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Fabrication and performance of MEMS-based piezoelectric power generator for vibration energy harvesting

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Abstract

A MEMS-based energy harvesting device, micro piezoelectric power generator, is designed to convert ambient vibration energy to electrical power via piezoelectric effect. In this work, the generator structure of composite cantilever with nickel metal mass is devised. Micro-electronic-mechanical systems (MEMS) related techniques such as sol–gel, RIE dry etching, wet chemical etching, UV-LIGA are developed to fabricate the device and then its performance is measured on vibration testing setup. The investigation shows that the designed device is expected to resonantly operate in low-frequency environmental vibration through tailoring the structure dimension. Under the resonant operation with frequency of about 608 Hz, a first prototype of the generator result in about 0.89 V AC peak–peak voltage output to overcome germanium diode rectifier toward energy storage, and its power output is in microwatt level of 2.16 μW.

Keywords: Piezoelectric power generator; MEMS; Composite cantilever; Vibration; Energy harvesting

1. Introduction

Recently, stand-alone or embedded electronic devices such as RFID tags and remote sensors become more attractive. For such devices to achieve their full potential, however, practical solutions must be developed for self-powering these autonomous units. Such units need small amounts of energy supply and their miniaturization and low-power consumption trend will continue. They are often powered by conventional batteries now. However, batteries have several disadvantages: the need either to replace or to recharge them periodically and their large size and weight compared to those of microelectronic devices. To break the restriction of the batteries, energy harvesting from ubiquitous environmental vibration by micro-electronic-mechanical systems (MEMS) technology is one of the promising alternatives.

The vibration can be converted to electric energy using three types of electromechanical transducers: electromagnetic [1–3], electrostatic [4–6], and piezoelectric [7–10]. The most effective generator type depends, to some extent, on the specific operating conditions. Generally, piezoelectric generator shows higher energy conversion [9]. In addition, its simplicity is particularly attractive for use in MEMS.

Several examples of such micro-generators have been reported [1–10], and there have been relatively few reported studies especially experimental studies on the piezoelectric power generators [7–10]. Glynne-Jones et al. [7,8] provided an approach to design and model the vibration generator, in which a bulk piezoelectric generator was described. Roundy et al. [9] reported a kind of prototype of tiny, piezoelectric cantilever (9–25 mm in length) with a relatively heavy mass on the free end, which can generate 375 μW from a vibration source of 2.5 m/s^2 at 120 Hz. The scale of the device, however, is larger than that of most MEMS devices; furthermore the device fabrication is limited by manual assembly. Sood [10] presented a

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piezoelectric micro power generator (PMPG) in his dissertation. The PMPG utilized PZT d33 mode for conversion of acoustical energy to electrical power. The structure of PMPG is released from the bulk silicon by a way of XeF_2 isotropic etch step. Its acoustic operation frequency is set between 20 and 40 kHz, its power output is about 1 μW.

So far, there has been scarcely any film piezoelectric generator developed at the scale of MEMS for conversion of low-frequency vibration to electrical power. In this study, An MEMS-based composite piezoelectric cantilever structure is designed for the vibration energy harvesting. Micro fabrication process and test of the device are also emphatically described.

2. Structure design

Among common MEMS support structures, such as cantilever, doubly supported beam, diaphragm, cantilever is the most compliant one for a given input force [10]. Therefore, a composite micro-cantilever with optional proof nickel mass is designed as structure type of our generator. The metal mass on free end (tip) of the cantilever is used to decrease the structure's natural frequency for application in low-frequency vibration. As depicted in Fig. 1, the composite cantilever is made up of an upper piezoelectric thick film, sandwiched between a pair of metal (Pt/Ti) electrodes, and with a lower non-piezoelectric element. The electrodes are used to exploit 31 excitation mode of the PZT material. Though piezoelectric 33-mode conversion can achieve higher voltage output, for very low-pressure source, limited size and the simplicity in electrode arrangement, the 31-mode conversion may have a greater advantage in MEMS application [11].

The device operates as follows: when base frame of the device is vibrated by environmental groundwork, simultaneous input force feed into a second-order mechanical system, some parts of the device will move relatively to the base frame, the relative displacement cause the piezoelectric material in the system to be tensed or compressed. This in turn induces charge shift and accumulation due to piezoelectric effect. Magnitude of this electric charge voltage is proportional to the stress induced by the relative displacement.

