

High temperature performance of a piezoelectric micro cantilever for vibration energy harvesting

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Abstract. Energy harvesters withstanding high temperatures could provide potentially unlimited energy to sensor nodes placed in harsh environments, where manual maintenance is difficult and costly. Experimental results on a classical microcantilever show a 67% drop of the maximum power when the temperature is increased up to 160 °C. This decrease is investigated using a lumped-parameters model which takes into account variations in material parameters with temperature, damping increase and thermal stresses induced by mismatched thermal coefficients in a composite cantilever. The model allows a description of the maximum power evolution as a function of temperature and input acceleration. Simulation results further show that an increase in damping and the apparition of thermal stresses are contributing to the power drop at 59% and 13% respectively.

1. Introduction

Energy harvesting has become over the recent years the main focus to supply low-power miniaturized sensor nodes from on-site available energy. For industrial machine surveillance, smart infrastructure or aerospace and automotive structures monitoring, the applications of sensor networks often involve harsh environment conditions, such as high g accelerations or high temperatures, that the energy harvester has to withstand as well. Understanding and predicting the effects of high temperatures on a harvester structure could help designing more robust devices and anticipate potential negative effects on the harvested power. In that objective, this work focuses on experimentally studying the effects of temperatures up to 160 °C on the power harvested by a classical MEMS energy harvester, and in a second part proposes a model to explain the harvester behavior.

2. Experimental study

2.1. Structure of the MEMS harvester

A classical cantilever type energy harvester described in a previous publication [1] is studied. A beam is clamped at one end and a proof mass is suspended at the other end to adjust the resonance frequency of the device. The harvester is fabricated using a MEMS process which involves a 400 μm thick silicon substrate used as a proof mass, with a 10 μm doped silicon device layer on which a 0.5 μm aluminum nitride (AlN) piezoelectric layer is patterned, and finally a 1 μm aluminum layer is used as a top electrode (Figure 1). Figure 2 shows a picture of the die composed of 4 such cantilevers. While most piezoelectric thin films lose piezoelectric properties when heated up, AlN has been shown to be stable at high temperatures [2]. However, when it is integrated as a thin-film piezoelectric layer on a resonating silicon micro-

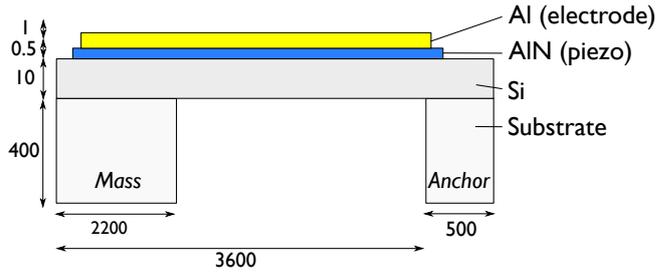


Figure 1. Schematics of the cantilever, dimensions in μm .

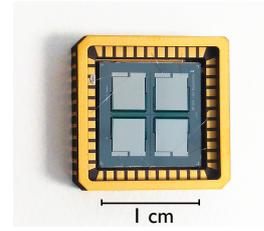


Figure 2. Picture of the die.

cantilever, other mechanical or electrical effects induced by temperature can affect the harvested power, which are investigated in this study.

2.2. Experimental setup

The die is glued to a ring, itself placed inside a socket (shown in Figure 2). The chip is soldered to a PCB and fixed onto an electromagnetic shaker driven by a function generator and amplifier. The experimental setup is described in Figure 3. The shaker is placed inside a vacuum chamber regulated at 0.33 mbar. Heaters pads are used to heat up the device and a thermocouple provides feedback on the temperature close to the harvester. Three frequency sweeps are performed at each temperature and fixed input acceleration: with the device in open circuit, in short circuit and on a matched $300\text{ k}\Omega$ resistive load. At each step the RMS voltages are recorded.

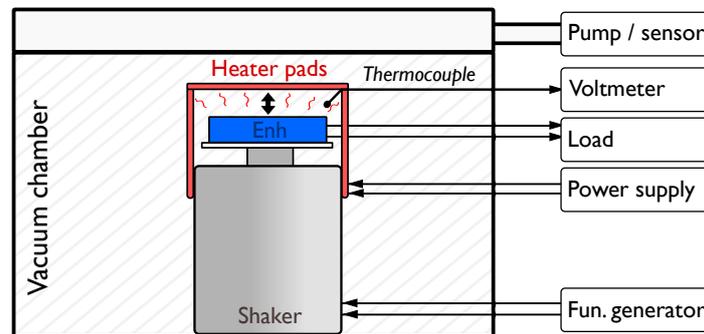


Figure 3. Schematic diagram of the experimental setup.

