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Fabrication of micro multilayer energy harvesters based on stainless-steel substrates

Yin-Jie Wang[1], Shou-Peng Ye[2], Shun-Chiu Lin[1] and Wen-Jong Wu[1]

[1]Department of Engineering Science and Ocean Engineering, National Taiwan University, Taipei, Taiwan
[2]Department of Engineering Electronics Engineering, National Taiwan University, Taipei, Taiwan

Abstract

In this paper, we present the development of a multilayer piezoelectric micro energy harvester. We have adopted the cantilever structure to harvest the vibration energy from environment. The multilayer type was formed by stacking three lead zirconate titanate (PZT) thick film layers on the same side, which were fabricated on stainless steel substrate. Each of the PZT thick film layers were directly deposited by the aerosol deposition method at room temperature. Generally, the drawbacks of the single PZT layer device are that they can't provide large enough current for electronic components. Therefore, in order to study the power transforming performance of our multilayer devices and improve the value of output current, we polarized each PZT layer in the same direction and connected every layer in parallel. A tungsten proof mass bonded at the tip for adjusting the resonance frequency was also demonstrated. After fabricating, we measured the output performance of our device by mounting it on the shaker to get vibration source. The device can successfully scavenge vibration energy from the environment and transform it into useful electrical energy. Finally, the experimental results show that the multilayer device can enhance the value of current by connecting every PZT layer in parallel.

1. INTRODUCTION

In recent years, the Internet of things (IOT) is a very popular concept. In short, anything connected to the internet can be controlled, monitored, or utilized. As the wearable devices and smart electronics become hot topics, IOT is expected to be the next big market. The internet of things is mainly divided into three layers. The bottom layer is the perception layer, it is formed by many different kinds of sensor components. By using the middle layer, network layer, which consists of wired or wireless network technologies, we can obtain the data accumulated from the perception layer. The topmost layer is application layer, which is a data center with great processing capabilities. It could be used for electric grid, transportation, environmental monitoring, and many other applications in different fields.

The internet of things is to use the sensing devices spread throughout different objects as the sensing layer. The data and signal obtained by these sensors can be sent via wireless transmission. These signals can be used in the application layer. There requires a large amount of energy to power the sensing devices; however traditional batteries have many disadvantages such as low lifetime, big volume, and the need to be replaced frequently. Therefore, a self-powered system to replace batteries is an important discussed topic. And the

VLSI fabrication processes have been improving, thus more and more micro scale devices require power that have gradually decreased to mere tens of microwatts. In past research [1], PMEH device can provide up to hundreds of microwatts.

A self-powered system can harvest energy from the environment. The energy harvesting device can convert that energy into electrical energy. This energy can be enhanced and stored within the electric circuit for further applications. From Roundy's research [2] that the highest power density is solar energy. However, solar energy requires a steady sun light environment, thus most of applicable areas of smart devices are restricted. Other commonly found energy source is vibration energy, piezoelectric material has the next optimal power density. Therefore we can choose piezoelectric material such as PZT to fabricate our energy harvesters. But PZT material stull faces issues such as high voltage but low current, and the current optimal load for piezoelectric harvesters are still very high. So there will be limitations for supplying energy for common electric components. So we try to change the structure of the cantilever beam. By stacking multiple layers of piezoelectric layer and connecting them in parallel, we can study the improvements in the current value.

2. DESIGN CONCEPT

2.1 Select substrates

In order to harvest the vibration source from the environment, we try to deposit the piezoelectric material on stainless-steel substrate to create a micro-scale cantilever beam design. In many studies [3], most of the piezoelectric energy harvesters are fabricated on Silicon or SOI wafer. But it has more expensive fabrication costs and cantilever beam is more brittle. So we try to use stainless-steel to be the substrate. The advantage of using stainless-steel to be substrates is that it has lower cost, ease for preparation, good mechanical properties and high extension. And a cantilever-beam structure using piezoelectric micro energy harvester will lower the production cost because it would be more easily fabricated by the wet etch method of the stainless-steel substrates [4]. Stainless steel based cantilever beam can operate for long period time under high magnitude and not break easily.

