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Vibration piezoelectric energy harvester with multi-beam

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This work presents a novel vibration piezoelectric energy harvester, which is a micro piezoelectric cantilever with multi-beam. The characteristics of the PZT ($Pb(Zr_{0.53}Ti_{0.47})O_3$) thin film were measured; XRD (X-ray diffraction) pattern and AFM (Atomic Force Microscope) image of the PZT thin film were measured, and show that the PZT ($Pb(Zr_{0.53}Ti_{0.47})O_3$) thin film is highly (110) crystal oriented; the leakage current is maintained in nA magnitude, the residual polarisation Pr is 37.037 $\mu C/cm^2$, the coercive field voltage Ec is 27.083 kV/cm, and the piezoelectric constant d_{33} is 28 pC/N. In order to test the dynamic performance of the energy harvester, a new measuring system was set up. The maximum output voltage of the single beam of the multi-beam can achieve 80.78 mV under an acceleration of 1 g at 260 Hz of frequency; the maximum output voltage of the single beam of the multi-beam is almost 20 mV at 1400 Hz frequency. © *2015 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution 3.0 Unported License.* [http://dx.doi.org/10.1063/1.4919049]

I. INTRODUCTION

Energy harvesters have received significant attention in recent years, which is led by the growing potential application of low-power electronics.[1,2] The trend of microelectronic devices is smaller, cheaper, and more energy-efficient, such as the input power for a wireless sensor which is usually 10 ~ 1000 mW.[3] Vibration piezoelectric energy harvesting is promising for micro-power energy harvesting, because it is easier to fabricate by the MEMS fabrication process, and provides higher energy densities than other systems, and require no physical connection to the outside of the system. Moreover, it has a long service life.[4,5]

There have been many vibration piezoelectric energy harvesters demonstrated in the literature; the designs of most vibration piezoelectric energy harvesters were based on monospar,[6,7,10] but in fact, the high output and micro-size could not be obtained at the same time. On one hand, the pursuit of high output power leads to the size of the beam that is bigger and bigger. On the other hand, high output power always needs a high frequency vibration source. However, there are not many high frequency vibration sources in actual application. The frequency of ambient vibration sources is typically 100~300 Hz.[9] Lokesh Dhakara[8] presented a new energy harvester, which is designed for high power output at low frequencies; the maximum output voltage of this energy harvester was more than 10 V, but its length reached 176 mm, which was too big for the microelectronic

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devices. J. C. Park[4] designed a bent cantilever with a volume of $3000 \times 2000 \times 18\ \mu m^3$, but the maximum output voltage of this energy harvester was only 16 mV. So it is necessary to design a high-efficiency vibration piezoelectric energy harvester based on ambient vibration sources. This work presents a novel vibration piezoelectric energy harvester with multi-beam, which can work more efficiently and with a long service life.

II. EXPERIMENTAL DETAILS

A. Design and fabrication

A novel vibration piezoelectric energy harvester with multi-beam has been designed, as shown in Fig. 1. There are six beams on the cantilever for the vibration piezoelectric energy harvester, distributed on both sides. The size of the cantilever is $2600 \times 760 \times 20\ \mu m^3$, the size of the beams is $2320 \times 400 \times 20\ \mu m^3$, and the size of the proof mass is $800 \times 600 \times 170\ \mu m^3$.

The fabrication process flow is schematically shown in Fig. 2. (1) A piece of 2-inch double-side-polished silicon wafer was selected as substrate. Then, a 2500 nm of SiO_2 layer was synthesised on the n-type (100) Si by oxidation. (2) The SiO_2 layer was patterned on the backside of the wafer. (3) The bulk silicon was anisotropically etched onto the backside using the back patterned SiO_2 as a mask layer. (4) The front-side SiO_2 layer was patterned by a U-shape that would be used to free the microcantilever. (5) A 50 nm thick Ti layer and a 200 nm thick Pt film were sputtered as the bottom electrode. (6) The PZT thin film was deposited on the $Pt/Ti/SiO_2/Si$ substrate. (7) The Pt/Ti top electrode was sputtered and patterned by lift-off technology. (8) The PZT thin film was corroded and the bottom electrode contact holes were patterned. (9)-(10) An insulating layer of Si_3N_4 was prepared and patterned to expose the top/bottom electrode contact holes. (11) A Pt/Ti layer was sputtered and patterned to form the bonding pads using the lift-off process. (12)-(13) The cantilever was freed by a dry etching process.

