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Ultra large deflection of thin PZT/aluminium cantilever beam

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Flexible piezoelectric cantilever beam has been realized by depositing lead zirconate titanate (PZT) thin film ($4.5\ \mu\text{m}$) by chemical solution deposition (CSD) onto very thin aluminium foil ($16\ \mu\text{m}$). The tip deflection of the beam has been measured as a function of the frequency of the applied sinusoidal voltage to the PZT film for different amplitudes. Resonance curves have been compared to a classical model of an oscillating system under sinusoidal stress with a very good agreement. Despite of weak ferroelectric properties (remnant polarization: $13\ \mu\text{C}/\text{cm}^2$), ultra-large deflection amplitudes have been measured under very moderate applied voltage values: $750\ \mu\text{m}$ @ $10\ \text{V}$ for quasi-static mode and $5\ \text{mm}$ @ $10\ \text{V}$ at the resonance frequency ($\sim 12\ \text{Hz}$), which makes this PZT/aluminium composite film very promising for highly flexible actuation applications where large displacements are wanted.

Keywords: PZT thin film; flexible film; cantilever; aluminium foil; large deflection.

Flexible piezoelectric films are gaining major interest because of the multitude of electromechanical applications that might be associated with them. Two materials are subject to extensive studies because of their best piezoelectric properties in their category: In polycrystalline form, lead zirconate titanate (PZT) thin films present transverse piezoelectric coefficients d_{31} ranging from $\sim 10\ \text{pm}/\text{V}$ to $\sim 200\ \text{pm}/\text{V}$.¹⁻³ Polyvinylidene fluoride (PVDF), a semi crystalline polymer, presents the advantage of the natural flexibility of polymers, but with piezoelectric coefficients 5–10 times lower than the highest reported PZT thin film coefficients.^{4,5} While it seems difficult to improve the d_{31} coefficient of PVDF already flexible, researchers have rather tried to make flexible PZT films while keeping their excellent piezoelectric properties. In general, PZT thin films are grown on stiff silicon substrates for applications in microelectronics. Some other different substrates like stainless steel, alumina, sapphire, MgO were also used, but they remain still too rigid for applications requiring flexible actuating micro devices. The main drawback of the synthesis of PZT thin films is the conventionally required large thermal budget ($600\text{--}800^\circ\text{C}$) to

obtain a complete crystallization of the perovskite phase, which makes the use of polymer substrates very limited (at least during the heat treatment). PZT films have already been deposited by sputtering onto a thermally stable polyimide film ([®]Kapton), but piezoelectric properties remained low.⁶ Recently, piezoelectric beams have been obtained by laminating a PZT ceramic on polyethylene terephthalate (PET), yielding good vibrating properties which can be used for micropower energy harvesting applications.⁷ Another way that is being developed is to synthesize conventionally PZT thin film on a rigid substrate, and transfer it by various techniques (buffer, laser lift-off) on polymer like PET and polydimethylsiloxane PDMS films.⁸⁻¹⁰

In this paper, the authors present the realization of a cantilever-based PZT thin film deposited onto an ultra thin aluminium foil as a substrate and show that a very flexible actuator with low voltage-induced ultra large deflections can be obtained by this method.

The piezoelectric cantilever has been prepared by depositing a PZT thin film onto aluminium foil (with a thickness $t_s = 16\ \mu\text{m}$) by a chemical solution deposition (CSD) process^{11,12} using zirconate, titanate alkoxides and lead acetate as precursors and acetic acid as solvent. The Zr/Ti ratio is 57/43 typically used at the laboratory for other

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applications. Multiple spin-coating at 6000 rpm leads to a PZT thickness of around $t_p = 3 \mu\text{m}$. Each layer has been crystallized at 650°C for 2 min in an open air furnace, resulting in a perovskite phase without preferred orientation. In order to apply the electric field to obtain the piezoelectric effect, aluminium top electrode of $1 \text{ cm} \times 4 \text{ cm}$ area ($\sim 200 \text{ nm}$ thick) has been evaporated through a shadow mask, the aluminium foil being directly used as bottom electrode. The piezoelectric film has been poled using a Sawyer-Tower circuit with a $4.7 \mu\text{F}$ serial capacitor under a 200 kV/cm sinusoidal electric field at 50 Hz . The resulting P-E measurement leads to a $13 \mu\text{C/cm}^2$ value for the remnant polarization and a 76 kV/cm value for the coercive field. The remnant polarization could be improved by increasing the applied electric field, but it would increase the risk of dielectric breakdown because of the large size of the sample and the top electrode. Moreover, the aluminium substrate is not oriented and does not promote the crystallization of the PZT film. The ferroelectric properties are also mitigated by the oxidation of the metal during the heat treatment, which forms an interfacial dielectric oxide layer at the aluminium/PZT interface leading to a high coercive field value. For bending-mode actuation measurements, the aluminium/PZT sample has been clamped on one side resulting on an unimorph cantilever beam of 3.4 cm long, 1.1 cm wide and $20.5\text{-}\mu\text{m}$ thick. A laser vibrometer (Polytech OFV 2200) has been used to measure the tip deflection at the free end of the beam.

