CANTILEVERS WITH PIEZOELECTRIC THIN FILMS FOR WEAKLY VIBRATING ENVIRONMENT

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Abstract: This paper deals with the conception of simple macro piezoelectric cantilevers for energy harvesting to power low consumption sensors. Because some applications do not necessarily require micron-scale dimensions, it has been decided to prospect the potential of macro cantilevers made of piezoelectric material in order to convert low frequency vibrations into a sufficient electrical power for autonomous communicating sensors. This study has been made in three different parts: choosing the proper piezoelectric material, mechanically designing the macro cantilever and experimenting to prove the high potential for energy harvesting of these types of devices. Here we present piezoelectric vibrating macro cantilevers based on AlN thin films deposited on Silicon. Once released, these devices resonate at 143Hz and exhibit a voltage reaching 4V for a 1MOhm-load and an initial deflection of 1mm. This last associated with a quality factor reaching 71 as observed from experiment corresponds to a rather weak acceleration (0.3g). Therefore, it lets expect a harvested energy as high as 18µW which is the right order of magnitude required for basic applications as autonomous sensors.

Keywords: Power harvesting, piezoelectric, cantilever, low frequency vibrations, PZT, AlN

INTRODUCTION

With the recent surge of micro scale devices, piezoelectric power generation can provide an alternative to traditional power for low consumption devices. Numerous studies have shown the potential of micro devices based on piezoelectric materials to transform kinetic energy, like vibration, into electrical power. Yet, in a large number of cases, these types of systems are in the micrometer range: they provide only few tens of nW and exhibit resonance in the kHz range. These behaviors do not fit with the needed properties of nowadays potential applications as autonomous sensors. Indeed, the three typical specifications that can be highlighted for harvesting vibrating systems dedicated to autonomous applications are the following: a frequency range between 50 and 200Hz, a vibration amplitude (much) lower than 1g (i.e. 10 m.s^{-2}) in order to harvest at least 10µW continuously. That means that macro devices are mandatory to fulfill these requirements.

The idea here is to use simple devices which can convert low frequency vibrations (100 to 200 Hz) with a small acceleration (<10m.s^{-2}) into electrical power able to power low consumption devices, as autonomous sensors. It is generally accepted that these lasts need at least an electrical power of 10µW. An existing device is the one proposed by Micropelt [1], which uses the thermoelectric effect. Our purpose here is to propose energy harvesting devices able to convert low frequency vibrations into power in the range about tens of µW by the use of macro cantilevers.

A large number of studies on piezoelectric harvesters have already been reported by other groups for higher frequency [2] or using bulk piezoelectric materials [3]. Our choice has been to use a piezoelectric thin film deposited on silicon substrate allowing thinking about mass production.

SYSTEM AND MATERIALS

Having the principal features in mind (<10m.s^{-2}, 100-200Hz, at least 10µW) and considering our background on piezoelectric thin films, we focused on simple cantilevers clamped on one end and free to vibrate at the other (Figure 1). Since source vibrations are very low frequency, microsystems are not well suited, so we focus on macro devices because their length permits to decrease resonance frequencies, or eigen frequencies, to efficiently harvest these low frequency vibrations.
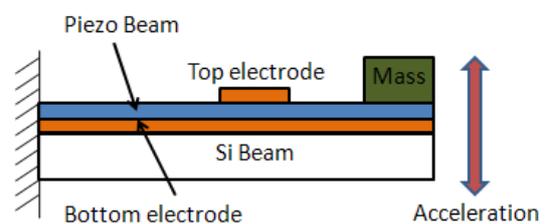

Fig.1: Scheme of a simple piezoelectric cantilever.

Figure 1 describes the device studied. The cantilever has a length L, a width w, a thickness t of silicon, while the thin piezoelectric film has a thickness $t_{piezo.}$ S is the area of the top electrode.

The operation principle of this device is to use the piezoelectric effect to create charges when stress is applied on it. By putting the cantilever inside a vibrating environment the cantilever tends to vibrate and support a stress which is converted into electrical power. This effect is mathematically described by the

effective piezoelectric transverse coefficient, e_{31}, which permits to evaluate output electrical behavior of the cantilever under this type of stress.

