Design and implementation of a vibration cantilever energy harvester with suspended piezoelectric beam

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Abstract

The frequency response and energy conversion efficiency are the critical issue for vibration energy harvester. In this paper, a vibration energy harvester with suspended piezoelectric beam is proposed. This harvester structure is composed of a discrete support beam in the bottom and a suspended piezoelectric beam on top. This suspended beam structure is beneficial to the higher response frequency and the energy conversion efficiency by applying the tension on the shear mode piezoelectric layer. An analytical bending model of suspended piezoelectric beam is developed, based on the actual deformation: rotational and translational movement modes. The characteristic of suspended piezoelectric beam is also analyzed by Finite element method. Finally, a 1000:1 prototype is fabricated and measured. The optimums acquired experiment results show that it is matching well with the model. The maximum of output voltage is 6.5 V.

Keywords: energy harvester, vibration, suspended piezoelectric beam, piezoelectric layer

1 Introduction

Energy harvester is the device, which can convert environment energy, such as vibration, temperature, solar energy, etc., into useful electrical energy [1-6]. And with the development of NMES/MEMS technology, and wireless network sensors, the micro-scale energy harvester can generate electric energy at milli watt level. At the same time, the power consumption of wireless sensors drastically reduced to milliwatt and even nanowatt level. Thus, the micro-scale energy harvester is popular to power sources. Among the different energy forms, the vibration energy is a good choice due to its widespread existence. The vibration harvester can harvest vibration energy via different materials and structure [7-11]. And among different structure of vibration energy harvesters, the cantilever-mass structure is regarded as a promising structure due to the small size, little power consumption, low cost, and compatibility with integrated circuits [12-16].

However, the lower energy efficiency and lower response frequency limit the cantilever-mass energy harvester further application. To resolve these problems, several approaches were chose.

Firstly, selecting suitable material such as PZT, PMNT, and PDVF, etc. is a useful method to enhance efficiency [17].

Secondly, increasing the thickness of the piezoelectric layer is also a good choice since the normal strain experienced by the piezoelectric layer is proportional to its thickness [18, 19].

Thirdly, using the proper coupling mode of piezoelectric material is also worth considering, since the different coupling mode relate to the different electrode pattern [20]. Finally, choosing novel configuration such as tapered cantilever beam, L-shaped beam and so on can affect the frequency of harvester [21-24].

This paper reports an energy harvester with suspended piezoelectric beam for d31 mode. The cantilever structure is composed of a discrete support beam in the bottom and a piezoelectric beam on top. And a gap is forming between the top beam and the bottom beam. The electrode mode is selected as d31 mode based on the distribution of strain. To achieve more accurate analysis, the frequency formula of the suspended piezoelectric beam is derived, considering the two actual deformation modes. Furthermore, it also discussed how the geometrical parameters of suspended piezoelectric beam affect harvester's performance. This model is verified by a prototype and experiments afterwards.

2 Modeling analyses

The conventional mass-cantilever structure is shown in Figure 1, it consists of three parts, the piezoelectric layer, the support layer and the proof mass. And the piezoelectric layer is often attached on the support layer.

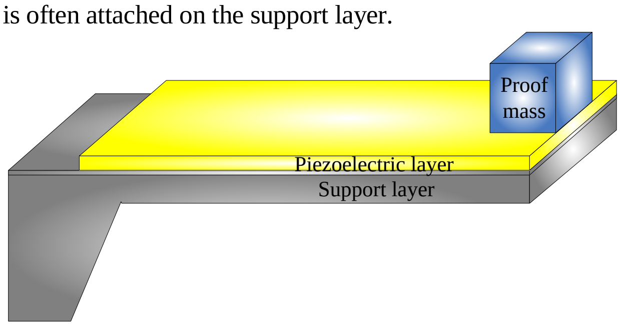

FIGURE 1 Conventional cantilever structure

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Different from conventional mass-cantilever structure, the suspended piezoelectric beam energy harvester is constructed as Figure 2.

