A NOVEL PIEZOELECTRIC THICK-FILM FREE-STANDING CANTILEVER ENERGY HARVESTER

Swee L. Kok*, Neil M. White, and Nick R. Harris
School of Electronics and Computer Science, University of Southampton, UK
***slk05r@ecs.soton.ac.uk, Tel. +44 (0)2380 593234, Fax. +44 (0)2380 592901**

Abstract: Research on energy harvesting from ambient vibration sources has been attracting tremendous attention recently. Free-standing piezoelectric structures are among the devices used as the energy harvester. The structures are commonly fabricated by using thin-film technology. However, their electromechanical properties are typically lower than those of thick-film materials. In this paper, a method of fabricating thick-film free-standing cantilevers, operated in d_{31} and d_{33} are described and the measurement results are presented. These devices are able to be operated at relatively low level of vibrations (frequencies below 500 Hz and acceleration levels below 10 m/s^2) in ambient environment.

Keywords: piezoelectric, thick-film technology, free-standing structure

INTRODUCTION

There have been several reports on free-standing thick-film structures fabricated from piezoceramic (cermet) thick-films printed on alumina in the literature [1, 2] and the method reported here is an extension of these techniques. Although free-standing structures have been fabricated with other technologies, such as thin-film and silicon micro-engineering [3], the technique described here results in a free-standing residual structure from the burning process of a sacrificial layer at elevated temperatures, which does not involve additional chemical processing. This gives an environmental advantage over competing technologies.

A combination method using standard thick-film processing and sacrificial layer technique is used to fabricate the free-standing structures, in the form of cantilever beams, consisting of multilayer co-firing of cermet materials. Lead zirconate titanate (PZT) pastes were used as the active piezoelectric layer and carbon pastes are used as the sacrificial layer, which burnt out during the firing process, resulting in a free-standing structure. The cantilevers were then polarised to make active piezoelectric structures that can harvest vibration energy from ambient environment.

CANTILEVER ENERGY HARVESTER DESIGN

A cantilever piezoelectric can be designed to operate in either d_{31} or d_{33} modes of vibration depending on the arrangement of the electrodes [4]. d_{31} is a thickness mode polarization of plated electrode on the piezoelectric materials, with stress applied orthogonal to the poling direction, as shown in Fig. 1(a). d_{33} mode on the other hand, can be implemented by fabricating interdigitated (IDT) electrodes on piezoelectric materials for in-plane polarization where stress can be applied parallel to the poling direction, as shown in Fig. 1(b). The output voltage, V_{3i} of the piezoelectric device is dependent on the distance between the electrodes, h_i as given by,

$$V_{3i} = h_i \sigma \left(\frac{d_{3i}}{\varepsilon_T} \right) \tag{1}$$

where σ is the stress (N/m^2), d_{3i} is the piezoelectric charge constant (C/N), which depends on the electrode arrangement and ε_T is the permittivity of the material (F/m).

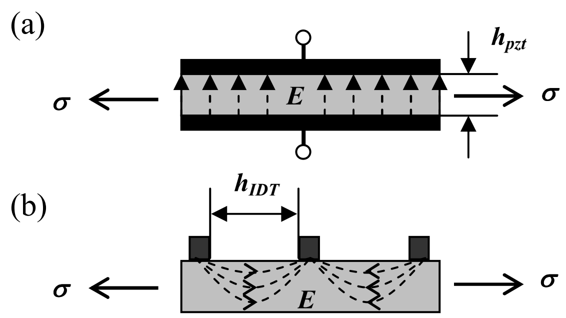

Fig. 1. Electrode with (a) plated and (b) IDT electrodes.

A resonant energy harvester can be modeled as a spring-mass-damper system [5], as shown in Fig. 2.

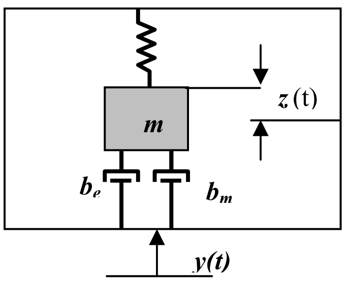

Fig. 2. Generic vibration energy conversion model.

When the system having mass, m is excited with a displacement of $y(t)$ relative to the system housing, a net displacement $z(t)$ is produced and the generic equation derived from the Newton's second law can be written as,

$$m\ddot{z}(t) + (b_e + b_m)\dot{z}(t) + \kappa z(t) = -m\ddot{y}(t) \qquad (2)$$

where, b_e and b_m are the electrical and mechanical damping coefficients respectively. Both damping coefficients can be written as a relative damping ratio, and related to the resonant frequency, ω_n of the system, through $b = 2m\zeta\omega_n$. The system is designed to be operated at its resonant frequency, where the maximum output power equation can be simplified as,

$$P_{\max} = \frac{m\zeta_e A_{in}^{2}}{4\omega_n(\zeta_e + \zeta_m)^2} \qquad (3)$$

The mechanical damping factor is a property of the system, which is difficult to control. However, the electrical damping factor can be varied by using different resistive loads. Once the resistive load is matched to the mechanical damping, maximum energy is transferred from the mechanical to electrical domain.

