

A Free-Standing, Thick-Film Piezoelectric Energy Harvester

Swee L. Kok, Neil M. White and Nick R. Harris

School of Electronics and Computer Science, University of Southampton,
Southampton SO17 1BJ, UK

Email: {slk05r, nmw, nrh}@ecs.soton.ac.uk

Abstract—In this paper, free-standing structures in the form of cantilevers, fabricated by using a combination of conventional thick-film technology and sacrificial layer techniques, is proposed. These structures were designed to operate as energy harvesters at low-levels of ambient vibration and were characterised using a shaker table over a range of frequencies and acceleration levels. A cantilever with dimensions of 13.5 mm long by 9 mm wide and total thickness of 192 μm was found to have Young's modulus of $3.8 \times 10 \text{ N/m}^2$, effective mass of 0.035g and spring constant of 362 N/m. Samples of length 18 mm and functional elements (Lead Zirconate Titanate, PZT) of thickness 80 μm were found to produce an output voltage of up to 130 mV at their resonant frequency of 229 Hz, for an acceleration level of 0.981 ms^{-2} when driving into a resistive load of 60 k Ω . The addition of a proof mass was shown to improve the electrical output power generation. In a series of experiments, the electric power generated by a beam having a proof mass of 2.2 g, resulted in a nine-fold improvement of output power compared to a device with no proof mass. The size of the proof mass is also an important factor in determining the output power of the device.

I. INTRODUCTION

Conventionally, thick-film piezoelectric materials are fabricated and used as sensors and actuators. However, with the improvement of high piezoelectric activity in lead zirconate titanate (PZT), useful electrical energy is generated and can be used in powering a variety of microelectronic devices. The first reported thick-film micro-generator described by White *et al* [1] was fabricated by printing the functional materials on stainless steel. The device was capable of generating powers up to $3 \mu\text{W}$ at 80 Hz for an acceleration of 225.6 m/s^2 . Recently, thin-film and micromachining technologies have also been used in fabricating energy harvesters as reported by Jeon *et al* and Choi *et al* [2, 3]. However, these devices were operated at relatively high resonant frequencies (13.9 kHz) and high acceleration levels (252 m/s^2), which are not suitable for harvesting energy from typical ambient environments. These are typically at levels of acceleration in the range $0.05 - 2 \text{ m/s}^2$ at frequencies from 10 Hz to 300 Hz.

A better solution for harvesting low level vibrations is by fabricating thick-film piezoelectric materials in free-standing form, where the functional material can move freely without

the constraint of the substrate material. The first thick-film free-standing structures were reported by Stecher, G in 1987 [4], who fabricated a form of circular membrane that was used as pressure sensor.

Free-standing thick-film piezoelectric cantilevers fabricated by a combination of conventional thick-film technology and sacrificial layer techniques will now be described further. The structures were fabricated to have different lengths between 4.5 mm and 18 mm. They were characterised on a shaker table excited by sinusoidal vibration, at different acceleration levels over a range of different frequencies near to the resonant frequency of the beam. Various sizes of proof mass were attached to a sample of length 13.5 mm and evaluated to determine the electrical output performance and to estimate the Young's modulus and effective mass and spring constant of the structure.

II. TYPICAL AMBIENT VIBRATION SOURCES

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. In order to design piezoelectric micro-generators suitable for the ambient environment, a few typical vibration sources were characterised as shown in Fig. 1.

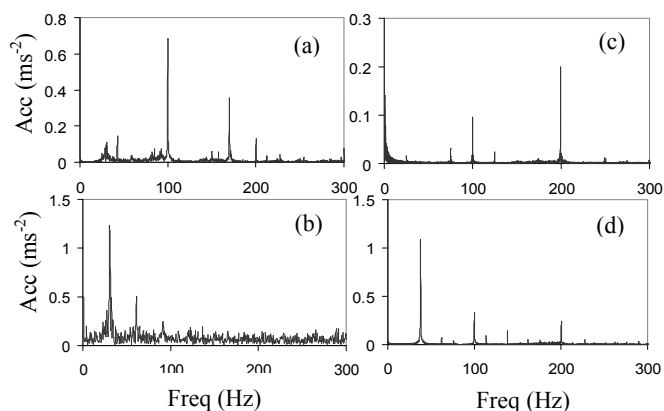


Figure 1. Typical ambient vibration sources measured with an accelerometer and presented in the frequency domain: (a) Microwave casing, (b) engine of a stationary car, (c) kitchen ventilation fan at lower speed and (d) kitchen ventilation fan at higher speed.

Table 1 shows a summary of the measured vibration sources in terms of peak acceleration levels and resonant frequencies.