The PZT thin film was produced by the spin coating process with the speed of 3000 rpm. By using the sol-gel method, each of the odd layers of the coated PZT thin film was baked at 180 °C, and then at 350 °C. The even layer of coated PZT thin film was not only baked at 180 °C then at 350 °C, but also annealed at 600 °C. The above process was repeated 20 times, then a 1.2 μm thick PZT thin film was deposited.

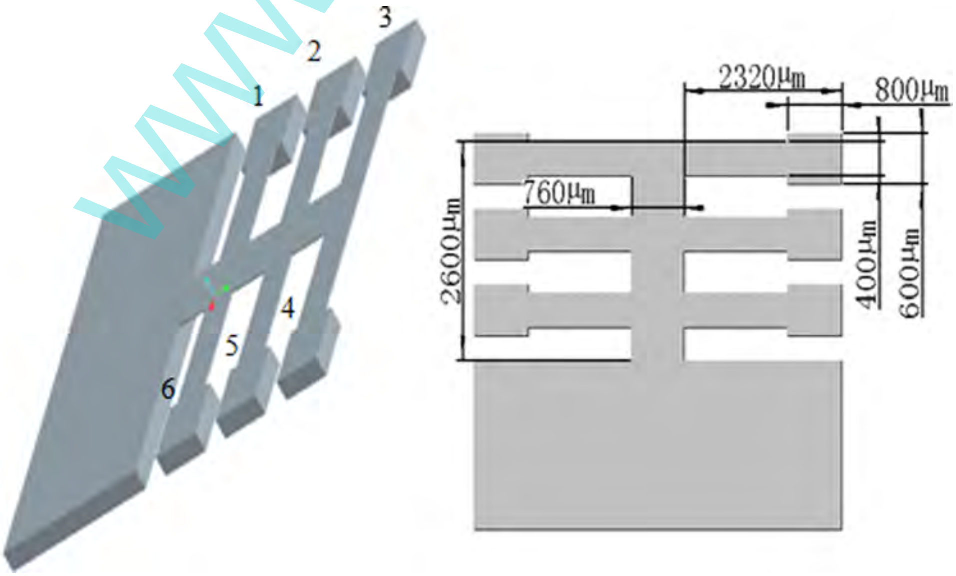

FIG. 1. The model of piezoelectric energy harvester.

