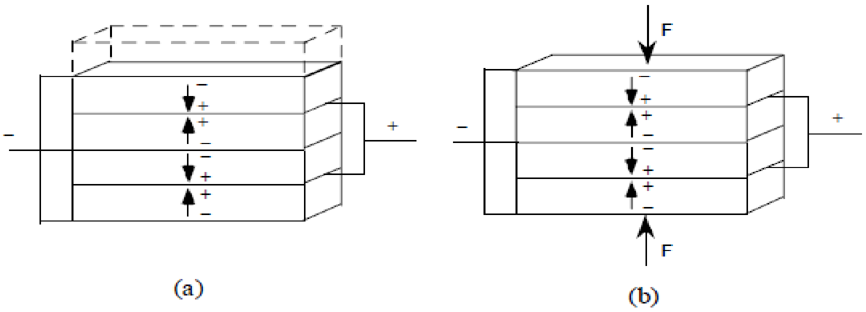


Figure 2.5: Piezoelectric Stack Actuator and Generator. (a) Actuator device (b) Energy Harvester.

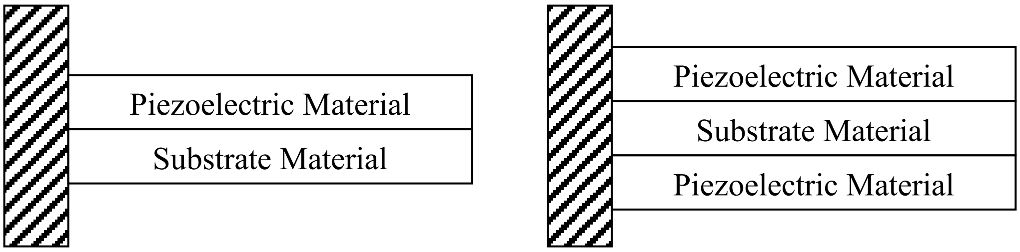
2.6 Piezoelectric cantilever/ bender device

The cantilever beam is another piezoelectric device commonly used as an actuator or generator. The cantilever is able to create relatively large deflections and take up less space than its stack counterpart. As an energy harvester, cantilever beams work well in vibration applications because high stress is induced with very little force as compared to a stack (Graham, 2000).

Since piezoelectric materials are brittle, it is common to have multiple layers in piezoelectric cantilever devices. A piezoelectric layer is used to actuate or produce energy and a non-piezoelectric layer is used to add stiffness as well as make the device more durable. When the beam has only a piezoelectric layer attached to a substrate layer, the device is known as a unimorph. When a substrate material is sandwiched between two piezoelectric materials, the device is known as a bimorph. A piezoelectric unimorph and bimorph are shown in Figure 2.6.

A piezoelectric unimorph cantilever (PUC) consists of a piezoelectric layer (PL) and a non-piezoelectric layer (NPL) as shown in Figure 2.7. The NPL is mandatory because, if the cantilever consists of only the PL, the strain neutral plane is located in the middle of the PL thickness. Above and below the strain neutral plane, the strain/stress is of opposite signs but the same magnitude (Roundy & Wright, 2004). Thus the net strain/stress in the PL is zero and no net charges can be generated. The function of the NPL is to bring the neutral plane away from the center of the piezoelectric layer so that the net strain/stress is non-zero. Preferably, the neutral plane should be outside the piezoelectric layer such that the strain/stress within the PL is of the same sign to minimize the charge cancellation.

A metal NPL is usually used which enhances the robustness of the PUC. For MEMS PUC, the NPL is typically the Si wafer. Due to the ease of construction, the PUC is widely used in both macro and micro devices (Wang, et al., 2003).



(a) (b)

Figure 2.6: Piezoelectric Cantilever Benders. (a) unimorph (b) bimorph (J. A & Staner, 2005).