TABLE 1. SUMMARIES 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

III. CANTILEVER MICRO-GENERATOR DESIGN

A cantilever micro-generator was designed based on spring-mass-damper system [5]. When the cantilever is excited with a displacement of $Y(t)$ relative to the system housing, a deflection, z is produced as shown in Fig. 2.

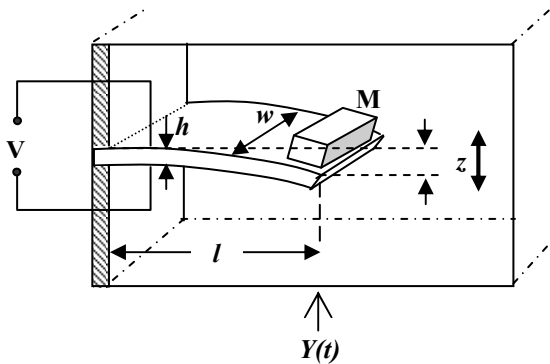


Figure 2. A schematic diagram of a cantilever clamped on one end, with dimensions of length, l , width, w and thickness, h . The free-standing structure is loaded with a proof mass, M , excited with a displacement of $Y(t)$ and producing a deflection of z .

The resonant frequency of a cantilever is determined by the mechanical properties of the structure, which is related to its length, l , thickness, h , Young's modulus, γ and density, ρ given by [6],

$$f_n = \frac{v_n^2}{2\pi\sqrt{12}} \left(\frac{h}{l^2} \right) \sqrt{\frac{\gamma}{\rho}} \quad (2)$$

where v_n^2 is the eigenvalue of n th mode of vibration, which is depended on the boundary conditions. The eigenvalue of the fundamental mode of a cantilever beam is 3.52. This equation can be used to estimate the resonant frequency for a uniform beams. However, the dimensions of a cantilever beam change after fabrication because of shrinkage, therefore, the effective mass, m_{eff} of the materials is used to determine the resonant frequency of the structure, which is given as,

$$m_{eff} = \frac{\kappa}{12.71} \left(\frac{v_n^2}{2\pi f_n} \right)^2 \quad (3)$$

The spring constant, κ of the structure can be determined by experiments with varying proof masses and excited at its resonant frequency.

When the device is excited at its resonant frequency, the maximum power driving a resistive load is related to the total mass of the system, m , input acceleration, A_{in} , angular frequency, ω_h and damping coefficient as,

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

The mechanical damping factor, ζ_m is a property of the system which is difficult to control. However, the electrical damping factor, ζ_e can simply be varied by using different resistive load. Once the resistive load is matched with the mechanical damping, maximum energy is transferred from the mechanical to electrical domain. The electrical output power does not increase indefinitely with the proof mass. At some point with additional mass, the damping effect in the structure increases, therefore increasing the energy dissipation, hence decreasing the output power.

IV. FABRICATION TECHNIQUE

The materials for fabricating the free-standing structures consisted of PZT paste, carbon sacrificial paste, silver/palladium (Ag/Pd) conductor pastes and alumina substrates. The functional element, PZT pastes were formulated as according to [7], and the carbon pastes similar to that described by Birol *et al* [8] was used as the sacrificial layer.

The fabrication process commences by screen-printing a carbon sacrificial layer (Fig. 3), followed by Ag/Pd printed over the sacrificial layer as the lower electrode. Eight layers of PZT were then printed 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. The whole composite films were then co-fired together at a peak temperature of 850 °C, holding for 10 minutes, in a multi-zone furnace. During the co-firing process, the carbon sacrificial layer was burnt off in air thus releasing a composite free-standing structure, that breaks free and bends away from the surface of alumina substrates because of the different thermal expansion coefficients between PZT ceramic and Ag/pd conductor. Finally, the samples were then polarised at around 3 MV/m with a temperature of 200 °C for 30 minutes.

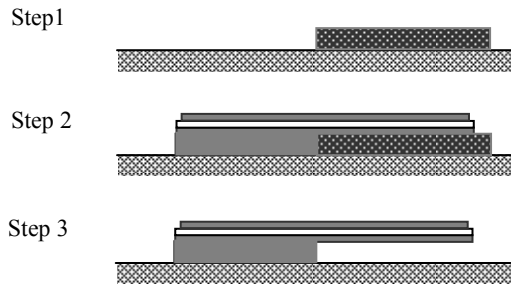


Figure 3. Sacrificial layer technique fabrication steps for releasing a cantilever free-standing structure.

