Properties and Performance of General Piezoelectric Materials on a Novel Cantilevered Energy Harvester

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Abstract. Piezoelectric materials are held wide attention for they introduce a renewable and convenient method on vibration energy harvesting technology. Many kinds of piezoelectric materials are investigated in the past few years. Different properties of the materials are discussed on the influences of power output. In this paper, a novel harvester are proposed to research the performance of different general piezoelectric materials. With vertically staggered rectangle-though-holes (VS-RTH) combined with the cantilevered energy harvester, modal and harmonic response analyses are simulated to test the properties of the materials. For further experimental preparation, fabrication of the material layers are introduced in detail. In addition, the charges generation mechanism is shown in the aspects of piezoelectric effect, mode and polarization. The paper lists parameters for general piezoelectric materials properties. Besides, it provides the vibration performance under different piezoelectric materials condition. Therefore, it could benefit further applications and selections of energy harvesting materials.

1. Introduction

Piezoelectric materials have been proposed as the active elements for employing in transducer, actuator, ultrasonic motor, sensor elements and robots [1]. In this paper, piezoelectric vibration energy harvester of a typical transducer is studied as its high power density, long operating life, easy micromation and compatibility with MEMS, etc. Different piezoelectric materials have been explored through synthesis, composition, fabrication and other aspects [2].

For recent years, researchers have studied on basic properties and performance of piezoelectric materials on experimental devices. Some of them are focusing on new materials which are created by adding different elements into general piezoelectric materials [3, 4]. These materials have better output generation abilities and more sustainable properties. However, they are not generally used because of difficult generation and high cost, e. g. Polyvinylidene Fluoride-Trifluoroethylene (P(VDF-TrFE)) [5, 6]. More studies are regarding on general piezoelectric materials including lead zirconate titanate (PZT), zinc oxide (ZnO) and other polymerides [7, 8]. Wang et al have researched on piezoelectric generator utilizing ZnO nanowires, which is a great advance in energy harvesting [9]. Piezoelectric polymerides and composite piezoelectric materials are gained extensive concerns for their outstanding features. Poly(vinylidene fluoride) (PVDF) is a kind of piezoelectric polymerides with large quantities employment for flexibility and high voltage constant [10]. Composite materials are welcomed since they have more advantages, such as high sensitivity of power- electricity conversion, well impedance matching, strong mechanical properties, etc. The most useful piezoelectric material is PZT [11], which is accepted by most researchers. With different classifications of PZT, it can suit for a lot of different applications.
A novel structure of energy harvester is proposed which is a cantilevered beam with four vertically staggered rectangle-through-holes. This device can interact vibrations in multi-directions. Each direction has two paralleled beams connected and vibration in the same way. More output power will be collected into superposition through VS-RTH piezoelectric energy harvester with two sets of piezoelectric layers in horizontal and vertical directions of four identical beams.

In this paper, the properties and performance under different piezoelectric materials applied to the VS-RTH energy harvester is considered. Firstly, the way of charges outputting is introduced. Secondly, different kinds of materials with their typical represents are classified. Thirdly, the modal and harmonic response analyses are simulated to gain inherent frequencies and output voltages under resonant modes. Lastly, the fabrication of the VS-RTH energy harvester are described.

2. Methodology

Properties and performance of piezoelectric materials are based on device reaction, which is the VS-RTH piezoelectric energy harvester in this paper. The VS-RTH energy harvester is a cantilevered structure with two sets of piezoelectric layers in horizontal and vertical directions of four identical beams. It vibrates in two vertically staggered directions and generates output power in superposition. The following Fig.1 shows the model of VS-RTH energy harvester, whose maximum dimension is 10 millimetres of length. This dimension is under the condition of the mesoscale and microcosmic. This research gives other energy harvesters an example to utilize and select the piezoelectric materials under the potential of minimizing their dimensions.

2.1. Charge Generation Mechanism

2.1.1 Piezoelectric effect. Direct piezoelectric effect is a phenomenon of piezoelectric crystals generating charges under mechanical stress (Fig. 2(a)). On the contrary, inverse piezoelectric effect is appearing mechanical stain in a certain direction under electrical field (Fig. 2(b)). In this paper, direct piezoelectric effect is adopted since the cantilevered device is working under vibration. The schematic diagram of piezoelectric effects is shown in Fig. 2.

Putting the microcosmic particles projection on the axis of Z to explain the piezoelectric effect. When the material is not affected by external force, three electric dipole moments \( \vec{p}_1 \), \( \vec{p}_2 \), \( \vec{p}_3 \) are mutually at 120°, whose centre of positive and negative charges are coincide, which is \( \vec{p}_1 + \vec{p}_2 + \vec{p}_3 = 0 \) shown in Fig. 2(d). When there is a pressure in the axis of \( X \), the electric dipole moment in \( X \) component is \( \vec{p}_1 + \vec{p}_2 + \vec{p}_3 > 0 \) but equals to 0 in \( Y \) and \( Z \), which means the axis of \( X \) generates positive charges and the other two arises no charges. Besides, compression and tension in axis of \( Y \) has same phenomenon shown in Fig. 2(e) and (f). In conclusion, the direct of piezoelectric effect occurs only in the direction of \( X \) [12].
2.1.2 Polarization. In order to generate charges under piezoelectric effect, piezoelectric materials should be polarized by applying a fixed DC voltage to two electrodes at a certain temperature for a period of time. Remnant polarization vectors are left between two electrodes after polarization. Thus, the direction of the electric field generated in the piezoelectric transformation will be determined, and charges accumulate on the electrodes. The polarization of the piezoelectric materials is demonstrated in Fig. 3.