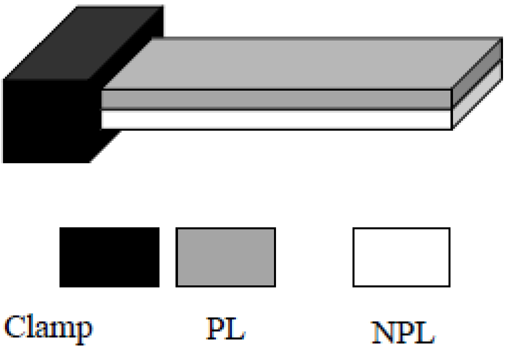


Figure 2.7: Piezoelectric unimorph cantilever (Jeon, et al., 2004).

A piezoelectric bimorph cantilever consists of two PL's sandwiching a NPL as shown in Figure 2.8. Typically the two PL's consist of the same materials of the same dimensions thus the strain neutral plane is in the middle of the cantilever thickness. The purpose of having a NPL is to provide mechanical support and electrical connection. The two PL's can be connected in serial (Figure 2.8 (a) or parallel Figure 2.8(b) to generate high voltage or current, respectively. The bimorph cantilevers are also well adopted by many. However, for MEMS energy harvesters, it is not a preferred configuration due to the limit of the thin film deposition method and the complicated fabrication process.

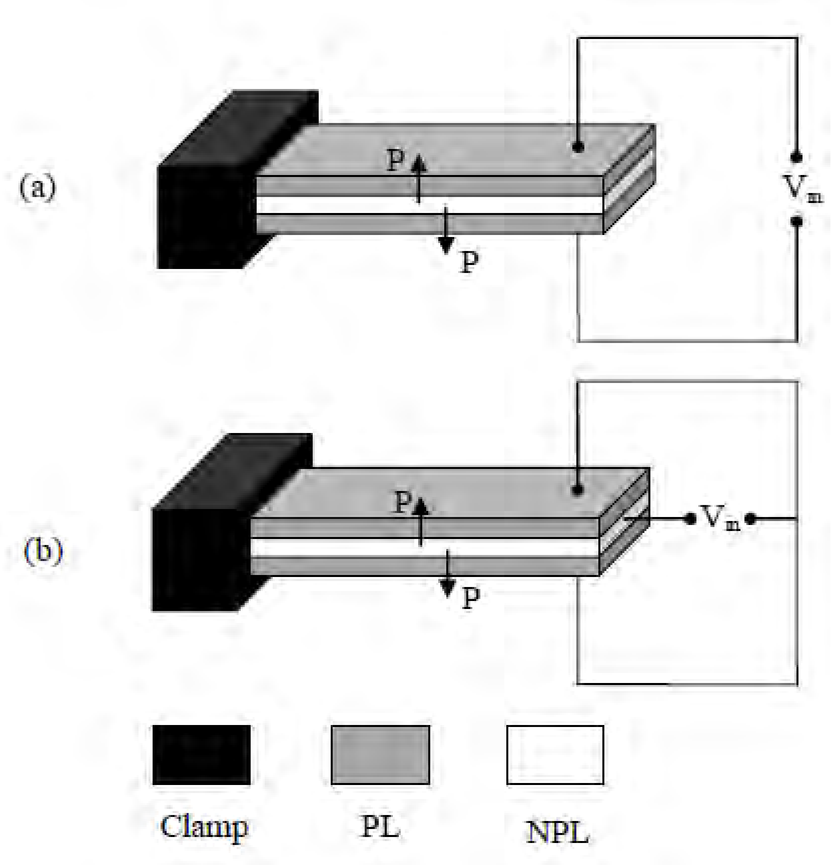


Figure 2.8: Piezoelectric bimorph cantilevers in (a) serial and (b) parallel connections. Arrows indicate the poling direction.

A multimorph cantilever has more than two PL's. It is not as popular as the unimorph and bimorph cantilevers due to the complexity of fabrication. Song et al. compared cantilevered PEH's with one, two and five thin film PL's of the same total thickness as shown in Figure 2.9. The PL's were in parallel connection. They showed that the voltage output was inversely proportional to the number of PL's while the current output was proportional to the number of PL's. In practice, appropriate voltage and current can be generated by choosing a proper number of PL's (Kan, 2009).