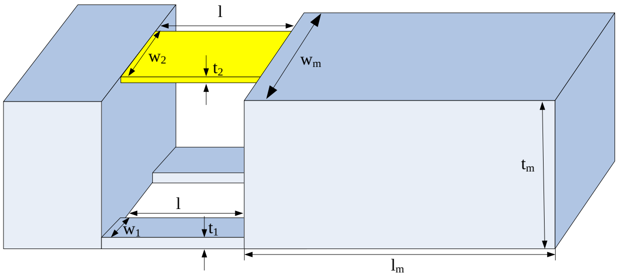


FIGURE 2 Structure of energy harvester with suspended piezoelectric beam

And the piezoelectric material operates in the d_{31} mode to enhance the output charge. The energy harvester is composed of a discrete support bottom beam and a piezoelectric top beam, so the gap structure exists between the top beam and bottom beam. And the discrete support bottom beam is composed of two small parallel beams, the geometric dimension of two parallel beams is same. The dimensions (width × thickness × length) of the bottom support beams, the piezoelectric top beam, and proof mass are $2\times w_1\times t_1\times l$, $w_2\times t_2\times l$, and $w_m\times t_m\times l_m$, respectively.

Cross-sectional view of suspended piezoelectric beam energy harvester is shown in Figure 3.

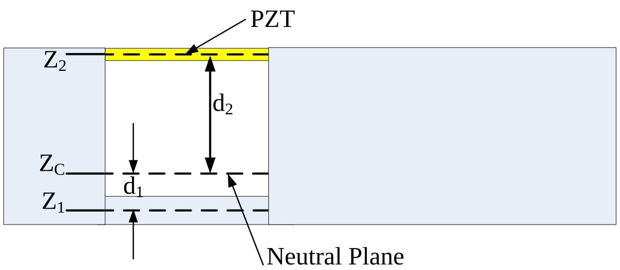


FIGURE 3 Cross-sectional view of energy harvester with suspended piezoelectric beam

Z_1 and Z_2 are the middle planes coordinates of the bottom and top beams respectively, and Z_C is the coordinate of neutral plane. In mechanics, the neutral plane is a conceptual plane where the stress is zero. When an inertial force is applied, the cantilever bends so that one surface of cantilever is in compression and the other surface of that is in tension. d_1 is the distance between the Z_1 and Z_C, d_2 is the distance between the Z_C and Z_2. Accordingly, the neutral plane coordinate Z_C of suspended piezoelectric beam can be expressed as:

$$Z_c = \frac{E_1A_1Z_1 + E_2A_2Z_2}{E_1A_1 + E_2A_2}. \tag{1}$$

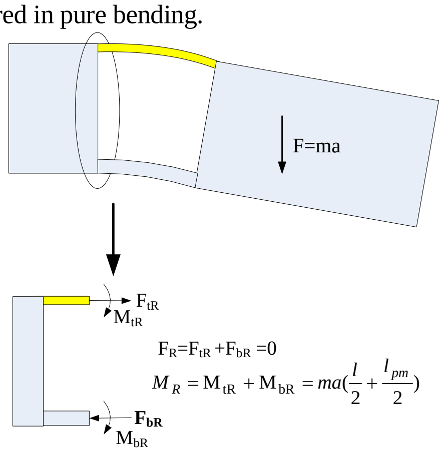
E₁, *E₂*, *A₁* and *A₂* are respectively defined as the Young modulus and cross-sectional area of bottom beam and top beam. A_1 is equal to the product of width $w1$ and thickness t_1 of bottom beam. A_2 is the product of width w_2 and thickness t_2 of top beam. Thus, the formulations of d_1 and d_2 can be expressed as:

$$\begin{cases} d_1 = \dfrac{E_2A_2(Z_2 - Z_1)}{E_1A_1 + E_2A_2} \\ d_2 = \dfrac{E_1A_1(Z_2 - Z_1)}{E_1A_1 + E_2A_2} \end{cases}. \tag{2}$$