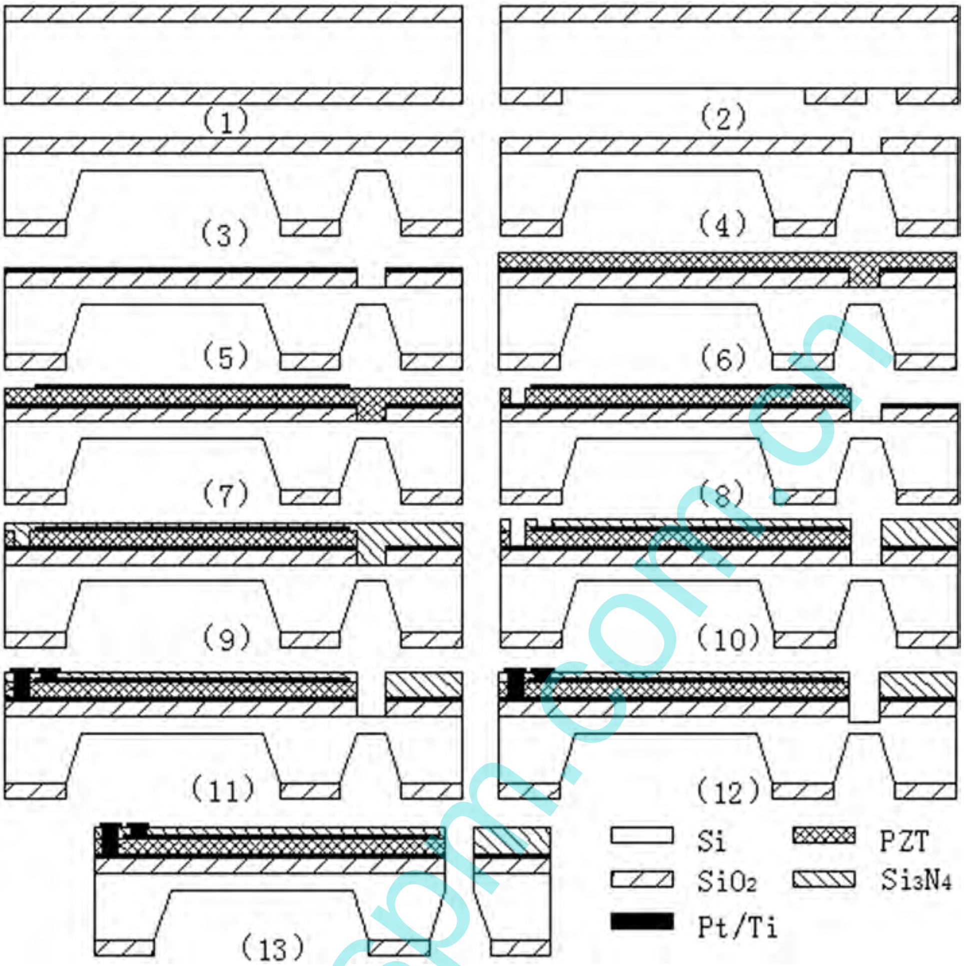

FIG. 2. The production process of the piezoelectric energy harvester.

III. MEASUREMENT

A. Characteristics of the PZT thin film

The XRD diffraction analysis of the PZT thin film was conducted by the D8 DISCOVER Diffraction Analyzer, as shown in Fig. 3. It can be seen that perovskite organisation was formed without crystalline pyrochlore, and three kinds of crystal orientation appeared in the PZT thin film: (100) crystal orientation, (110) crystal orientation and (111) crystal orientation; it is highly (110) crystal oriented.

The surface microstructure of the PZT thin film was measured by an atomic force microscope (CSPM3300 AFM), as shown in Fig. 4; the average grain diameter of the PZT thin film is 84.11 nm, and the average roughness (Ra) is 2.45 nm.

The capacitance, dielectric loss coefficient and dielectric constant of the PZT thin film were measured by an Intelligent LCR (Inductance Capacitance Resistance) Measuring Instrument (ZL5), as shown in Fig. 5. The measurement was performed in the frequency with a range of 0.05 KHz to 10 KHz at 1 V. The capacitance was very stable, as shown in Fig. 5(a); its maximum value of 15.614 nF appeared at frequency of 50 Hz, and the minimum value was 13.617 nF. The dielectric loss coefficient was less than 0.05, as shown in Fig. 5(b), and there was no significant change in dielectric loss coefficient. The dielectric constant was calculated by Eq. (1), and its curve is shown in Fig. 5(c). The dielectric constant was maintained between 2015 and 2352. So the dielectric constant of the PZT thin film was stable. It is very important for a

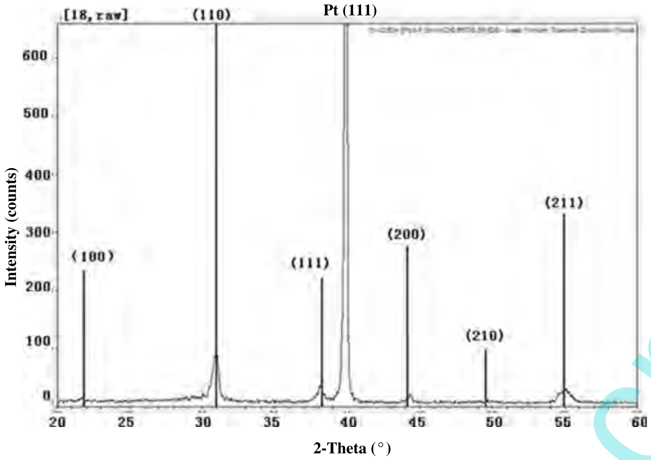

FIG. 3. XRD diffraction analysis.

vibration piezoelectric energy harvester to provide a constant output. The dielectric loss coefficient is very small, so its consumption of the vibration piezoelectric energy harvester is very small.