2.2 Deposition method

Akedo et al [5] and Lee et al [6] had already developed an aerosol deposition method to deposit PZT thin film directly at room temperature on silicon, stainless-steel and plastic substrates. The self-made aerosol PZT deposition chamber is able to deposit PZT film at a rate up to 5 micrometers per hour. As shown in the figure 1, it was made by powder chamber and deposition chamber. The operation of the Aerosol machine is putting the PZT powder with the particle size smaller than 1μm in diameter into a powder chamber. Vibration table will provide vibration source to powder chamber in order to suspend the PZT powder. Nitrogen or Helium gas was connected to the powder chamber so as to bring the PZT powder through the nozzle into the deposition chamber. With the chamber in a vacuumed condition, the PZT powder was jet out from the nozzle inside the chamber and bombarded onto the sample surface at high speed. As a result, the powder would be deposited to the sample surface.

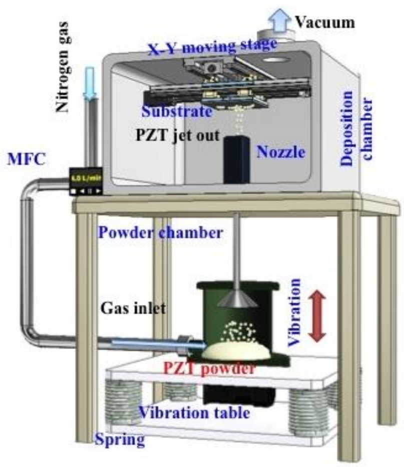


Figure 1. Schematic diagram of the aerosol PZT thin-film deposition chamber.

2.3 Structure design

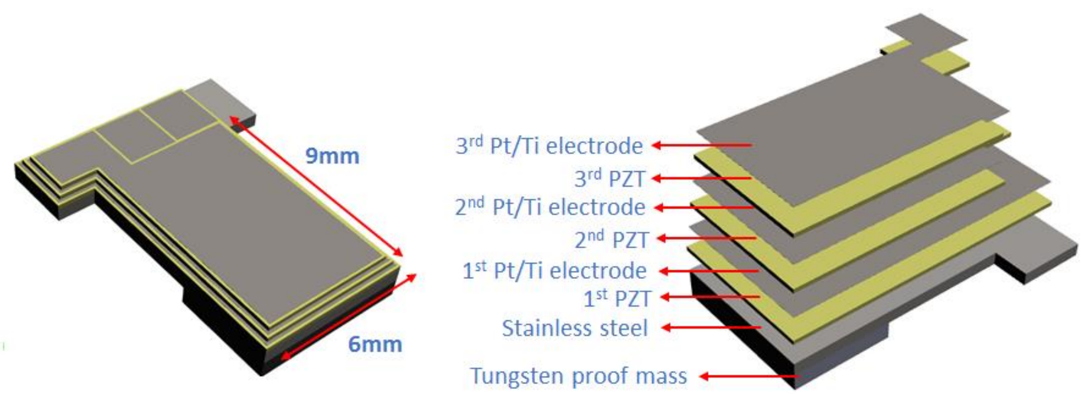


Figure 2.The schematic diagram of the cantilever beam with multilayer type.

The design diagram of the device is shown as these figure 2. Our cantilever beam structure design is to deposit three layers of PZT and electrodes on the 60 um stainless-steel substrate. Each layer of PZT is about 5 um thick, so that total thickness is around 75 um thick. The dimension of the cantilever beam is 9 mm* 6 mm. The piezoelectric layer is mainly deposited on this area. A tungsten based proof mass [7] is attached to adjust the energy harvester's resonant frequency. The volume of the tungsten proof mass is 6 mm* 4 mm* 0.9 mm. The resonant frequency of the structure is around 132 Hz (figure 3) as seen from Comsol simulation.