A sinusoidal voltage with amplitude V_0 has been applied to the PZT film and the deflections at the free end of the beam as a function of the frequency of the electric field are represented in Fig. 1 for different V_0 values, from 0.7 V to 10 V .

The noticeable point is the order of magnitude of the deflection at the resonance frequency, close to 12 Hz , whatever the V_0 values. Generally, for PZT thin film-based cantilever beams, the deflection magnitude is within the nanometer or micrometer range.^{13–15} Due to the very flexible substrate, the size of the beam and the low ratio between the aluminium and PZT thicknesses, ultra large deflection of the beam is obtained within the millimeter range, which can be easily observed to the naked eye. The resonance behavior of the curves leads to compare the vibration of the beam to the classical model of an oscillating system under sinusoidal excitation. In this theory, the amplitude d of the deflection at the end of the beam can be described by the equation¹⁶

$$d = d_0 \sqrt{1 - (f/f_0)^2 + (f/(f_0 \times Q))^2}, \quad (1)$$

where d_0 is the quasi-static deflection value, f is the frequency of the applied voltage $v = V_0 \cos(2\pi ft)$, f_0 is the frequency of the oscillator of the free mode and Q is the mechanical quality factor.

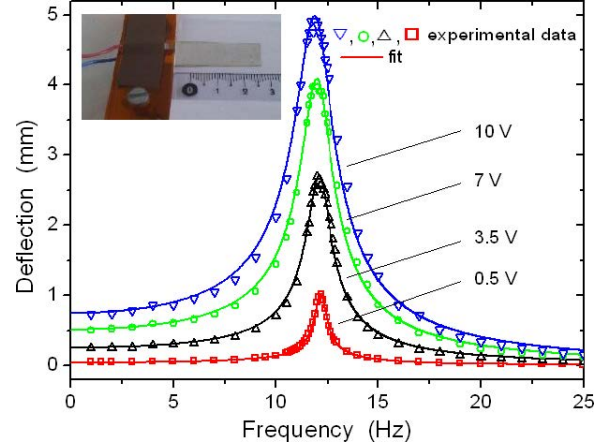


Fig. 1. Tip deflection of the cantilever beam as a function of the frequency for different amplitudes of the applied voltage and the associated fits. The inset shows a photograph of the PZT/aluminium cantilever beam and the clamp fixture.

Figure 1 also shows the very good agreement between this model and the experimental deflections. By fitting the experimental curves obtained for different applied voltages, the Q , d_0 , and f_0 values have been extracted. In this model, the quality factor Q should not depend on the external excitation, but it is not the case here as it is shown in Fig. 2, where the Q values are represented as a function of the amplitude V_0 of the applied voltage.

The quality factor value decreases from 22 to 6.6 for V_0 starting from 0.7 V to 10 V . This point has already been observed by another group¹⁷ and was attributed to the air friction. This is particularly relevant here by the use of a lightweight (30 mg) and large (3.7 cm^2) cantilever beam. The velocity of the vibrations increases with the amplitude of the applied voltage, then, the increasing influence of the air on the cantilever explains the decrease of the quality factor value, which reflects the mechanical frictions in the oscillator system.

In Fig. 3, are represented the maximum of the experimental deflection d_{max} at the resonance frequency, the resonance frequency f_r as a function of the amplitude of the

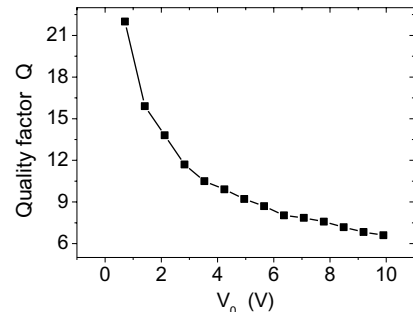


Fig. 2. Quality factor values as a function of the amplitude of the applied voltage.