The energy harvesters are designed to be operated at low levels of vibration in ambient environment, with frequency usually smaller than 500 Hz The vibration frequency of any particular source is generally consistent but its acceleration level can be varied in a range of 0.01 – 10 m/s^2. Therefore, the cantilever energy harvesters have to be designed to suit to the various acceleration levels. There are many possible vibration sources having a wide range of frequencies at various acceleration levels, which are available around us and can be used for harvesting energy for powering low energy microelectronic devices. A few typical vibration sources were characterised and summarized in Table 1.

In order to obtain maximum energy, a cantilever resonant frequency is designed to match with the frequency of vibration sources. The resonant frequency is adjusted by attaching proof mass on the tip of a beam, as according to [6],

$$f_n = \frac{v_n^2}{2\pi}\frac{1}{\sqrt{12.71}}\sqrt{\frac{\kappa}{m_{eff}}} \qquad (4)$$

m_{eff} is the effective mass and κ is the spring constant of the cantilever. Besides that, proof mass increase the electrical output power, however, the power does not increases indefinitely with the mass. At some point with additional mass, the damping effect in the structure increases, therefore increasing the energy dissipation, hence decreasing the output power.

Table 1. Summary of measured vibration sources.

Vibration Sources		Acc. (m/s^2)	Freq. (Hz)
Microwave (Casing)		0.68	100
Refrigerator (Coil)		0.09	100
Vending machine (Casing)		0.12	100
Kitchen ventilation fan	Speed I	0.2	200
	Speed II	1.1	38
Desktop PC	Normal operation	0.21	543
	Running CD ROM	0.26	154
Laptop	Normal operation	0.26	90.2
	Running CD ROM	0.66	43.2
Bus (floor)	Stationary	0.37	111
	Travelling at moderate speed	1.04	10.8
Stationary Car (1.0cc)	Engine	1.23	30.5
	Dashboard	0.04	30

FABRICATION TECHNIQUE

The PZT was made into piezoceramic (cermet) paste, by mixing with lead borosilicate powder as the permanent binder together with an organic vehicle to make a printable paste [7]. Carbon paste, similar to that described by Birol *et al* [8], was used as the sacrificial layer and silver/palladium (Ag/Pd) paste was used as the lower and upper electrodes for the composite thick-film cantilever.

The paste were printed layer by layer, starting with carbon sacrificial layer on an alumina substrate, as shown in Fig. 3 (step 1), followed by Ag/Pd layer, printed over the sacrificial layer as the lower electrode. Four layers of PZT were then printed (to achieve 80 μm thick) and dried in infra-red dryer individually at 140 °C for 10 minutes, before a final layer of Ag/Pd was printed and dried as the upper electrode layer (step 2). The whole composite films were then co-fired together at a peak temperature of 850 °C, holding for 10 minutes. During the co-firing process, the carbon sacrificial layer was burnt off in air thus releasing a composite free-standing structure (step 3), that bends away from the surface of alumina substrates because of the different thermal expansion coefficients between PZT ceramic and Ag/Pd conductor. Finally, the plated samples and IDT samples were polarised at 200 V and 300 V respectively, with a temperature of 200 °C for 30 minutes.

The fabricated free-standing composite cantilevers (Fig. 4) were found to shrink by around 10 % from their original design dimensions because of the high negative thermal expansion coefficient of the conductors.

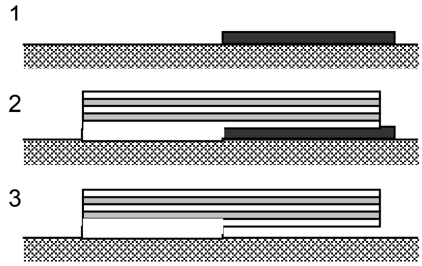

Figure 3. Fabrication steps.

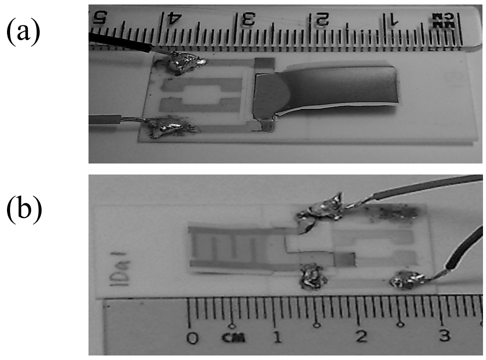

Figure 4. Fabricated prototype with (a) plated and (b) IDT electrodes.