In general, with the increase of frequency, the dielectric constant, capacitance and dielectric loss coefficient decreased. Because dielectric constant (capacitance and dielectric loss coefficient) is mainly caused by certain polarization, and polarization is generated by the orientational arrangement of some dipole. The dipole invert with the applied electric field, due to the change of frequency, under the condition of high frequency, the inversion of some dipole stopped, therefore, their contribution to the dielectric constant (capacitance and dielectric loss coefficient) is zero (polarization relaxation). In general there are several kinds of polarization, various polarization relaxation occur at different frequency, so with the increase of frequency, the dielectric constant (capacitance and dielectric loss coefficient) decreased.

$$\varepsilon_r = \frac{C \times d}{A \times \varepsilon_0} \tag{1}$$

C is the capacitance of the PZT thin film, d is the thickness of the PZT thin film, A is the area of the up electrode, ε_r is the dielectric constant of the PZT thin film, and ε_0=8.85×10^{-12} is the vacuum dielectric constant.

The leakage current of the PZT thin film was measured by a Semiconductor Parameter Tester (UB3-07) and Manual Probe Station (MM6150); the I-V curve is shown in Fig. 6. The PZT thin

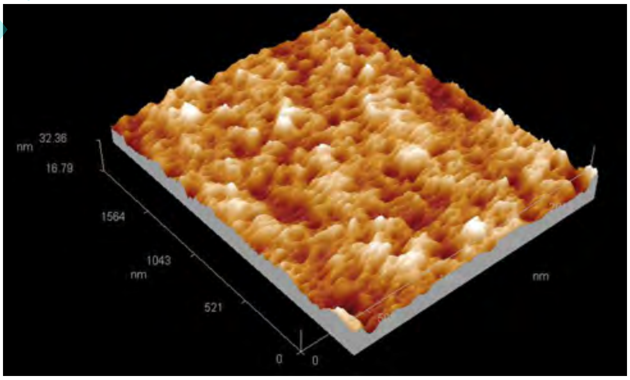

FIG. 4. AFM surface image of PZT thin film.