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

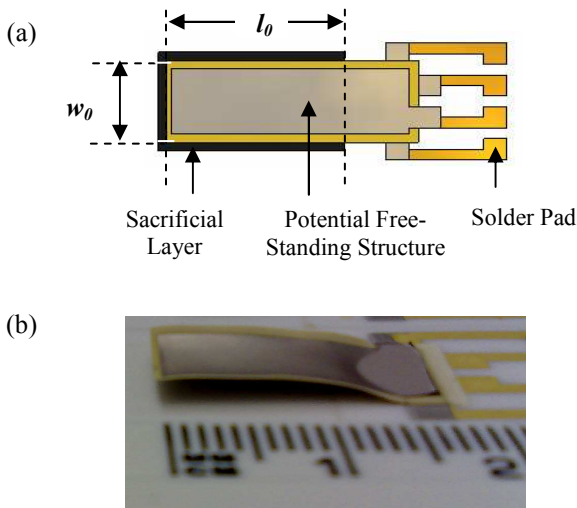


Figure 4. Free-standing cantilever: (a) Design layout and (b) fabricated prototype.

V. RESULTS AND DISCUSSION

The resonant frequency of the cantilever decreases with increasing length and added mass according to equations (2) and (3), which were verified experimentally as shown in Fig. 5 (a) and (b) respectively. The density of the sandwich structure of PZT-Ag/Pd was measured at 6240 kg/m³, which gives an average Young's modulus of 3.8×10^9 N/m². A sample having 13.5 mm length and 9 mm width was found to have a spring constant of 362 N/m and the calculated effective mass of the cantilever beam is 0.035 g.

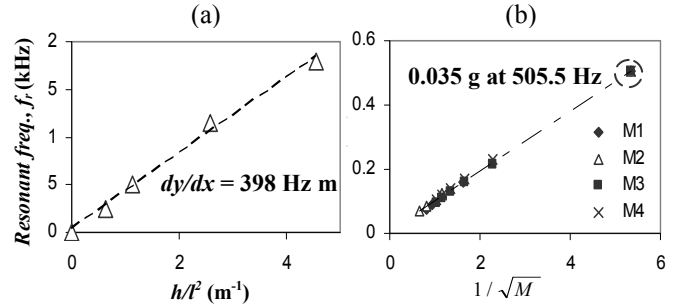


Figure 5. Resonant frequency is inversely proportional to (a) square of length and (b) square root of mass. The gradient of the graph of f_r Vs h/l^2 can be used to estimate the Young's modulus of the samples. Extrapolation of graph f_r Vs $1/\sqrt{M}$ can determine the effective mass of the cantilever beam.

The output voltage of the device increases with the length of the cantilever beam as shown in Fig. 6. An open circuit output voltage for a cantilever of length 18 mm was measured at 130 mV for an acceleration of 0.981 m/s² (0.1 *G*). However, the voltage dropped to around 20 mV when driving an optimum resistive load of 60 kΩ, which gives an electrical output power of about 7 nW.

Higher vibration acceleration levels can improve the electrical output power. The power increases by a factor of more than 25 when accelerated at 9.81 m/s² (1 *G*), as shown in Fig. 7. However, a higher acceleration level induces a nonlinearity for power generated by the cantilever structures, where the fundamental resonant frequency was found to be shifted to a lower frequency as the acceleration increases and also due to the fact that the acceleration level is not consistent in the ambient vibration source. Therefore micro-generators with a wider band of resonant frequencies have to be designed to harvest a wider range of different and inconsistent acceleration levels of ambient vibration.

The output power can be increased by attaching a proof mass at the tip of a piezoelectric cantilever. Larger masses produced more power, to an extent. Excessive proof masses, however, can result in energy dissipation through damping effects in the structure. The dimensions of the proof mass are also an important factor in determining the output power. From the experiments conducted, a proof mass that had its centre of mass focused on the tip of the beam and spread

across the width of the beam, produced the most output power, which is shown by a proof mass, $M1$ with dimensions of 9 mm width, 2.5 mm length and 1 mm thickness compare to other proof mass as shown in Fig. 8. This is because, in this configuration, more stress was induced when the cantilever was vibrated at its resonant frequency.

VI. CONCLUSION

This is the first time that thick-film free-standing structures, in the form of a cantilever, have been fabricated by a combination of thick-film and sacrificial layer techniques. The structures were designed to operate in an ambient environment to harvest energy from low acceleration levels and frequencies. In a series of experiments with different cantilever lengths and attaching different proof masses, the mechanical properties, Young's modulus and spring constant of the free-standing structures were determined. Because of the fact that, the devices were not identical to the desired design dimensions, the effective mass of the composite structures is an important parameter to determine their resonant frequencies. Owing to nonlinear effects and the inconsistency of acceleration levels of ambient vibration sources, the design of energy harvesters having wider band of resonant frequencies is desirable. The addition of a proof mass improves the output power to some extent, but the effectiveness decreased for large inertial masses. Although the powers generated from the vibration devices are relatively small (270 nW at 9.81 m/s^2), they have the potential to be improved further i.e. by increasing the thickness of the functional elements.