EXPERIMENTAL PROCEDURE

The samples were characterised on a shaker table (Fig. 5) operated at sinusoidal vibration in a range of different frequencies near to the resonant frequency of the beam. The acceleration level was maintained at a constant level by using a feedback system. The accelerometer in the shaker measures the actual value of frequency and acceleration level and is fedback into the control processor. A processed signal is then generated and amplified to drive the shaker to produce the desired acceleration level at a given frequency. The output voltage power from the device is driven into a programmable resistance load and subsequently converted to a digital signal and is measured with National Instrument Sequence Test Programme.

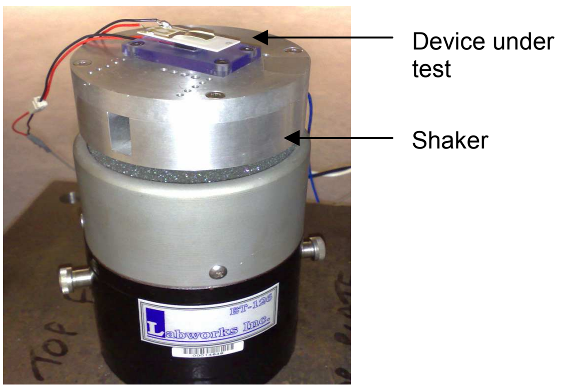

Figure 5. Device under test on a shaker table.

RESULTS AND DISCUSSION

A cantilever sample with length of 13.5 mm was excited at its resonant frequency of 500 Hz and was connected to various resistive loads to measure its output power. As the resistive load increases, the output voltage increases and reaches a maximum at 13 mV when driving a resistive load of 39 kΩ, which gives an maximum electrical power of 3 nW. The output power gradually decreases with further increment of resistive load as shown in Fig. 6. The resonant frequency of the cantilever structure does not influence by the resistive load, however, the resistive load induces damping effect on the structure as shown in Fig. 7. A maximum damping ratio was measured at 0.00615, when the sample was connected with 39 k Ω of resistive load, which is the load used to produce maximum output power. This shows that maximum energy is produced when electrical resistive load is matched with the mechanical damping factor of the structure.

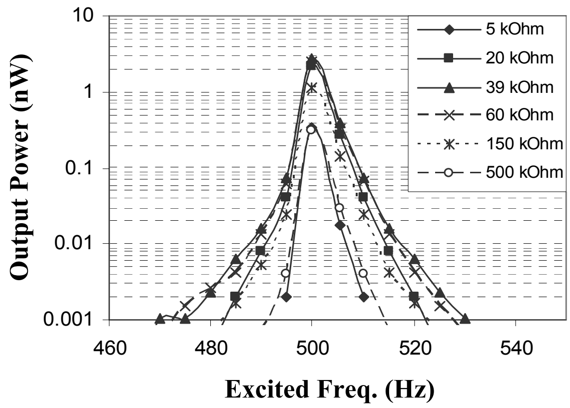

Figure 6. Output power as a function of excited frequency at various resistive loads.

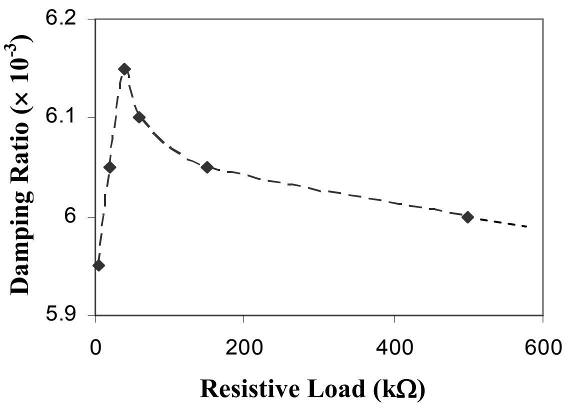

Figure 7. Damping ratio reached maximum when output power reached maximum.

In another experiment with a sample of length 18 mm, a maximum voltage of 145 mV was measured at an acceleration level of 1.25 ***G*** (1 ***G*** = 9.81 m/s^2) at a frequency of 228 Hz, which produced an output power of 352 nW when driving a resistive load of 60 kΩ.

However, if the vibration frequency is fixed at 230 Hz and excited with the same level of acceleration, the output power was reduced to 298 nW. As the excited acceleration level reduced to 0.8 ***G***, maximum output power of 208 nW was produced at a resonant frequency of 230 Hz. It is clearly seen from Fig. 8 that, the maximum output power is influenced by the acceleration level. In this case, the design of the cantilever is suit to be operated at an ambient vibration frequency of 233 Hz, which has a wider coverage of acceleration level compare to source with vibration frequency of 230 Hz, although it does not produce optimum output power at higher acceleration level. It is a case of trade off between wider coverage of acceleration levels and higher output power at higher acceleration level.

