Free-standing thick-film piezoelectric device

S.L. Kok, N.M. White and N.R. Harris

A free-standing thick-film cantilever sensor structure is presented. Such devices find use in applications such as vibration detection or energy harvesting. The structure was fabricated by screen printing layers of lead zirconate titanate between silver/palladium electrodes and co-firing the layers together with a carbon sacrificial layer (deposited underneath) in an air environment at a temperature of 850°C. The free-standing structure, of dimensions 18 mm long by 9 mm wide and thickness of 50 μm, was found to produce electrical powers of up to 95 nW at an acceleration level of 9.81 m/s^2 (1 *g*), when driving a 60 kΩ load resistance.

Introduction: Thick-film lead zirconate titanate (PZT) layers fabricated onto substrates such as alumina and stainless steel suffer from problems associated with the clamping effect, because the substrate material has to be accounted for, with regard to device sensitivity and frequency response. Therefore free-standing structures, in the form of cantilevers, provide improved solutions for obtaining more precise values of piezoelectric parameters such as the strain coefficient, coupling coefficient and damping ratio. Free-standing structures based on both thick and thin films as well as polymers have been reported by other researchers [1–3]. In this Letter, we describe a method of fabricating screen printed free-standing thick-film cantilevers of functional materials using a one-step firing process in an air environment.

Material processing: Conventional thick-film processes were used to fabricate the structure. To make a free-standing PZT layer above the substrate, a carbon sacrificial layer was initially printed prior to the functional layers. This would subsequently be burnt out during the firing stage, thereby leaving a free-standing, sandwich structure of PZT and silver/palladium (Ag/Pd) (ESL 9633B). In addition to being used as an upper and lower electrode, the Ag/Pd plays an important role as a supporting structure for the brittle and fragile PZT ceramic. The functional element of the structure is made up from a mixture of PZT powder (Ferroperm Pz29) with particle sizes of 0.8 and 2 μm in a ratio of 1:4, 10% by weight of lead borosilicate glass (Ferroperm CF7575) and appropriate amount of vehicle (ESL 400) to make a screen printable paste [4]. The carbon paste was made by mixing graphite (Sigma-Aldrich 282863) with the organic binder ethyl cellulose (Sigma-Aldrich 433837) in a ratio of 1:3. Ethyl cellulose was dissolved in terpineol (Fluka 86480) in advance before mixing with graphite and acetyl acetone together to reduce the paste viscosity [5]. Both pastes were homogenised using a triple-roll mill before screen printing on an alumina substrate.

The fabrication process was commenced by screen printing the carbon sacrificial layer. Ag/Pd was then printed over the sacrificial layer as a lower electrode (and also as supporting structure). To achieve a thickness of 50 μm, four layers of PZT were printed on top of the lower electrode layer. Finally another Ag/Pd layer was again printed to function as an upper electrode. Each printed layer was dried in an infra-red dryer at 140°C for 10 min, before successive layers were printed on top. The complete printed and dried layers were then fired together in an eight-zone belt furnace, using a sintering profile with a peak temperature of 850°C (held for 10 min). This results in a total firing time of around one hour. During the firing process, the organic binder in the sacrificial layer was first burnt off and therefore the sandwich layer of electrode-PZT-electrode breaks free from the surface and begins to bend away from the substrate because of the different thermal expansion coefficients between PZT ceramic and Ag/Pd. The graphite, which acted as filler in the sacrificial layer, was then burnt off totally in air as CO_2 before the PZT ceramic was sintered at 850°C.

Polarisation process: Six samples of cantilevers having the same width (10 mm), but different lengths (5, 7.5, 10, 12.5, 15 and 20 mm) were fabricated. Structures having a length, *L*, smaller than the width, *W*, tended to rise at an angle of about 45° away from the substrate after firing. For devices having $L \geq W$, these tended to be relatively flat and elevated to a height, *H*, of about 20% of the width, as shown in Fig. 1. The samples were polarised simultaneously with an electric field strength of 4.4 MVm^{-1} on a hotplate at 200°C for 30 min. The samples were then allowed to cool to room temperature before the electric field was removed.