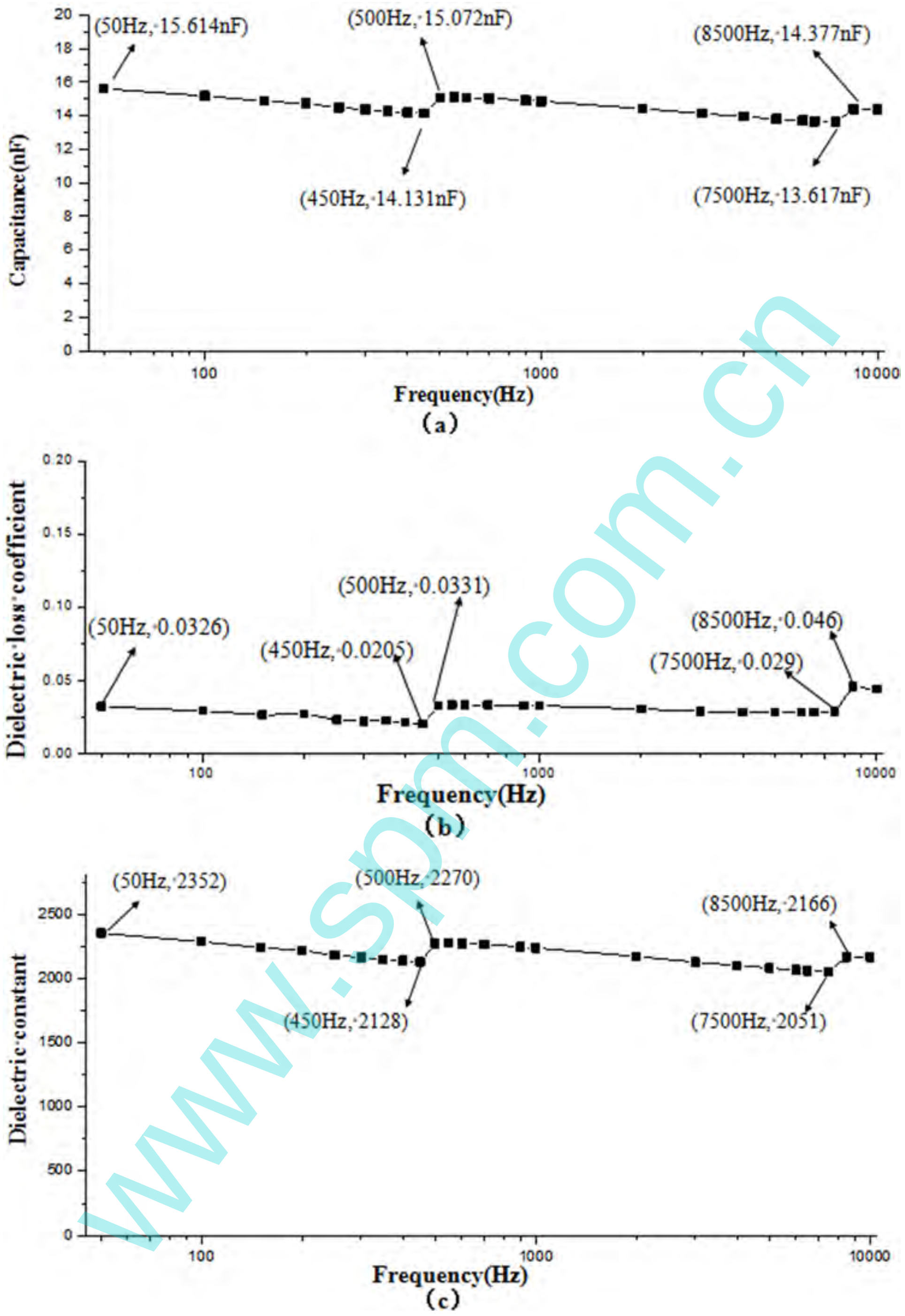

FIG. 5. The LCR measuring result. (a) Capacitance, (b) Dielectric loss coefficient, (c) Dielectric constant.

film still works when the applied voltage reaches 30 V, and the leakage current is maintained in nA magnitude, which indicates that the proposed PZT thin film is not easy to break down.

A Sawyer Tower circuit was used to measure the ferroelectric characteristics of the PZT thin film. The ferroelectric hysteresis loop curve is presented in Fig. 7; the remanent polarisation Pr is 37.037 $\mu C/cm^2$ and the coercive field voltage Ec is 27.083 kV/cm. The piezoelectric constant d_{33} is measured by YE1730 d_{33} METER, and d_{33} is 28 pC/N.

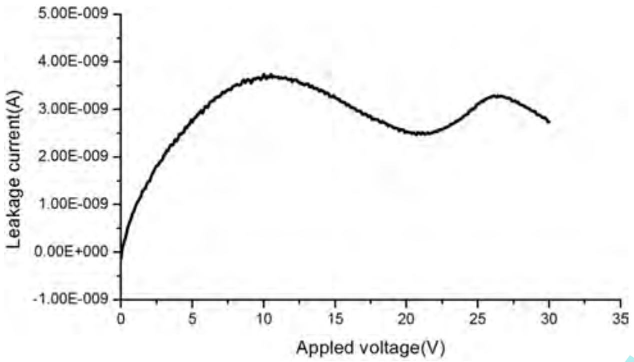

FIG. 6. The leakage current curve.

B. Characteristics of the energy harvester

A novel measuring system was designed to test the dynamic characteristics of the vibration piezoelectric energy harvester, as shown in the Fig. 8. This measuring system includes a digital phase-locked amplifier, shaker, power amplifier and accelerometer. The open-circuit voltage of the vibration piezoelectric energy harvester is measured by this measuring system, as shown in Fig. 9. The applied voltage is 0.002 V, the frequency changes between 100 Hz ~ 700 Hz, and the acceleration of the shaker is 9.8 m/s^2.

The maximum output voltage of the single beam achieved 80.78 mV under an acceleration of 1 g at 260 Hz. The output of beam 1 and beam 6 is very approximate, so is the output of beam 2 and beam 5, the beam 3 and beam 4. In addition, it is easy to observe that the output voltage of beam 3 and beam 4 is between 61.67 and 80.87 mV, the output voltage of beam 2 and beam 5 is between 41.17and 48.78 mV, and the output voltage of beam 1 and beam 6 is between 9.09 and 20.52 mV. This is because the vibration amplitude and intensity of the beam that is far away from the anchored end are greater than the one near the anchored end.