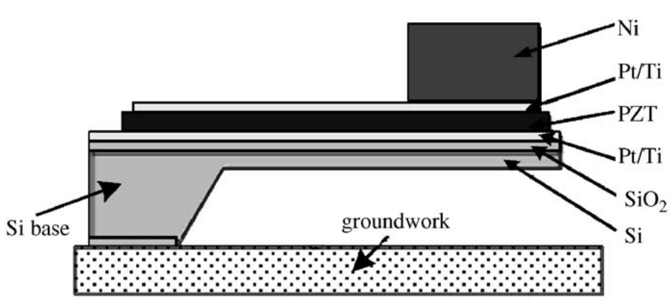

Fig. 1. Cross-sectional sketch of the generator.

It is known that resonant vibration can amplify the relative displacement remarkably. Thus, in order to generate maximum electrical power, the micro generators should be designed so that they can mechanically resonate at a frequency tuned to ambient vibration. And it is found that most of available environmental vibrations are at low frequency, no more than several tens to hundreds Hz [6]. Structure natural frequency is approximately given as $\varpi = \sqrt{k/m}$ by its stiffness (k) and mass (m). This indicates that the natural frequency of the power generator can be regulated by varying structure dimension of the moving parts.

3. Micro fabrication

The techniques of micro fabrication used here mainly involve functional films preparation and pattern, bulk silicon micromachining, structure release and mass assemblage. Fig. 2 shows the brief fabrication process.

Firstly, a (1 0 0) oriented silicon wafer, of 500 μm thickness, was wet oxidized. The layer of 2 μm thick silicon oxide serves to improve the adhesion of the bottom Ti/Pt electrode to the wafer surface and will act as mask during silicon wet etching in later process. Following that, the bottom electrode, of 30 nm thick Ti and (1 1 1) oriented 300 nm thick Pt successively, was sputtered on the oxide layer. And then, PZT films were deposited by sol–gel method [12,13]: a precursor solution was prepared from Pb acetate, Zr isopropoxide and Ti tetrobutoxide, in 2-methoxyethanol solvent, where Zr/Ti ratio is of 52/48. The 0.25 M PZT precursor with 20 mol% excess lead content in solutions was prepared and spin-on coated on $Pt/Ti/SiO_2/Si$ substrates at 3000 rpm for 20 s, followed by pyrolysis at 300 °C for 2 min. The process was repeated and PZT films with different coating layers were obtained, respectively. Finally, the rapid thermal annealing process at 650 °C for 30 min was carried out to obtain the perovskite phase PZT film. A crackless PZT film layer of 1.64 μm thick was achieved after depositing 15 coats. On the PZT film, top electrodes Ti/Pt were then sputtered.

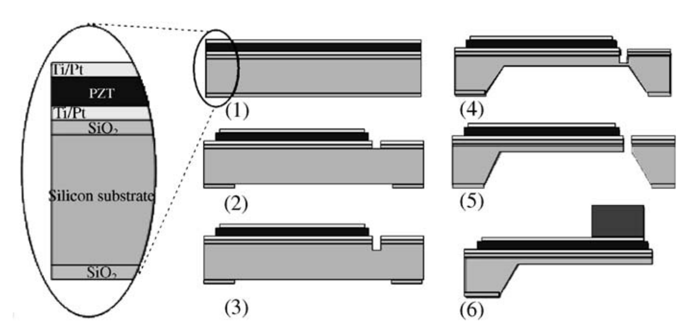

Fig. 2. Fabrication process of micro piezoelectric power generator. (1) Functional films preparation: $SiO_2/Ti/Pt/PZT/Ti/Pt$, (2) functional films pattern, (3) silicon slot etching by RIE, (4) back silicon deep etching by KOH solution, (5) cantilever release by RIE, and (6) metal mass micro fabrication and assemblage.

The wafer with prepared films was then patterned using standard photolithography technique. Back oxide window with align-mark were created by HF solution etching. And then front electrodes and PZT films were patterned orderly, using RIE and wet etching ($HF:HCl:H_2O = 1:25:74$), respectively, through double side alignment process. After bottom electrodes and the oxide/Si layers were etched by RIE process, Bulk Si micromachining of the wafer's backside was carried through. KOH chemical etching was used here. In order to avoid the KOH solution eroding the functional films, a delicate jig was employed to protect them and the wet etching process stopped with thin Si layer left before the Si wafer was etched through (the etch depth controlled by etch rate and etch time). Silicon RIE process was then utilized to release composite cantilever ultimately.