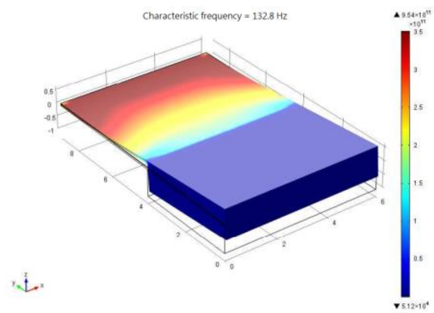


Figure 3.The simulation of the Von Mises's stress distribution of the multilayer cantilever beam with Comsol.

3. FABRICATION PROCESS

The fabrication process of the MEMS energy harvesting device with multilayer cantilever beam is shown in figure 4. The device is fabricated on a 60μm stainless-steel substrate and the fabrication process is divided into six steps. Firstly, H_2SO_2 (sulfuric acid) and H_2O_2 (hydrogen peroxide) were used to clean the stainless-steel substrate. Secondly, the first PZT layer is patterned by a lift-off process using photo-resist and deposited for 5μm-thickness by an aerosol deposition system. After the PZT film was deposited, the upper electrode was deposited by E-beam evaporator for Pt/Ti electrode. The same procedure is done for second and third layer. Lastly we used Aqua Regia to etch out the portions of stainless-steel that defined the beam shapes, and used epoxy to bonding the tungsten proof mass. The figure 5 is eight by eight centimeter stainless-steel that can be used to fabricate thirty cantilever beams and each cantilever beam is in micro scale.

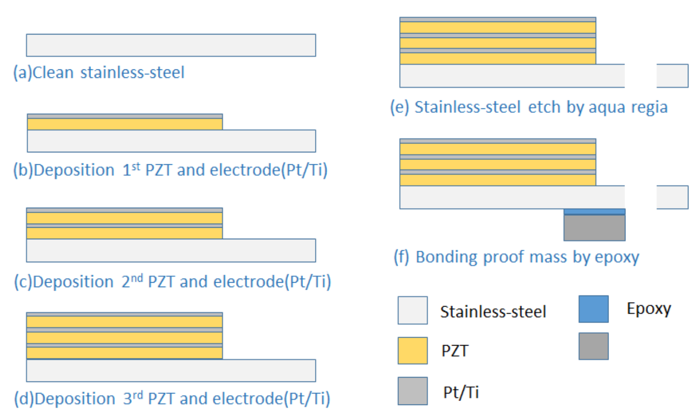
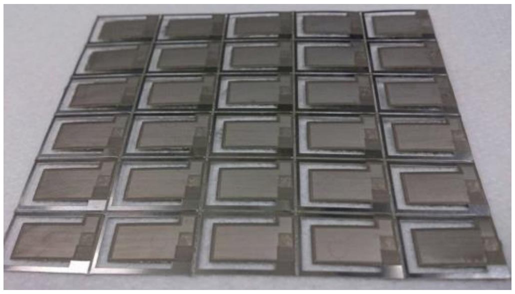
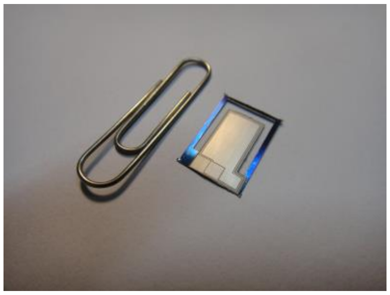


Figure 4. Schematic Diagram of the fabrication process of multilayer cantilever.





(a) (b)

Figure 5.The photograph of the multilayer MEMS energy harvester.

The devices were annealed in a furnace and then cooled down to room temperature. After annealing, the PZT layer needs to be poled under a high electric field. This process is necessary to make the dipoles within the multilayer structure to align in a specific way, such as the parallel formation seen in figure 6. By using a parallel poling method, we connect the first and third layer electrodes to positive charge, second and fourth electrodes to negative charge. The device was heated up to 160 ℃ by using a hot plate and was polled the micro piezoelectric energy harvester under 100V. The electric field was also applied during the cooling process where the device is left to cool down slowly until it reaches the room temperature.