The characteristic of beam 3 is measured at 1400 Hz of frequency; the output curve after being filtered is shown in Fig. 10, where it is a sine curve and the maximum output voltage is almost 20 mV.

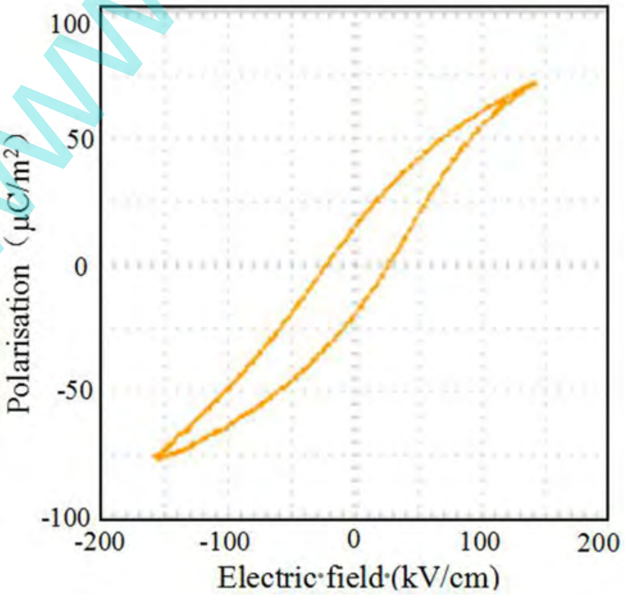

FIG. 7. Ferroelectric hysteresis loop.

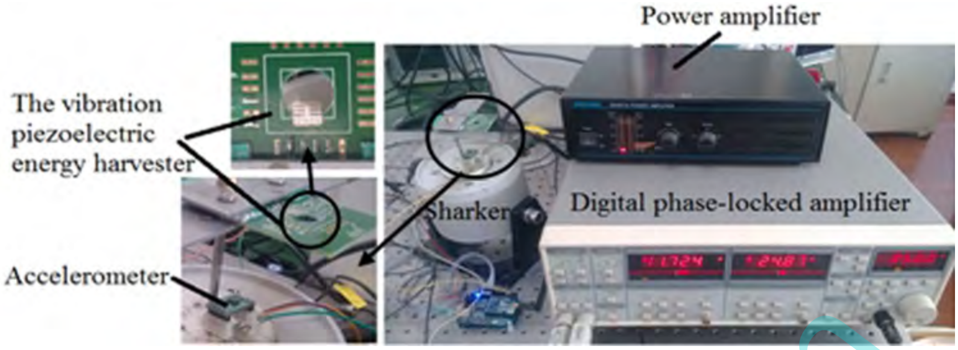

FIG. 8. The dynamic characteristic measure system.

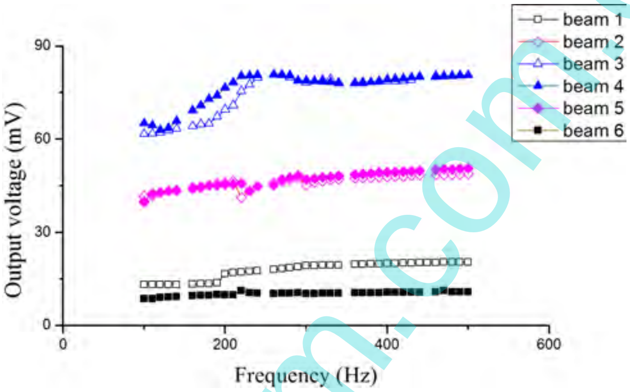

FIG. 9. The low frequency dynamic characteristic.