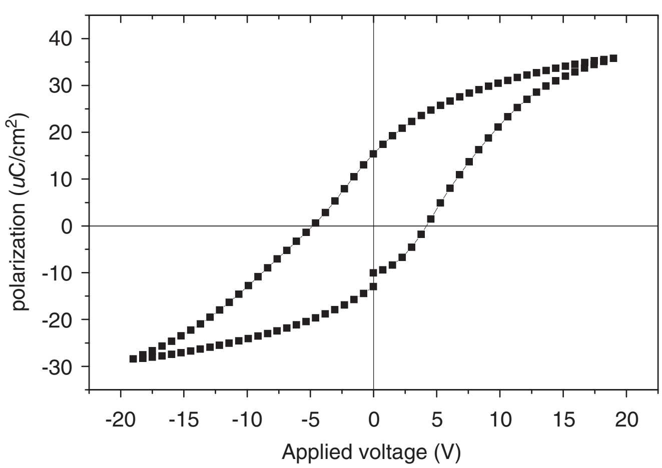

Fig. 3. *P–V* hystersis curve of the PZT device, remnant polarization magnitude is $14\,\mu C/cm^2$.

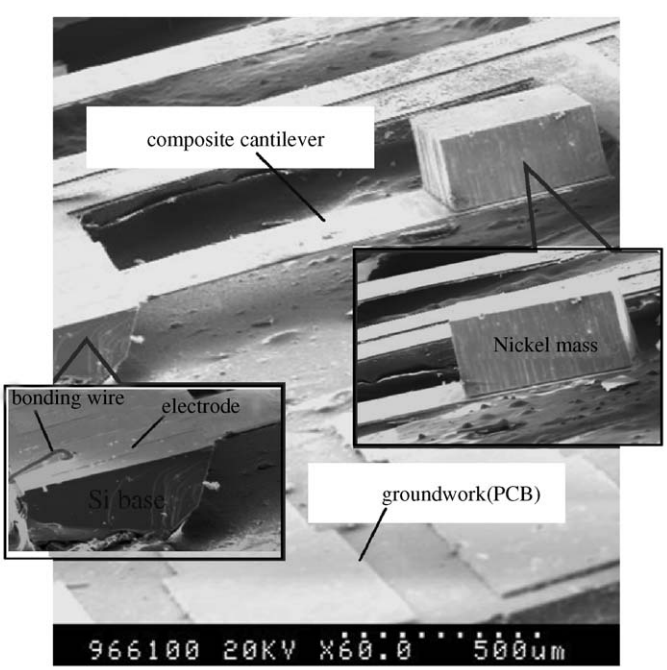

Fig. 4. SEM photo of the fabricated prototype.

Subsequently, well-chosen nickel mass fabricated by UV-LIGA SU-8 technique [14] was then affixed on the cantilever using glue. After wire bonding process, the PZT film was poled by applying a 10 V DC voltage for 5 min. Thus the micro piezoelectric power generator was fabricated. Fig. 3 shows *P–V* hysteresis curve of the PZT device, which measured by RT6000HVS FE measurement system. Fig. 4 demonstrates the photo of the final prototype. The dimension of the device is of cantilever length × width: $2000 \times 600\,\mu m^2$, with silicon layer thickness $12\,\mu m$, PZT layer thickness $1.64\,\mu m$ and the added Ni metal mass is of length × height: $600 \times 500\,\mu m^2$.

4. Device testing setup

The designed device acts as an AC current generator when it is mechanically vibrating. The PZT film experiences a time-varying change in mechanical stress, alternating between tensile and compressive stress. This results in a time-varying generated charge within the PZT layer, which is the source of the AC current.

Performance of the prepared prototype was tested by the system shown in Fig. 5. The vibrator (SINOCERA JZK-5) is utilized to supply reliable mechanical vibrations to the testing sample. The vibrator can be program controlled by Agilent 33220A function/Arbitrary Waveform Generator. And a SINOCERA YE5872 power amplifier was incorporated with the waveform generator to drive the vibrator and regulate vibration strength. An accelerator (SINOCERA CA-DR-1005) is attached to spindle of the vibrator, which make that the vibration strength, acceleration, amplitude or velocity, can be measured and the strength signal is delivered to an output display unit, SINOCERA YE5932A vibrograph. At last, an oscillograph (TEK tronix TDS3014B) is used to monitor the voltage signal from the testing sample.