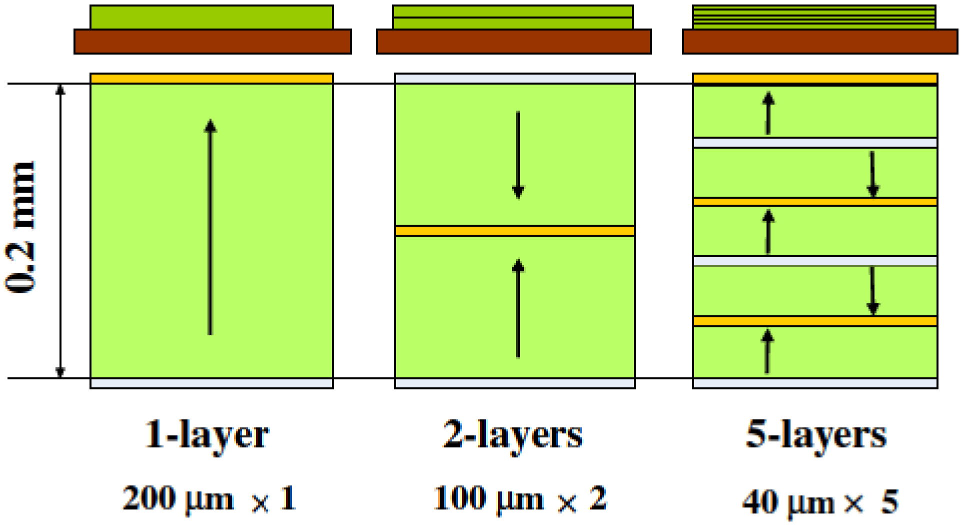


Figure 2.9: Multilayer piezoelectric energy harvester.

2.7 Applications

Piezoelectronic material as a smart material offers many different applications. It is commonly used as sensor devices. However, with the discovery of high performance piezoelectric materials such as lead zirconate titanate (PZT), the application of piezoelectric has extended to the generation of small level of electrical power. Combining the application of sensor and micro-power generator, piezoelectric can be a good candidate for developing self-power electronic devices which will be discussed in the next sub section.

2.7.1 Piezoelectric Sensors

There is a strong demand for piezoelectricity in the industrial sector more than in other sector. It is for that reason that piezoelectricity is used widely in the manufacturing and industrial applications. Automotive industry is also another sector that utilizes piezoelectricity. Apart from industrial application, piezoelectricity is also used in the design of medical equipment and instruments. In the communication sector, piezoelectricity is used to design telecommunication devices that are self-powered. Due to its wide applications, the global demand for piezoelectricity has gone up: in 2010, the value for piezoelectric devices had reached US$ 14.8 billion (Akizuki et al, 1979). Traditionally, piezocrystal has been used in various applications. However, piezopolimer in currently the fastest growing technology in the generation of piezoelectricity because of its small size and light weight design.

Piezoelectricity is used the design of high voltage power sources. Piezocrystal substances such as quartz are known to generate thousands of volts without incurring heavy costs like the geothermal and hydropower generation (Kan, 2009). In small scale application, piezoelectric principle has been used in the design of cigarette lighters, and in the auto ignition mechanism of the gas cookers and stoves.

2.7.2 Piezoelectric micro-power generator

As micro-electromechanical systems (MEMS) and smart technologies mature, the remote systems and embedded structures attract more and more interest. In applications such as micro-airplanes, the system needs an independent power supply. Traditional batteries are usually used as the source of electric energy (Zeng, 2008). The mass to electrical power ratio is quite high for batteries. Advances in battery technology have not matched the rapid advances in integrated circuit technology. Developing a miniature self-contained renewable power supply is an alternative solution for applications of remote micro-systems. The energy conversion of light, thermal or mechanical sources is an important aspect for power generators (Elwnspoek & Wiegerink, 1993). Piezoelectric materials are prospective materials for energy conversion since they have good electrical–mechanical coupling effects. As well as the solar generator and electromagnetic generator, the piezoelectric microgenerator is an alternative for small-sized equipment applications, especially for dynamical systems involving mechanical vibration (Fedder, 2003). In addition, the simplicity of the piezoelectric micro-generator is particularly attractive for use in MEMS.

So far, there have been relatively few reported studies on the piezoelectric power generators for MEMS applications. A small number of experimental studies on electrical