2.3. Power as a function of temperature

The frequency sweeps allow for the calculation of the coupling coefficient, the resonance frequency, the mechanical quality factor and the maximum power as a function of the input temperature. The results at low acceleration are plotted in Figures 4 and 5. The harvested power is linearly decreasing from $9.6\ \mu\text{W}$ to $3.2\ \mu\text{W}$, showing a decrease of around 67%. The resonance frequency is decreasing from 217.7 Hz to 216.1 Hz, corresponding to a 0.7% drop and the mechanical quality factor is going from 726 to around 475 over the tested range, or a 35% decrease. Other parameters, like the coupling coefficient or the optimal load show very small variations over the tested range. For various acceleration levels the resonance frequency and quality factor show the same rate of decrease, whereas the power slope gets steeper for higher accelerations.

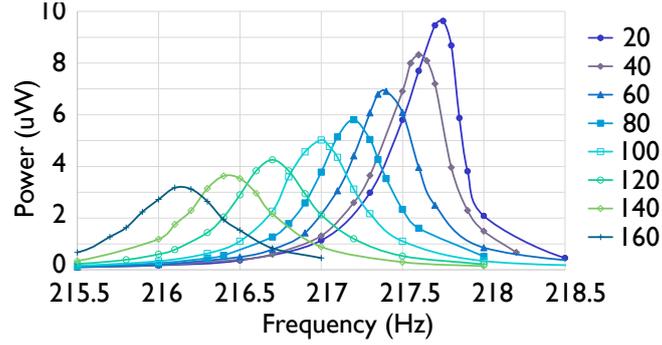


Figure 4. Experimental power as a function of input frequency, for several temperatures.

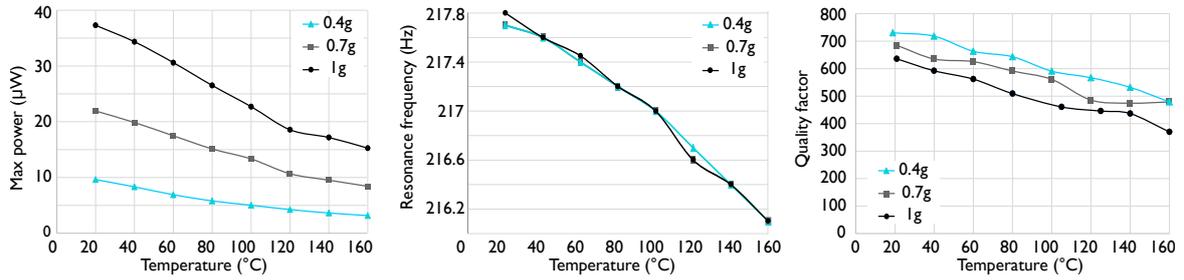


Figure 5. Experimental maximum power, resonance frequency and quality factor as a function of input temperature.

3. Modeling of a micro cantilever energy harvester with temperature

3.1. Thermal-dependent parameters

Experiments show that the resonance frequency and the mechanical quality factor have both a linear and significant decrease versus temperature. The resonance frequency is defined as the square root of the beam stiffness over the equivalent mass, and those two parameters can in turn be defined as a function of the material parameters and cantilever dimensions. The decrease of the silicon Young modulus as a function of temperature has been experimentally measured by several studies reporting temperature coefficients at around: $\frac{1}{E} \frac{dE}{dT} = -80e^{-6} \text{ } ^\circ\text{C}^{-1}$ [3, 4]. Another phenomenon contributing to the change in stiffness and mass values, is the thermal expansion of the materials, described by their linear thermal expansion coefficient. The expansion notably leads to a slightly larger mass at higher temperature. Both those phenomenon are contributing to the decrease in resonance frequency.

The mechanical quality factor is primarily limited by air damping, thermoelastic dissipation and support loss. All those terms are linked to the temperature, therefore inducing that the mechanical quality factor is a strong function of temperature [5]. A further article will be dedicated to calculating those parameters from the geometric and material parameters and include them into the model. For the present study, the experimental values of the quality factor drop are used and input into the model.