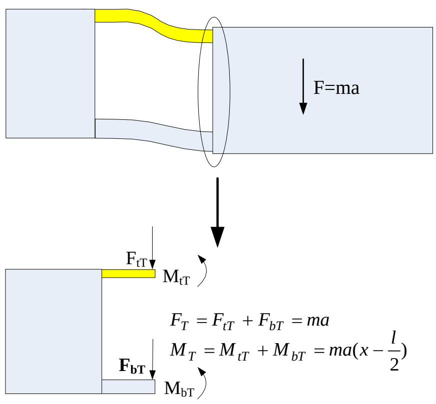
Since the thickness of PZT film prepared by Sol-Gel is generally less than 4 um, and then the bottom should be thick enough to support the big proof mass. As a result, the location of neutral plane will be shift down to close to the bottom beam. From the Equation (2) and Figure 3, the distance d_2 can approximately equal to the gap distance when considering the thickness of top beam and bottom beam.

Next the analysis model is discussed. The Euler-Bernoulli beam theory based on Kirchhoff's assumption is not accurate for the suspended beam structure. Therefore, it is necessary to establish a new model to describe this structure. In practice, we can observe two deformation modes: rotational movement and translational movement, shown in Figure 4. In our analysis, the beam's mass and the proof mass deformation are ignored.

For the rotational movement, the bending moments M of beam is constant and the shear force of beam is zero. Thus, the deformation of suspended piezoelectric beam can be considered in pure bending.



a) Rotational movement mode



b) Translational movement mode

FIGURE 4 Two movement modes

From the theorem of multilayer structure cantilever, rotary inertia of parallel axis is obtained by $I_R = I_i + A_i(d_i)^2$.

The bending rigidities of rotational movement can be expressed as:

$$(EI)_R = E_1 I_b + E_2 I_t + E_1 A_1 d_1^2 + E_2 A_2 d_2^2 . \quad (3)$$

For the translational movement, the mass remains in horizontal direction after deforming, this means the bending moment is a linear function of the horizontal position and the bending moment at the middle of the beam is zero, the shear force is constant. The bending rigidity of translational movement is $(EI)_T = E_1 I_b + E_2 I_t$.

Thus, the total bending rigidities of suspended piezoelectric beam is:

$$(EI)_Z = \frac{4(EI)_R}{[3\gamma^2 + \mu]} , \quad (4)$$

where $\gamma = \frac{l + l_{pm}}{l}$, $\mu = \frac{(EI)_R}{(EI)_T}$.

Finally, the resonant frequency of vibration energy harvester with suspended piezoelectric beam can be expressed as:

$$f = \frac{\pi}{11.24} \sqrt{\frac{(EI)_R}{ml^3(3\gamma^2 + \mu)}} . \quad (5)$$

Equation (5) describes the length of cantilever and the mass of proof mass as the function of frequency.

From the energy perspective, the piezoelectric layer was expected to store as much stretching energy as possible to transform into the electric energy from the total mechanical energy applied. Thus, the energy conversation efficiency should be discussed. As shown in Figure 4, the force F_{tR} of rotational mode stretch the piezoelectric layer, which means the strain is generated. But the force F_{tT} translational modes don't contribute the strain. As a result, the rotational mode is domain in contributing the strain of whole structure. Thus, the energy of rotational mode is composed of bending energy and normal stretching/compress energy. The value η defined as ratio of stretching energy stored in the top piezoelectric layer to the total mechanical energy, and η can be expressed as:

$$\eta = \frac{E_2 A_2 d_2^2}{(EI)_R} . \quad (6)$$

Finally, the output voltage and charge also can be considered. To generate as much output voltage as possible, the piezoelectric layer should be experience the maximized stretching stress accordingly. But the shear force of translational movement cannot contribute any stretching/compress strain for the top piezoelectric layer. Thus, the mainly electric energy is generated in the rotational movement and the contribution of translational movement can be negligent.