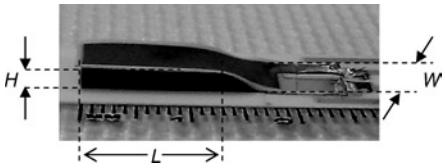

Fig. 1 *Photograph of PZT ceramic, free-standing structure*

Results and discussion: With a careful selection of load resistance, the electrically induced damping is adjusted to be equal to mechanical damping ratio. Once the optimal load resistance is matched to the PZT free-standing device, a maximum output power will be produced. From the relation between mechanical damping ratio, ζ, PZT capacitance, *C*, natural frequency of the free-standing structure, ω_n, and optimal load resistance, R_o, the piezoelectric coupling coefficient, k_{31}, can be calculated [6].

$$k_{31} = \left[\left(\frac{2\zeta}{R_o \omega_n C} \right)^2 - 4\zeta^2 \right]^{1/4} \qquad (1)$$

Samples were tested under harmonically excited vibration on a shaker at 0.981 m/s^2 (0.1 *g*) acceleration level, and the frequency response from the free-standing devices was measured on a spectrum analyser. The measured *Q*-factors for the samples were between 120 and 214 and these gave damping ratio between 0.0023 and 0.0042. From (1), the piezoelectric coupling coefficient is calculated and found to be between 0.05 and 0.09.

The natural frequency dropped from about 2.2 kHz to 238 Hz for free-standing structures with length of 5 and 20 mm, respectively. At 0.1 *g* acceleration level, structures with lengths of 18 mm produced up to 130 mV on an open-circuit test. This, however, dropped to around 20 mV with optimum load resistance at 60 kΩ. As the length of the free-standing structure increases, the elastic modulus *Y* (N/m^2) decreases, this in turn developed more strain when the same force was applied, which produced more electrical power; this agreed with the piezoelectric constitutive equations:

$$S = \frac{\sigma}{Y} + dE; \quad D = \varepsilon E + d\sigma \qquad (2)$$

where *S* is mechanical strain, σ is mechanical stress (N/m^2), *d* is the piezoelectric strain coefficient (C/N), *E* is electric field (N/C), *D* is charge density (C/m^2) and ε is the dielectric constant of the piezoelectric material (F/m).

Greater load resistances are needed for longer cantilevers in order to draw out the maximum power from the PZT layer, as shown in Fig. 2. As the shaker acceleration level increased from 0.1 to 1 *g*, the output power for sample D6 increased about ten times, as shown in Fig. 3.

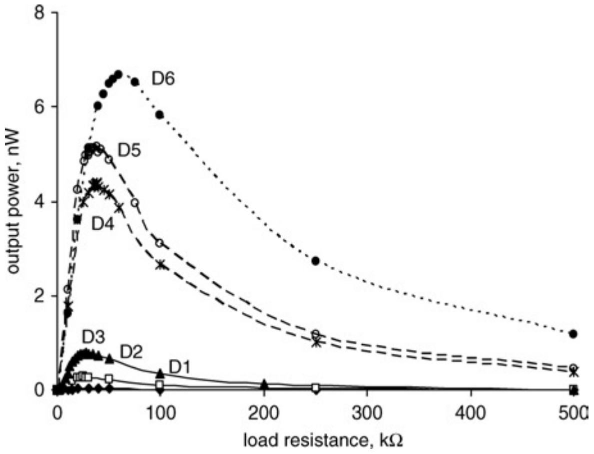

Fig. 2 *Output power at different load resistance for samples D1 (L = 4.5 mm), D2 (6.75 mm), D3 (9 mm), D4 (11.25 mm), D5 (13.5 mm) and D6 (18 mm), measured at 0.981 m/s^2 (0.1 g)*

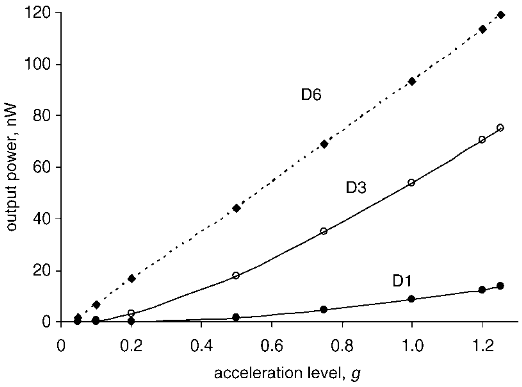

Fig. 3 *Output power against acceleration level*

Conclusions: We have used thick-film technology to fabricate a free-standing sensor structure in the form of a cantilever. Traditional piezoelectric cantilevers are built on substrates, which cause problems associated with clamping effects and may prohibit the PZT from producing optimum performance. With free-standing structures, more accurate values of the electrical parameters of PZT films can be calculated, in addition to improving the output power when used as a vibration energy harvester. The nature of the carbon sacrificial layer, silver/palladium electrodes and PZT ceramic needs to be further investigated, in terms of design and fabrication, to allow larger scale fabrication of flexible and robust piezoelectric free-standing devices.

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