So the first part of our work was to be able to obtain a cantilever with a resonant frequency between 100 and 200Hz. In order to reach this value, a simple calculation of the resonance frequency can give us the influence of geometry and material parameters. Mechanical theory states that the first eigen frequency of a simple cantilever is given by [4]:

$$f_r = \frac{1}{2\pi}\sqrt{\frac{k}{m}} \propto \frac{Et}{\rho L^2} \qquad (1)$$

This equation reveals the influence of geometric parameters. For instance, w has no influence on frequency while the predominant factor is the free length of the beam. E is Young's modulus and ρ is the mass density.

With a cantilever of a few cm, the resonance frequency is too high, but we have several possibilities to reduce it, given from equation 1:
- Increase the vibrating length
- Reduce the silicon thickness
- Increase the total mass by adding an additional mass at the end of the beam

Addition of mass has two advantages, reduction of f_r and increase of the total stress in the cantilever, permitting to generate more electrical charges and thus a better electrical output power.

Once the mechanical behavior of the cantilever studied, the second part of this work is to obtain a piezoelectric material with the best piezoelectric transverse coefficient e_{31} to convert vibrations into electrical power. We have developed an experimental protocol to extract and evaluate this coefficient for different types of piezoelectric materials.

This protocol consists in applying an initial deflection on a clamped beam made of piezoelectric material and to release while monitoring the generated voltage (figures 2 and 3) [5].
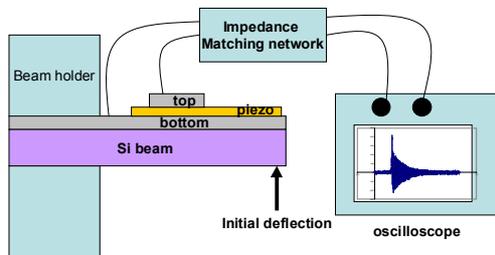
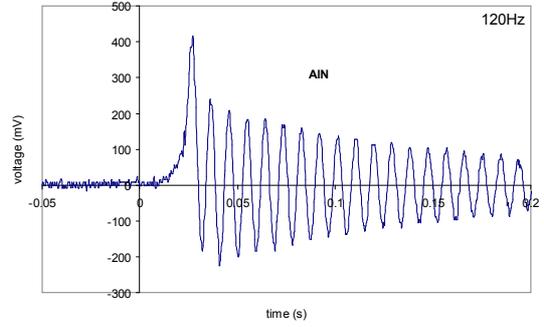Fig. 2: Dedicated setup to measure voltages extracted from piezoelectric cantilevers.

Fig. 3: Voltage measured on a 100nm-thick AlN based cantilever after release (initial deflection = 300µm)

Figure 2 shows the experimental set up to extract the e_{31} coefficient of the thin piezoelectric layer. Figure 3 shows an example of voltage response after release. This last corresponds to a 100nm-thick AlN film deposited by sputtering at LETI.

By integrating the signal and using the geometry of the device we are able to extract the desired coefficient. This experiment has three benefits in our study: it permits to determine the e_{31} coefficient but also the eigen frequency of the beam and the mechanical damping factor.

With this set up, experiments have been made on several types of piezoelectric materials; results lead us to choose two privileged material: AlN and PZT with e_{31} coefficients of respectively 0.8 C/m² for AlN and about 10C/m² for PZT, which is very close to the state-of-the-art. The PZT is obtained by the Sol Gel method, whereas. AlN is deposed by reactive pulsed-DC magnetron sputtering. Details concerning deposition of these films are given elsewhere [6, 7]

So now we know which materials we are going to use, the technology to obtain thin piezoelectric films and how to design our device. We will see in the second section that we developed, thanks to the previous e_{31} coefficient extraction model, an analytical model of our piezoelectric cantilever.

THEORETICAL MODEL

Based on the theory of piezoelectricity and on the set up to extract the e_{31} coefficient, we have also developed an analytical model to predict the behavior of a piezoelectric macro cantilever. The principle of this model is shown in figure 4.
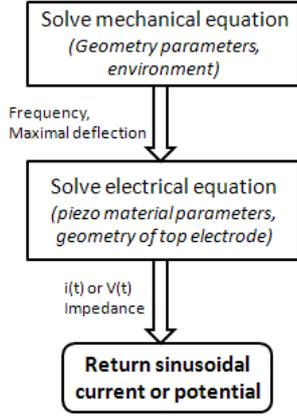
Fig. 4: Scheme of the theoretical model of prediction of the behavior of macro piezo cantilever.