The output voltage and charge under d_{31} mode can be expressed as:

$$\begin{cases} V = \dfrac{F_{tR} \cdot d_{31}}{\varepsilon_{33} \cdot \varepsilon_0 \cdot w_2} \\ Q = -F_{tR} \cdot A_{elec} \cdot d_{31} \end{cases} , \quad (7)$$

where ε_{33} is the dielectric constant, A_{elec} the electrode area [25]. Substituting F_{tR} shown in Figure 4 into Equation (7), the output voltage and charge can be expressed as:

$$\begin{cases} V = \dfrac{ma \cdot (l + l_m) \cdot d_2 \cdot E_2 \cdot A_2 \cdot d_{31}}{2 \cdot (EI)_R \cdot \varepsilon_{33} \cdot \varepsilon_0 \cdot w_2} \\ Q = -\dfrac{ma \cdot (l + l_m) \cdot d_2 \cdot E_2 \cdot A_2^2 \cdot d_{31}}{2 \cdot (EI)_R \cdot \cdot w_2} \end{cases} . \quad (8)$$

3 Optimum design

To obtain the better performance, some parameters of suspended piezoelectric beam structure should be considered, especially in MEMS scale. The Figure 5 shows the relationship between frequency and the cantilever length and the proof mass length. The frequency is range from 1.5 KHz to 308 KHz. And the length of proof mass is from 10 um to 50 um and that of suspended piezoelectric beam of is 1 um to 50 um, respectively.

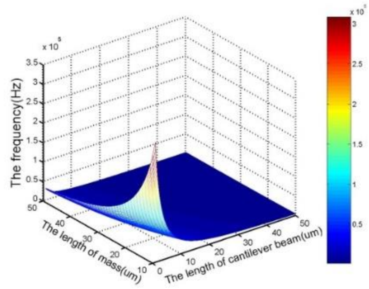
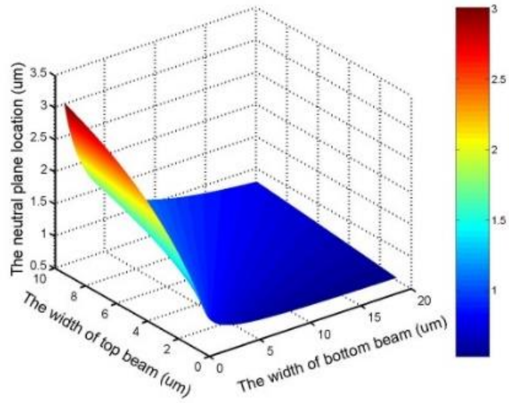


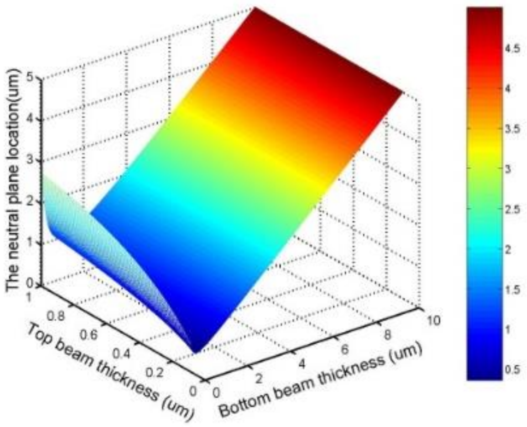
FIGURE 5 The frequency depending on the length of mass and that of cantilever

As shown in Figure 5, the smaller length of suspended beam and proof mass can lead to the higher frequency. Giving the width, the thickness, and the density, the length of proof mass can represent the mass. Thus, a conclusion can be derived that the frequency of suspended beam structure is affected the mass of proof mass and the length of suspended beam.