2.1.3 Piezoelectric modes. Piezoelectric effect can divide into three working modes: $d_{31}$, $d_{33}$ and $d_{15}$. $d_{33}$ and $d_{15}$ are under normal stress while $d_{15}$ suffers the shear stress shown in Figure 4. In this paper, $d_{33}$ and $d_{33}$ modes are focused mainly for normal stresses are applied on the harvester.

2.2. Piezoelectric Materials Parameters

The selection of piezoelectric materials has a significant influence on energy conversion, because performance of energy harvesting is directly related to piezoelectric materials' coefficients. The following parameters of piezoelectric materials are included.

- Electromechanical coupling factor $K$: Conversion efficient of mechanical energy and electricity:
  \[
  K^2 = \frac{W_{E-M}}{W_E} = \frac{W_{M-E}}{W_M}
  \]
  where $W$ is the energy. The subscript of $E$ and $M$ represent the electric and mechanic; and $E-M$ and $M-E$ indicate the process of energy transformation. Therefore, higher $K$ is needed to attain more efficient conversion effect.

- Piezoelectric strain factor $d$: The coupling relationship between piezoelectric elastic effect and electric polarization effect. Higher $d$ is requested for stronger coupling effect.

- Relative dielectric constant $\varepsilon_r$: Dielectric and polarized properties are presented. High frequency of the piezoelectric ceramics require low $\varepsilon_r$ constant.

- Dielectric loss $\tan\delta$: Loss of piezoelectric materials caused by electric polarization. Lower $\tan\delta$ is needed to meet the high quality of piezoelectric materials performance.

- Mechanical quality factor $Q_m$: Internal friction is the cause of energy consumption inside the material during vibration conversion. In order to reduce the consumption, the higher values of $Q_m$ are required:
  \[
  Q_m = \frac{W_{E-M\text{-resonance}}}{W_{M\text{-consumption}}}
  \]
  where the subscript resonance and consumption means the storage energy under resonant vibrating condition and the consumption energy of one whole cycle.

2.3. Piezoelectric Materials Classification

Piezoelectric materials are widely used in energy researches, which are divided in three classifications. Table 1 shows the performance parameters of some commonly used piezoelectric materials.
3. Modal and Harmonic Response Analysis

In this paper, finite element method analysis is utilized to characterize the performance of the harvester. The first two resonant frequencies are derived by modal analysis and the output is simulated by harmonic response analysis. Using different kinds of piezoelectric materials including quartz crystal, PZT-5H, ZnO, PVDF and P(VDF-TrFE), the distinctions of properties are derived and compared. In the analysis, element of Solid 185 is used to analyse the substrate, and element of piezoelectric part uses Scalar Tet 98 in coupled field.

| Parameter | Inorganic | Organic | Composite |
|-----------|-----------|---------|-----------|
|           | Quartz crystal | Single crystal | bicrystal | PVDF | P(VDF-TrFE) |
| $K$       | 0.06      | 0.89    | 0.95     | 0.1  | 0.8        | —       | —       | 14     | 0.25 |
| $d_{31}$  | -0.67     | -123    | -171     | -274 | -97       | -5      | -5.43   | -20    | -25  |
| $d_{33}$  | 2~3       | 289     | 374      | 593  | 225       | 12.4    | 5       | 30     | 20   |
| $\varepsilon_r$ | 4.6 | 38     | 50       | 100  | 29        | —       | 8.5     | 12~15  | 10~15 |
| $\tan\delta$ | —     | 0.004   | 0.02     | 0.02 | 0.004    | —       | —       | —      | 0.018 |
| $Q_m$     | 100       | 500     | 75       | 600  | 1000      | 1770    | 2490    | 3500   | 0.018 |
| $E$(GPa)  | 77.8      | 76.5    | 61       | 49   | 210       | 310     | 2~8     | 2.3    |      |
| $\nu$     | 0.17      | 0.32    | 0.31     | 0.36 | 0.3       | 0.33    | 0.25    | 0.33   | 0.4  |
| $\rho$(Kg/m$^3$) | 2650 | 7500    | 7750     | 7500 | 7600      | 5660    | 3260    | 1750   | 1890 |

Table 1. Performance parameters of commonly used piezoelectric materials [8, 11, 13, 14].

3.1. Modal Analysis

Modal analysis is a method of simulating the resonant frequencies using different piezoelectric materials, which is shown in Table 2.