For the power generator, rectifying circuit and electrical storage capacitor are required for harvesting the electrical energy. Therefore, a common four-germanium-diodes bridge rectifier circuit, with diode forward bias voltage 0.2 V at steady state, is introduced for rectification experiment. On the other hand, varying resistor connected

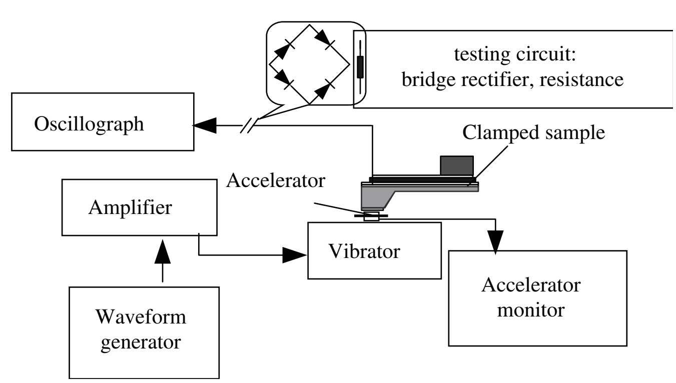

Fig. 5. Experimental setup for device testing.

to the power generator was monitored to measure and calculate its power output.

5. Results and discussion

Natural frequency of the prototype was searched using swept frequency process: The waveform generator supply fluctuant periodic chirp. Observing the oscillograph, an upsurge signal will occur when the resonant point is experienced. And then, the power generator device is excited under the resonant frequency with strength of 1 g acceleration, which is the general magnitude in environment [6].

The graph in Fig. 6(a) saved by oscillograph demonstrates the resonance frequency and voltage signal. The natural frequency is about 609 Hz. And the voltage output value is 898 mV AC peak–peak. It means the PZT layer oscillates between alternate extremes of maximum displacement. This indicates the voltage output under maximum displacement is $U_{peak-peak}/2 = 449\,\text{mV}$. Rectification experiment was carried out when the generator was resonantly vibrated. Fig. 6(b) illustrates full wave rectification effect of the sample using bridge rectifier. It seemed the diodes actualize AC–DC conversion successfully, which is vital for charge storage by capacitor.

The generator acts as AC current source, as shown in Fig. 7, its voltage increases with increased load, up to 898 mV at 112 kΩ. The power has a peak point as expected, which is 2.16 μW for 21.4 K resistance. And a 608 mV peak–peak AC voltage value is measured at the 2.16 μW power level. where

$$\text{power} = \left[\frac{U_{peak-peak}}{2} \Big/ \sqrt{2}\right]^2 \Big/ R,$$

$U_{peak-peak}$ is load voltage of AC peak–peak value, R is load resistance.

The experimental results disclose the promising development of the micro piezoelectric generator. However, the relatively low voltage and power output are not practicable to present general application. On the other hand, during the testing experiment, the effective bandwidth of voltage output, where the voltage value is high enough for rectification, is observed to be too narrow, it is about less than several tens Hz near resonant point. This is unsuited for the practical vibration source that its frequency is not steady but is up-and-down in some range.

So, the device should be improved to strengthen its performance, such as upgrading power, boosting voltage and tuning itself to practical variable vibration frequency. Easily structure dimension regulation can be used to adjust device natural frequency to match practical vibration condition. And parallel/serial connection cantilevers structure with close natural frequency combined as unified array will be introduced to widen the response bandwidth and accumulate electricity output in next generation design. At the same time, Optimizing structure type to dig the existing

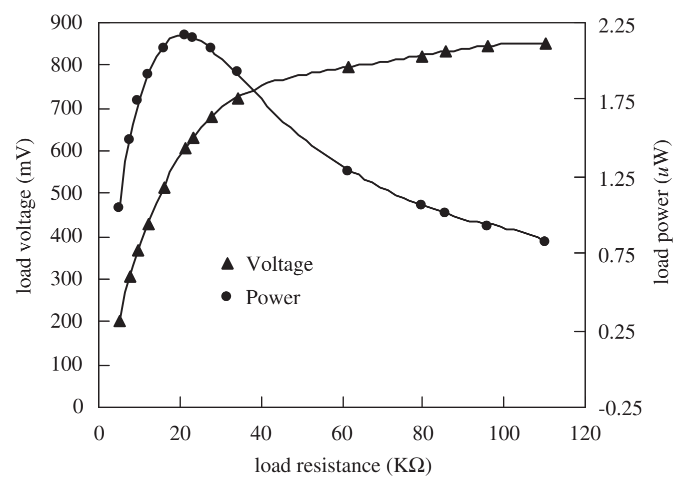

Fig. 7. Load voltage and power delivered to the load versus resistance.