The neutral plane also should be discussed. From Figure 3 and Equation (1), the location of neutral plane is linked with the Young modulus, the width and the thickness of bottom beam and top beam. For conventional cantilever, the neutral plane should be far away the PZT layer, which can generate strong output voltage. This case is suitable for suspended beam structure. The relationship of neutral plane and width of top beam and bottom beams is shown in Figure 6a. The location of neutral plane is distinctly dropped with the decreasing of top width, but there is tiny change to the bottom beam. As shown in Figure 6b, the similar conclusion on the neutral plane and thickness of the top and bottom beams is derived. The thinner top beam generates the lower neutral plane location. But the relationship between the thickness of bottom beam and neutral plane location isn't the linear function. And the neutral plane location is lowest when the bottom beam thickness is 1 um.



a) The relationship of neutral plane and thickness



b) The relationship of neutral plane and width

FIGURE 6 The parameter relationship: a); b)

Next, the optimum energy conversation efficiency should be considered. The relationship between the width ratio of two beams and energy efficiency is shown in Figure 7. It is obvious that the greater width of top beam can improve efficiency. When the width ratio is approximately equal to 0.5, the optimum efficiency is 87.5%. Similarly, the relationship between different thickness ratio of two beams and efficiency is shown in Figure 8, the optimum thickness ratio is 0.5.

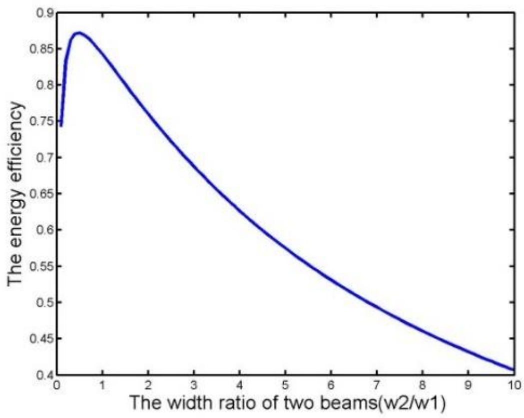


FIGURE 7 Relationship of width ratio and efficiency

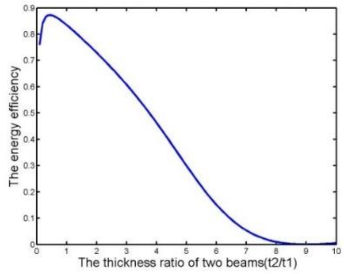


FIGURE 8 Relationship of thickness ratio and efficiency

Finally, the performance comparison of suspended piezoelectric beam structures and conventional structure is given in Table 1 based on Equation (5) and Equation (6). From the Table 1, we can observe that the suspended beam structure has the better performance than the conventional structure. Thus, a conclusion can be derived that the suspended beam helps to improve the resonant frequency and enhance the energy conversation efficiency.

TABLE 1 Comparison of suspended piezoelectric beam and conventional beam (l=8 um, w1=20 um, t1=1 um, w2=10 um, t2=0.5 um, L=40 um, wm=30 um, T=5 um)

	Suspended beam structure	**Conventional structure**
Frequency	372(K Hz)	102(K Hz)
Conversation efficiency	83.4	58.6

4 Measurement

In order to verify the analysis model and simulation results, the millimeters lever prototype is fabricated, and the dimension of prototype is a 1000:1 time than simulation parameter in Table 1.

To obtain the similarly performance compared with the silicon-based device, some candidate material should be considered. The bottom beam and proof mass is fabricated with 45# steel, since its mechanical property is very similar to that of silicon, and its Young modulus is 209 GPa.

The measurement system picture is shown in Figure 9. The device was fixed to a Vibrator (SINOCERA JZK-2), which is used to generate mechanical vibrations. Sinusoidal signals were applied to the vibrator at various frequencies. The voltages from the energy harvesting device were monitored by an Oscilloscope (YOKOGAWA DL850) at the same time, and the non-contact Doppler Vibrometer (Vibroducer V1002) is used to measure the contrastive voltage. The experiment frequency is 376.0 Hz, and the peak output voltage is 25.9 V, shown in Figure 10, which agrees well with the analysis frequency of 372 Hz.