Table 2. First two resonant frequencies of VS-RTH harvester with different piezoelectric materials.

| Material       | Quartz Crystal | PZT-5H | ZnO  | PVDF | P(VDF-TrFE) |
|----------------|----------------|--------|------|------|-------------|
| First mode frequency (Hz) | 316.35 | 315.43 | 368.52 | 278.28 | 270.24 |
| Second mode frequency (Hz)   | 611.33 | 534.38 | 672.98 | 569.71 | 567.98 |

In this device, relatively low frequencies as well as first two closed resonant frequencies are needed. According to the table, it can be inferred that the lowest first resonant frequency is P(VDF- TrFE), which means composite piezoelectric material is the easiest device material under resonant condition. In addition, PZT-5H has the most closed frequencies, which would vibrate more efficiently.

3.2. Harmonic Response Analysis

Adding a force of 1N in the direction of Y axis on the fixed terminal supporting by simulating the actual vibrating conditions. The output voltage of single horizontal beam is shown in Fig. 5.
According to the curves, the voltage peaks are at the second resonant frequencies since the force added in Y vibrating direction, in which the device vibrates under the second mode. It could be inferred that the ZnO material generates the highest voltage, whose voltage values are an order of magnitude higher than other materials. Besides, PZT-5H shows the high efficiency in resonant frequencies and output voltage, relatively. And the quartz crystal and P(VDF-TrFE) are familiar in charges generation performance. Although PVDF shows poor charges generation performance compared with other materials, it focuses on the flexibility and easy combination properties.

3.3. Comparison of Output Performance
Comparing the five piezoelectric materials above by the modal and harmonic analytical results, PZT-5H shows the best performance synthetically. In conclusion, choosing PZT-5H as the basic material to test the output performance by applying it on different energy harvesters. In this paper, unidirectional cantilevered (UC) energy harvester is simulated which is the most basic device. The dimension of its substrate is 190×10×0.1mm with 10µm thickness piezoelectric beam attaching. The conditions of each analysis are same as VS-RTH energy harvester. The resonant frequency of the UC energy harvester is 316.98Hz, and the harmonic response to 1N force generates the maximum voltage of 4.9V. Although the voltage of single beam of VS-RTH energy harvester is lower than it, the whole harvester including four same beams are far higher. Therefore, VS-RTH energy harvester is necessary in multi-directional power collection energy harvesting technology.

4. Fabrication
Different fabrication methods of the piezoelectric materials would lead to different performance of the energy harvester [11, 15-17]. In this paper, a basic fabrication is represented in detail. Four mask reticles are employed to fabricate graphics and locations on the substrate, which use the method of sputtering. The mask reticle makes use of two paralleled plates: upper paralleled plate is used for loading with target materials to sputter metal; bottom paralleled plate is used as a splash plate made of glass substrate. Then injecting the argon (Ar₂) gas into the reaction chamber to form plasma. The argon ion is accelerated in the electric field and rammed into the target, thus, the impacted target atoms are deposited on the glass substrate to form a thin film. The following Fig. 6 and Fig. 7 show the fabrication process of $d_{31}$ and $d_{33}$ modes piezoelectric energy harvesting materials. The $d_{31}$ mode energy harvester utilizes the paralleled electrodes as well as the $d_{33}$ mode energy harvester utilizes the interphalangeal electrodes.

In Fig. 6,
The layer of SiO$_2$ is acted as barrier of charge to prevent charges flowing into the substrate and escaping. (Fig. 6(b))

Sputtering Titanium (Ti) and Platinum (Pt) orderly with ratio 1:10, where Ti film enhances the combination of electrode and substrate. (Fig. 6(c))

Deposite PZT films repeatedly and gain thick films as charges generating layer. (Fig. 6(d))

Graphing the PZT layer with special etching solution, which consists of HF: HCl: H$_2$O = 1: 25: 74 mL. In addition, put the etching fluid into 50% HNO$_3$ solution. (Fig. 6(h))

Using SF$_6$ gas in RIE etching fabrication. (Fig. 6(i, j))

Etching the back substrate with KOH solution (KOH: H$_2$O= 44g: 100mL) in 80 °C. (Fig. 6(k))

In Fig. 7,

The layer of Zirconium Dioxide (ZrO$_2$) fabricates by electron beam thermal evaporation method. ZrO$_2$ utilizes with some low index material as multi-films structure for its good mechanical and chemical stability. (Fig. 7(c))

5. Conclusion

In this paper, different general piezoelectric materials are tested through the VS-RTH energy harvester. By discussing the charges generation mechanism, the piezoelectric effect and modes are introduced. To figure out the differences between typical piezoelectric materials, the properties of widely used materials are classified and listed. For better comprehension of charges generation performance, the analysis finite element is utilized to simulate the resonant frequencies and output voltage under resonance condition. From the simulation results, the conclusion can be derived that the P(VDF-TrFE) can response the lowest frequency and which could apply to the low frequency domain vibration. Besides, ZnO generates the highest output voltage and which could be used in other devices for its high efficiency. Fabrication processes of the VS-RTH energy harvester cantilever are characterized in detail with different methods. In addition, different influences of the cantilevered layers are analysed, which could give a guidance for other fabrication of cantilevered energy harvester. Further steps are attempted to manufacture physical device and experiment the actual output power, verifying the accuracy rate of formal simulations.

6. References

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