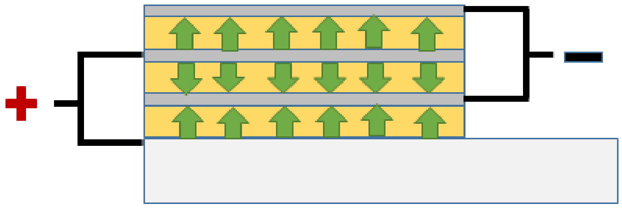


Figure 6. Parallel poling method for parallel dipole direction.

4. RESULT AND DISCUSSION

4.1 Experimental setup

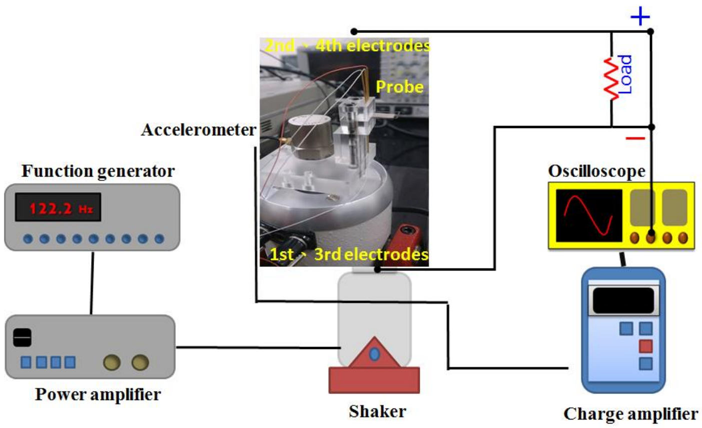


Figure 6.The schematic diagram for the experimental setup.

The schematic of the experiment setup is shown in figure 6. The multilayer piezoelectric micro energy harvester was clamped by a clamper, which was then mounted on a shaker. Then we connect the four electrodes in parallel form to measure the output voltage. The shaker acted as a vibration source to multilayer piezoelectric micro energy harvester and was controlled by a function generator through a power amplifier which provided a sinusoidal waveform, thus we can calculate the output power by measuring the output voltage when the device is parallel to the load impedance.

4.2 Experimental result

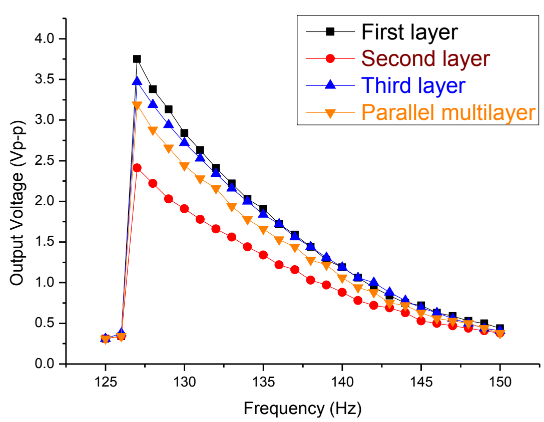


Figure 7. Output voltage versus frequency with excitation at 1.0 g acceleration.

Figure 7 shows the experimental results of the device. Under 1g acceleration, the output voltage according to different frequency for the first, second, and third layer is plotted. At resonant frequency of 127 Hz, the output voltage of each layer is 3.75 V, 2.41 V, and 3.47 V, respectively. Probes were used to connect the electrodes of each layer in parallel. Under the same acceleration of 1 g, the resonant frequency is also 127 Hz. The maximum output voltage is 3.19 V.

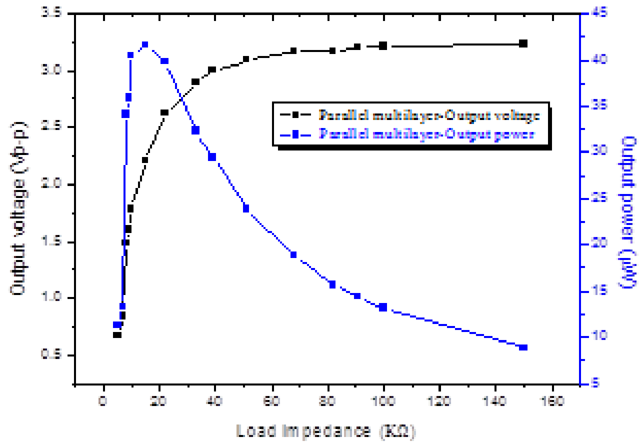


Figure 8. Output voltage and output power of different loading impedances excited at 1.0g in parallel connection.