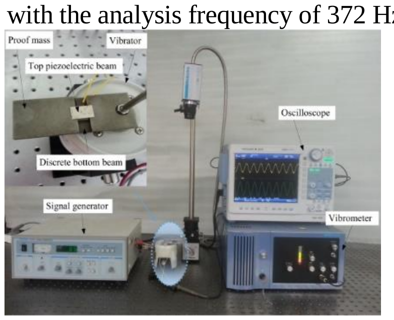


FIGURE 9 Measurement system plot

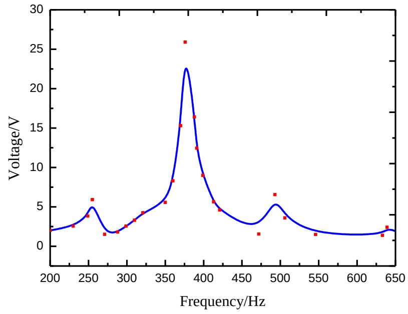


FIGURE 10 Frequency response of the suspended piezoelectric beam

Also, the plot of charging voltage/power is shown in Figure 11, the value of the capacitor was 100 μF. The capacitor voltage collected from the energy harvester is 6.5 V. Providing $E = \frac{1}{2}CV^2$ and $E = P \times t$, the 29.5 μW maximum power is derived.

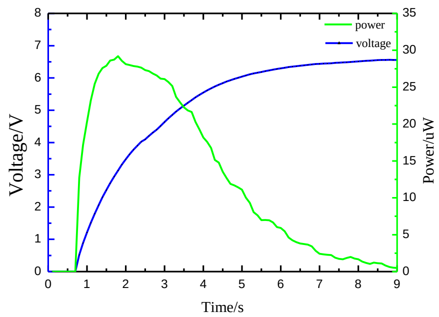


FIGURE 11 Plot charging voltage/power of the capacitor

5 Conclusions

The research on energy harvester with suspended piezoelectric beam, including structure design and optimum, modeling analysis, prototype fabrication and measurement are discussed in this paper. Considering the actual deformation in rotational and translational movement modes, the formulation of resonant frequency of suspended piezoelectric beam is derived. Furthermore, some parameters are considered to optimum the design. Accordingly, the acquired 1000:1 scale prototype is assembled. The prototype can generate the 6.5 V output voltage and 29.5 μW output power. The experiment frequency is 376.0 Hz that match well with 372.0 Hz of calculated frequency.

Compared to conventional cantilever, suspended beam structure can firstly enlarge the response frequency due to the existing gap which is affected the bending rigidities of system. The second advantage of suspended piezoelectric beam is the improvement of energy conversion efficiency by matching heavier mass, which improve output charge by stretching the piezoelectric layer. The finally advantage lies in the technology feasible of device fabrication [26].

Acknowledgments

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References

[1] Mateu L, Moll F 2005 Review of energy harvesting techniques and applications for microelectronics (Keynote Address) *VLSI Circuits and Systems II* **5737** 359-73

[2] Zhou L, Sun J, Zheng X J, Deng S F, Zhao J H, Peng ST, Zhang Y 2012 A model for the energy harvesting performance of shear mode piezoelectric cantilever *Sensors and Actuators A Physical* **179** 185-92

[3] Williams C B, Shearwood C, Harradine M A, Mellor P H, Birch T S, Yates R B 2001 *IEEE Proceedings on Circuits, Devices and Systems* **148**(6) 337-42

[4] Roundy S, Wright P K, Rabaey J M 2004 Energy Scavenging for Wireless Sensor Networks: With Special Focus on Vibrations *Springer*

[5] Roundy S, Wright P K, Rabaey J 2003 A study of low level vibrations as a powersource for wireless sensor nodes *Computer Communications* **26** 1131-44

[6] Noh J Y, Yoon G H 2012 Topology optimization of piezoelectric energy harvesting devices considering static and harmonic dynamic loads *Advances in Engineering Software* **53** 45-60