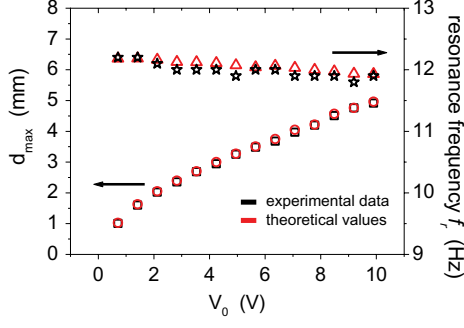


Fig. 3. Experimental and modelled values of the maximum of the deflection d_{\max} and of the resonance frequency f_r as a function of the amplitude of the applied voltage.

applied voltage and the calculated values obtained by the equations¹⁶:

$$d_{\max} = d_0 \times Q / \sqrt{1 - 1/4Q^2} \approx d_0 \times Q \quad (2)$$

and

$$f_r = f_0 \times \sqrt{1 - 1/2Q^2} \approx f_0. \quad (3)$$

For an applied voltage V_0 starting from 0.7 V to 10 V, the measured deflection ranges from 1 mm to 5 mm, which is very high compared to classical cantilevers elaborated with PZT thin films.^{18,19} Such large deflections can be reached because of the very thin, lightweight and flexible substrate used and larger deflection could be possibly reached with this cantilever by increasing the applied voltage, but the aluminium substrate folds under the mechanical stress. In this case, the folding is irreversible and the beam does not return to its initial position, even after removing the electric field. This is the reason why the applied voltage has been limited to 10 V in this study. Concerning the resonance frequency, the slight downward slope of the curve can be explained in part by the evolution of the quality factor as a function of V_0 but f_r stays close to the f_0 value of 12 Hz. In a first approximation, the first resonance frequency of the beam can be calculated with the following equation²⁰ (in our study, the Young's modulus has been replaced by an effective Young's modulus taking into account the thickness of the both materials).

$$f_r = \frac{(t_s + t_p) \times \alpha_1^2 \times \sqrt{(t_p E_p + t_s E_s) / (t_p \rho_p + t_s \rho_s)}}{2\pi L^2 \sqrt{12}}, \quad (4)$$

where the coefficient $\alpha_1 = 1.875$, is a constant for the fundamental resonance frequency, L is the length of the free part of the cantilever, E_p , ρ_p , E_s and ρ_s are the Young's modulus and the density of PZT and aluminium respectively. The Young's modulus values used here are: $E_p = 95.2$ GPa¹⁹ and $E_s = 69$ GPa. Although the assumption on the deflection level is not validated, the deflection level should be low

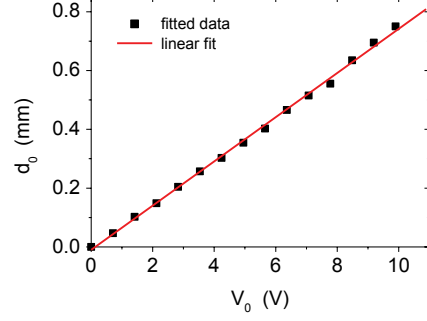


Fig. 4. Linear fit of the deflection d_0 in the quasi-static mode as a function of the amplitude of the applied voltage.

compared to the thickness of the cantilever, but here:

$$244 > \frac{d_{\max}}{(t_s + t_p)} > 49, \quad (5)$$

the calculated resonance frequency (12.1 Hz) using Eq. (4) is very close to the experimental results. The piezoelectric coefficient d_{31} has been calculated using the following equation²¹

$$d_{31} = \frac{-d_0 \times (s_s^2 t_p^4 + 4s_s s_p t_s t_p^3 + 6s_s s_p t_s^2 t_p^2 + 4s_s s_p t_s^3 t_p + s_p^2 t_s^4)}{3s_s s_p t_s (t_s + t_p) L^2 V_0}, \quad (6)$$

where $s_s = 1/E_s$ and $s_p = 1/E_p$ and the d_0/V_0 ratio is obtained by the linear fit of the dependence of d_0 upon V_0 shown in Fig. 4. The calculation yields a low piezoelectric coefficient of -10 pm/V. This can be explained by the derived Sol-gel process used (for which similar d_{31} value has been obtained),^{21,22} the nonoptimum Zr/Ti ratio (52/48 is preferred for piezoelectric applications²³), the low crystallization anneal (650°C) yielding the weak polarization of the PZT film²⁴ and the nonoriented metallic substrate also inducing weak ferroelectric properties.^{25,26} However, the deflection in the quasi-static mode d_0 is quite high, ranging from $46 \mu\text{m}@0.7$ V to $750 \mu\text{m}@10$ V.

In summary, this paper reports on the realization of a cantilever-based PZT thin film deposited on an ultra thin aluminium foil for bending-mode actuation. Very large deflections induced by low voltage appliance were measured, up to $5 \text{ mm}@10\text{V}$ at the 12 Hz resonance frequency. These values are much higher than those usually reported for PZT thin film-based cantilevers, which makes this PZT/aluminium composite film very promising for actuation applications where very moderate driving voltage is an asset, like in microfluidics. Besides, a good agreement was found between measured tip deflections and resonance frequency and calculated ones. To still get better electromechanical performances, future work will be devoted to the improvement of

both the piezoelectric properties of the films by modifying the CSD process and the poling step.

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