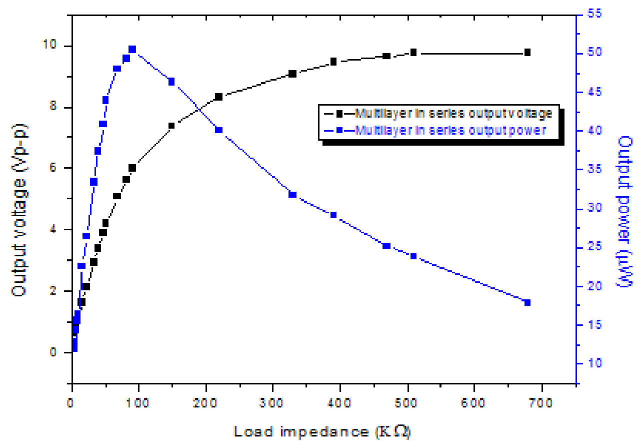


Figure 9. Output voltage and output power of different loading impedances excited at 1.0g in series connection.

Figure 8 shows the output voltage and output power of different load impendence in parallel connection at 1g acceleration under resonant frequency of 127 Hz. The black line represents the output voltage, and the blue line represents the output power. We found that the optimal load impendence is 15 kΩ and the optimal output power is 41.53 μW. To make a direct comparison with an energy harvester with the same fabrication process and structural thickness, we poled our multilayer device in the series direction. Figure 9 shows the output voltage and output power of different load impendence in series connection at 1 g acceleration under resonant frequency. We found that the optimal load impendence is 91 kΩ and the optimal output power is 50.46 μW. From these results we found out that using the multilayer structure in a parallel method can effectively lower the device's load impedance.

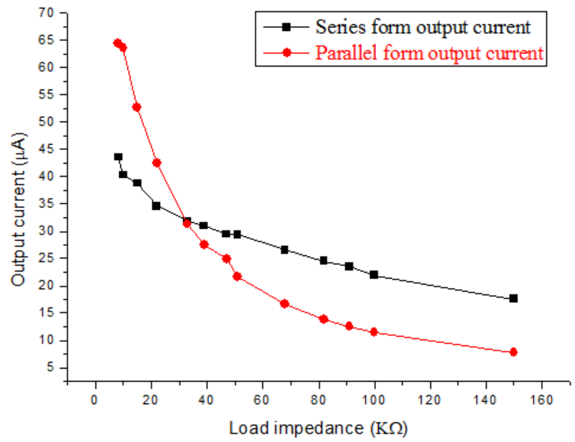


Figure 10. Comparing the output current of parallel and series from with different load impedance.

Figure 10 shows the series and parallel connection under 1g acceleration and resonant frequency the relationship between output current and load impedance. The black line represents the output current of series form. When in parallel, the optimal load impedance of 15 kΩ indicates that the output current is 52.62 μA. In series from, the optimal load is 91 kΩ and the output current is 23.55 μA. So the current is also significantly increased when the multilayer is connected in parallel at the optimal load.

5. CONCLUSIONS

In this paper, the piezoelectric micro energy harvesting device with multilayer cantilever beam has been achieved. The device has the ability to convert ambient vibration energy to useful electrical energy. The multilayer energy harvester with parallel connection can provide 3.19 volts peak to peak under 1g acceleration at the resonant frequency of 127 Hz. The optimal load at 15 kilo ohms can provide the most output power at 41.53 microwatts and output current at 52.62 microamperes. Compared to the series form, the optimal load has drastic decrease and the current value is also significantly increased.

ACKNOWLEDGMENTS

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