[7] Vullers R J M, Van Schaijk R, Visser H J, Van Hoof C 2010 *EEE Solid-State Circ Magazine* **2**(2) 29-38

[8] Singh K B, Taheri S, Priya S 2012 Piezoelectric vibration energy harvesting with an adaptive frequency tuning mechanism for intelligent tires *Mechatronics* **22** 970-88

[9] Van Schaik R, Elfrink R, Pop V, Vullers R 2012 Energy harvesting for self powered sensor systems-case study: vibration energy harvesting for 'intelligent tire' application *Proceedings of the 17th Workshop on Synthesis And System Integration of Mixed Information Technologies (SASIMI)* 141-6

[10] Lee J, Choi B 2014 Development of a piezoelectric energy harvesting system for implementing wireless sensors on the tires *Energy Conversion and Management* **78** 32-8

[11] Shu Y C, Lien IC 2006 Efficiency of energy conversion for a piezoelectric power harvesting systems *Micromech. Microeng* **16** 2429-38

[12] Kwon D, Rincón-Mora G A 2010 IC *IEEE Transactions on Biomedical Circuits and Systems* **4**(6) 400-9

[13] Shen Hui, Qiu JH, Ji HL, et al 2010 A lowpower circuit for piezoelectric bibration control by synchronized switching on voltage sources *Sensors and Actuators A* **161** 245-55

[14] Amarasinghe R, Dao D V, Toriyama T, Sugiyama S 2007 Development of miniaturized 6-axis accelerometer utilizing piezoresistive sensing elements *Actuators A Phys* **134** 310-20

[15] Dong P, Li X X, Yang H, Bao H, Zhou W, Li S Y, Feng S L 2008 High-performance monolithic triaxial piezoresistive shock accelerometers *Actuators A Phys* **141** 339-46

[16] Eklund E J, Shkel A M 2007 Single-mask fabrication of high-G piezoresistive accelerometers with extended temperature range *Micromech. Microeng* **17** 730-6

[17] Xue H, Hu Y T, Wang Q M 2008 *IEEE Transactions on Ultrasonics Ferroelectrics and Frequency Control* **55**(9) 2104-8

[18] Kim S, Clark W W, Wang Q-M 2005 Piezoelectric energy harvesting with a clamped circular plate: Analysis *Journal of Intelligent Material Systems and Structures* **16** 847-54

[19] Kim S, Clark W W, Wang Q-M 2005 Piezoelectric energy harvesting with a clamped circular plate: Experimental study *Journal of Intelligent Material Systems and Structures* **16** 855-63

[20] Ramsay M J, Clark W W 2001 Piezoelectric energy harvesting for bio-MEMS applications SPIE's 8th Annual International Symposium on Smart Structures and Materials *International Society for Optics and Photonics* 429-38

[21] White N M, Glynne-Jones P, Beeby S P 2001 A novel thick-film piezoelectric micro-generator *Smart Mater. Struct.* 10 850-2

[22] Glynne-Jones P, Beeby S P, White N M 2001 *IEEE Proceedings-Science, Measurement and Technology* **148**(2) 68-72

[23] Glynne-Jones P, Beeby S P, White N M 2001 The modelling of a piezoelectric vibration powered generator for microsystems *Proceedings of the 11th International Conference on Solid-State Sensors and Actuators, Transducers* **1** 46-9

[24] Erturk A, Renno J M, Inman D J 2009 Piezoelectric Energy Harvesting from an L-Shaped beam-mass structure with an application to UAVs *Journal of Intelligent Material Systems and Structures* **20** 529-44

[25] Tang Gang 2013 Research on MEMS energy harvester based on piezoelectric thick film [PhD Dissertation] *Shanghai: Shanghai Jiao Tong University*

[26] Chen X J, Qiu C J, Liu H M 2014 Research of Complex PZT Film Base on Shear Mode Energy Harvesting *Advanced Materials Research* **884** 363-9

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