ACKNOWLEDGMENT

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

REFERENCES

- [1] N.M. White, P. Glynn-Jones, and S.P. Beeby, "A novel thick-film piezoelectric micro-generator," *Smart Mater. Struct.*, vol. 10, pp. 850-852, 2001.
- [2] Y.B. Jeon, R. Sood, J. Jeong, and S.G. Kim, "MEMS power generator with transverse mode thin film PZT," *Sensor and Actuators A*, vol. 122, pp. 16-22, 2005.
- [3] W. Choi, Y. Jeon, J.H. Jeong, R. Sood, and S. Kim, "Energy harvesting MEMS device based on thin film piezoelectric cantilevers," *J. Electroceramics*, vol. 17(2), pp. 543-548, Dec 2006.
- [4] G. Stecher, "Free supporting structures in thick-film technology: A substrate integrated pressure sensor," *6th European Microelectronics Conf. Bournemouth*, pp. 421-427, 1987.
- [5] C.B. Williams, and R.B. Yates, "Analysis of a micro-electric generator for microsystems," *Transducers 95/Eurosensors IX*, pp. 369-372, 1995.
- [6] J. Merhaut, *Theory of electroacoustics*, McGraw-Hill, New York, 1981.
- [7] R. Torah, "Optimisation of the piezoelectric properties of thick-film piezoceramic devices," PhD thesis, University of Southampton, 2004.
- [8] H. Birol, T. Maeder, and P. Ryser, "Fabrication of LTCC micro-fluidic devices using sacrificial carbon layers," *J. Appl. Ceram. Technol.*, vol. 2, pp. 345-354, 2005.

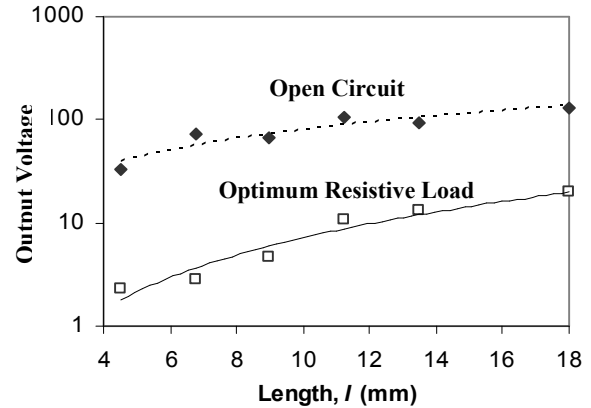


Figure 6. Output voltage as a function of length for the cantilever, with open circuit test and with optimum resistive load test for sample with length 18 mm, accelerated at 0.981 m/s^2 .

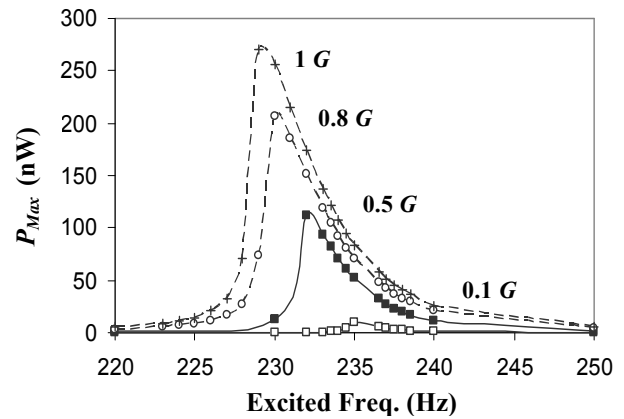


Figure 7. Resonant frequency and output power change as acceleration level changes. ($1 \text{ G} = 9.81 \text{ m/s}^2$).

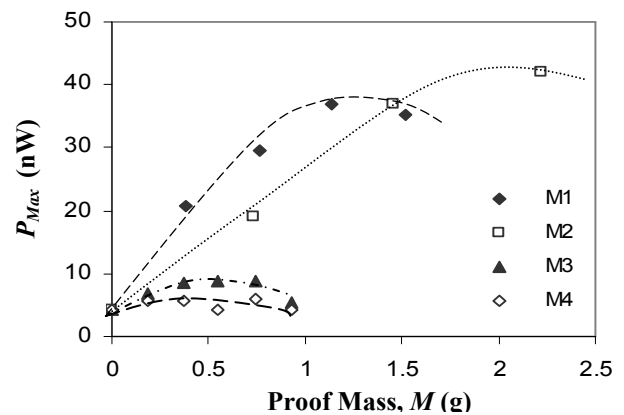


Figure 8. Output power of a cantilever with different proof mass weights and dimensions: width \times length \times thickness (M1 = $9 \times 2.5 \times 1$, M2 = $9 \times 5 \times 1$, M3 = $4.5 \times 2.5 \times 1$ and M4 = $2.5 \times 4.5 \times 1$) mm.