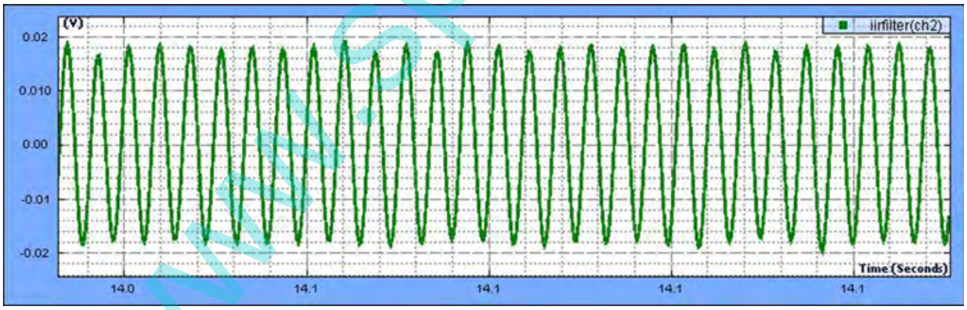

FIG. 10. The high frequency dynamic characteristic.

The relationship between output voltage and vibration acceleration of beam 4, beam 5 and beam 6 are shown in Fig. 11, which are linear correlations, and the output voltage increases with the increase of vibration acceleration. At the same vibration acceleration, the output voltage of beam 4 is bigger than the output voltage of beam 5, and the output voltage of beam 5 is bigger than the output voltage of beam 6; this is because beam 4 is closer to the free end, and the free end coupled vibration amplitude and intensity. So the output voltage of the free end is greater than the anchored end.

The relationship between the load voltage and the power/load resistance of beam 5 is shown in Fig. 12. The load voltage is proportional to the load, and the load voltage increases with the increase of the load resistance; the load voltage of 16.6 mV was generated when the load resistance was 50 kΩ. The power increases with the increase of the load resistance, and reaches the maximum of

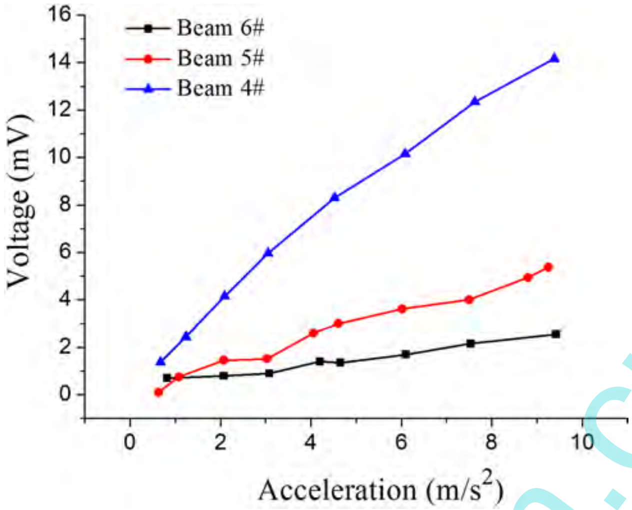

FIG. 11. The relationship between output voltage and vibration acceleration.

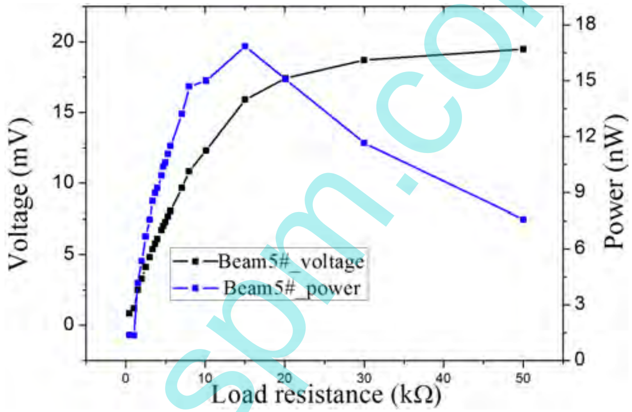

FIG. 12. The relationship between load voltage and power/load resistance.

16.74 nW when the load resistance is 15 kΩ,, which is the optimal resistive load. Then the power decreases with the increase of the load resistance.

IV. CONCLUSION

In this work, a novel piezoelectric cantilever with multi-beam has been proposed for vibration piezoelectric energy harvesting. It is fabricated by using MEMS processing technology, and PZT thin film is used as piezoelectric material. The characteristics of the energy harvester have been measured, which verify that that the proposed energy harvester could satisfy the demand of microelectronic devices on power. The output voltage of the vibration piezoelectric energy harvester is considerable in both low frequency and high frequency. There are also many details worthy of further study, such as how connecting the multi-beam in a parallel way can prolong the service life.

ACKNOWLEDGMENT

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