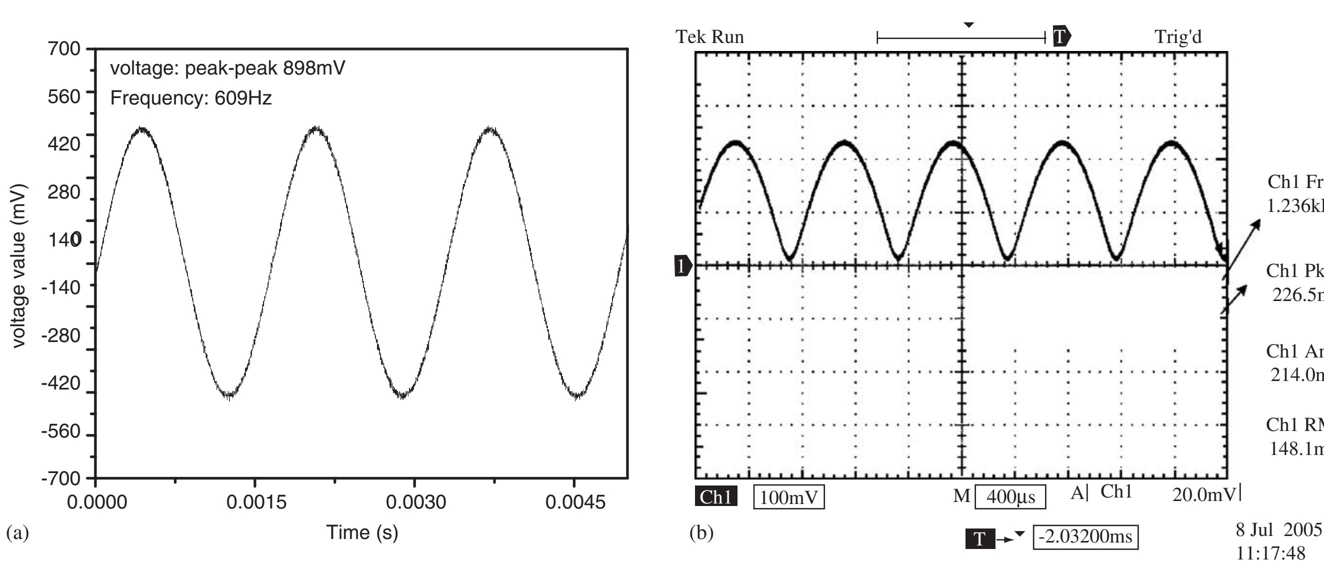

Fig. 6. (a) Resonance response to vibration source and (b) AC to DC conversion by full-wave rectification.

PZT potential, increasing PZT film thickness to upgrade the conversion of vibration strain to electricity, are also considered in following work.

6. Conclusion

The research on piezoelectric micro generator, including structure design, micro fabrication for MEMS implementation and performance test, was investigated. A composite cantilever with 1.64 μm PZT layer used to harvest vibration energy. The prototype fabricated by MEMS technology can result in the level of 898 mV voltage and 2.16 μW power output under resonant excitation with strength of 1 g acceleration.

The flexibility in tailoring structure parameter can adjust generator property such as natural frequency, which increases potential of its application in various conditions. And the further work will be carried out to enhance the performance of the generator, which includes PZT film improvement and introduction of cantilevers array. Furthermore, energy storage and management units should also be accomplished.

Compared to reported micro-generators for vibration energy harvesting, our device offers the advantage of good performance as far as promising voltage/power output and adjustable low natural frequency (to match general vibration sources) are concerned. Other advantage lies in the fact that the device is more compact and its fabrication process is more scalable, allowing for MEMS technology implementation, which has the potential of cost advantage by leveraging matured IC fabrication techniques.

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