In another experiment to compare the electrical output power, plated electrode sample, D3 having length, width and functional layer thickness similar to C3, but a slightly thinner non-active layer, was found to resonate at a lower frequency (875 Hz) compared to C2 (printed with two layers of ceramic) at 1155 Hz. Theoretically, an IDT electrode patterned beam operating in d_{33} mode produces more output voltage compared to plated electrode patterned beams operating in d_{31} mode. This is because the output voltage is proportional to the piezoelectric charge constant and the gap between the electrodes. From the experiments, an IDT sample with gap 1.95 mm between each finder and with same dimensions of sample C3 and D3, IDa1 produced 1.5 pW of electrical power when driving a 30 kΩ resistive load. However, the output power of the IDT sample can be improved by using higher poling voltages and denser fingers feature between two parallel arms.

As proof mass was attached to the tip of the cantilever, the output power was found to increase with a factor of about 10 times compared to sample with no mass attached as shown in Fig. 9. However, as proof mass beyond 1.14 g was added, the output power was found to be reduced from 37 nW to 35 nW for an increment of 0.38 g of mass, because of dissipation of energy through the corresponding increment of damping effects in the structure.

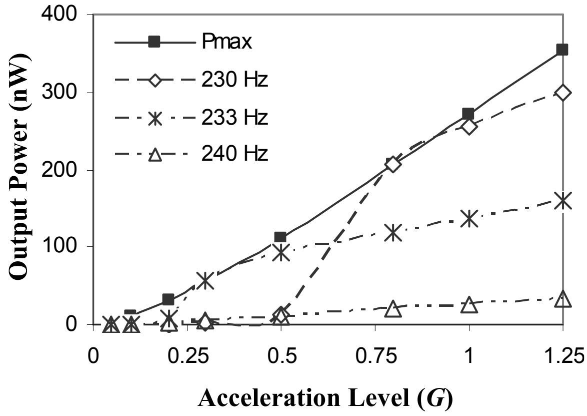

Figure 8. Frequency response of the cantilever for difference acceleration level (1G = 9.81ms^{-2})

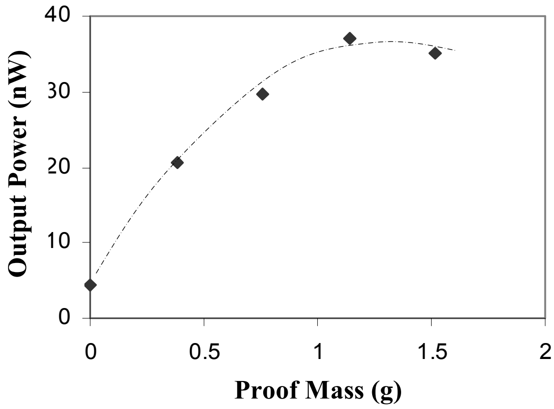

Figure 9. Output power increases from 4 nW with no proof mass up to about 37 nW when a proof mass of 1.14 g was attached to a sample with 13.5 mm length, and excited at 0.1 ***G****.*

CONCLUSION

Free-standing cantilevers fabricated by using thick-film technology were found to be capable of generating useful amounts of electrical power at low frequencies and acceleration levels. Such devices have the potential to be used as energy harvesters for powering wireless sensor nodes. Further research is underway to optimize the output power of the device by fabricating with thicker piezoelectric materials and optimum design with a combination of a few micro-cantilevers.

ACKNOWLEGMENT

A PhD scholarship from Universiti Teknikal Malaysia Melaka is gratefully acknowledged.

REFERENCES

[1] G. Stecher; *6th European Microe. Conf.*, Bournemouth 1987, pp 421-427.

[2] A. Singh, M. Prudenziati, B. Morten; *Microelectronics Reliability*, 25 (1985), pp 619-620.

[3] S.P. Beeby, J.N. Ross, N.M. White; *J. Micromech. Microeng*, 10 (2000), pp 322-328.

[4] J.J. Bernstein, J. Bottari, K. Houston, G. Kirkos, R. Miller, B. Xu, et al; *IEEE Ultrasonics Symposium*, NV 1999, pp 1145-1153.

[5] C.B. Willams, R.B. Yates; *Transducers 95/Eurosensors IX*, 1995, pp 369-372.

[6] J. Merhaut; *McGraw-Hill*, New York (1981).

[7] R. Torah, S.P. Beeby, N.M. White; *IEEE Trans. Ultrason Ferroelectr. Freq. Control*, 52(1) (2005) pp 10-16.

[8] H. Birol, T. Maeder, P. Ryser; J. Appl. Ceram. Technol., 2 (2005), pp 345-354.