This scheme is separated in 2 components; the first step is to solve the mechanical equations of oscillation by using geometric and material parameters with the use of the equations of motion [4]:

$$m\ddot{x} + b\dot{x} + kx = m\ddot{y} \qquad (2)$$

This first step of resolution is well know and provides the first eigen frequency of the beam and its maximal deflection. These results are obtained with the use of L, the density, the thickness of the material, and the additional mass. Once this first equation solved, its solutions are injected in the electrical model which is derived from the analytical model used for e_{31} extraction [8]:

$$V = A.R.def_{init}\left(\frac{\omega}{\sqrt{1+R^2C^2\omega}}\sin(\omega t) + \frac{RC\omega^2}{1+R^2C^2\omega^2}e^{\frac{-t}{RC}}\right) \qquad (3)$$

$$A = \frac{3.e_{31}.t(L-l_{electrode})*surface_{electrode}}{2L^3}$$

This equation uses the geometry of the top electrode: its surface and its distance to the clamped end of the cantilever but also the frequency and deformation of the beam and the coefficient e_{31} as well as C and R given in the equivalent electrical circuit of the cantilever (figure 5).
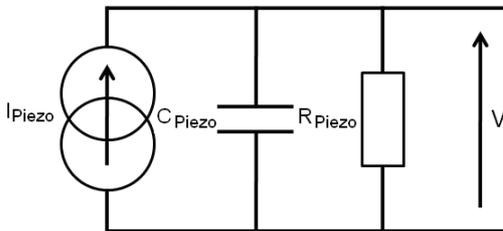

Fig. 5: Electrical equivalent circuit of the macro cantilever beam in vibration.

Thanks to this model we are able to estimate the electrical behavior of the macro cantilever and predict the behavior of our system at the eigen frequency of the beam.

EXPERIMENTS

For harvesting experiment, we focus on AlN thin films.

The model predicts that at the eigen frequency of the beam, calculated at 150Hz, vibration amplitude should reach 1mm under an acceleration of 0.3g.

The parameters used in the model are an acceleration of 0.3g@150Hz and a quality factor of 71. The value of this last will be discussed hereafter. Experiments were realized with the use of our set up and releasing the cantilever with a deflection of 1mm as reported below (figure 6 and 7).

Fig. 6: Experimental set up used to harvest the potential of our prototype.
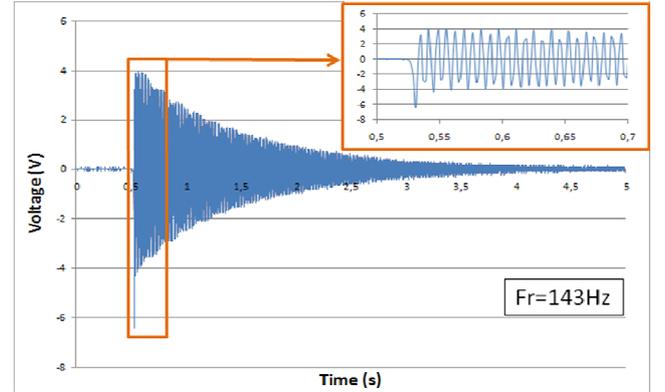

Fig. 7: Voltage measured on our AlN based cantilever after a release of 1mm.

Figure 8 shows the voltage response of our prototype. The comparison between model and results shows an error less than 5%. By fitting the model parameters to the results we extract a damping factor of 0.007 inducing a mechanical quality factor Q reaching 71 (eq. 4).

$$Q = \frac{1}{2b} \qquad (4)$$

By using these data, the output power expected here is 18µW by taking into account the input impedance of 1MΩ of the oscilloscope. This is very promising for the next step of our study which is to test this prototype under low vibrating environment.

CONCLUSION

In this paper, we presented piezoelectric vibrating macro cantilevers based on AlN thin films deposited on Silicon. Once released, these devices resonate at 143Hz and exhibit a voltage reaching 6V for a 1MOhm-load and an initial deflection of 1mm. This last associated with a quality factor reaching 71 as observed from experiment corresponds to a rather weak acceleration (0.3g). Therefore, it lets expect a harvested energy as high as 18μW which is the right order of magnitude required for basic applications as autonomous sensors.

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