3.2. Thermal stress

Each material composing the cantilever has a different thermal coefficient. When subjected to increasing temperature, the mismatched dilatations induce stresses on the surfaces. The Finite elements software Comsol is used to simulate those thermal stresses. The cantilever is simulated in 2D, with coupled thermal and mechanical study. Figure 6 shows the resulting stress distribution when the cantilever is submitted to 150 °C. The thermal expansion

coefficient of the metal layer being the largest, followed by the AlN one and finally the silicon one which is the smallest, an increase in temperature induces a downward curling of the cantilever and large stresses at the border between the layers. The average stress σ induced in the piezoelectric layer is evaluated for several input temperatures; its variation is shown in the graphic in the right in Figure 6.

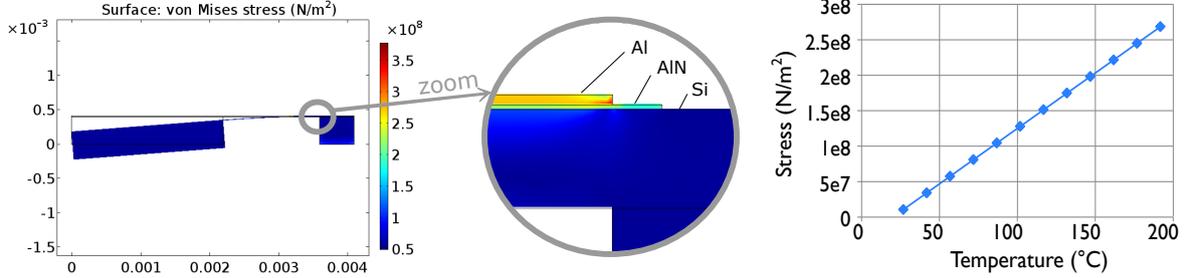


Figure 6. Comsol simulation of the thermal stresses when the cantilever is subjected to 150 °C, and average stress as a function of the temperature.

3.3. Model taking into account temperature

Around its resonance frequency and at small acceleration, the cantilever can be modeled as an equivalent mass-spring-damper system, and its behavior is described by two coupled mechanical and electrical equations involving the mechanical quality factor Q_m , the coupling coefficient k_m^2 , and the load coefficient ξ_c . The details of the normalization and parameters definitions can be found in [6].

The young modulus variation with temperature and the materials dilatation are included in the model, as well as the damping variation experimentally measured.

The thermal stresses are added to the model by means of a global force $\sigma^*(T) = \sigma(T)A$, where A is the active piezoelectric area, and $\sigma(T)$, is the stress defined by the Comsol simulation shown in Figure 6. The term is normalized by the mass $m(T)$ and the natural frequency of cantilever $\omega_0^2(T)$, both dependent on the temperature through material parameters.

The model can finally be written as the coupled equations (1) and (2), with y the input vibration displacement, u the cantilever tip displacement and \underline{v} the normalised generated voltage.

$$y'' + \frac{\sigma^*(T)}{m(T)\omega_0^2(T)} = u'' + u'/Q_m(T) + u + k_m(T)^2 \underline{v} \quad (1)$$

$$u' = \underline{v}' + 2\xi_c \underline{v} \quad (2)$$

Those two equations are translated into complex variables and solved by first extracting the displacement amplitude u_M to then calculate the power, function of u_M^2 [6]. The resolution is the same as the classical model except for the added term $\frac{\sigma^*(T)}{m(T)\omega_0^2(T)}$ to the displacement expression.

The final calculated power expression is a function of the temperature, the input vibration characteristics like the acceleration and frequency, and the load resistance.

When separately studying the power evolution as a function of the frequency, the quality factor diminution or the thermal stress, the model shows that the quality factor contributes the most to the power drop. The damping alone contributes to a power decrease of 49%, compared to the almost 67% experimentally measured. This result can also be seen as:

the degradation of damping when increasing the temperature accounts for 59% of the power drop. The thermal stresses contributes to 13% of that same decrease. All in all, the damping and thermal stresses explain 72% of the power drop.

Those results are shown in Figure 7 for 3 different input accelerations. The normalized power drop experimental and theoretical is plotted over the range of temperature. The dotted line corresponds to the model taking into account the damping drop only, in which case the normalized power does not depend on the acceleration. The other theoretical curves show the result for the global model, taking into account thermal stresses. In that case, the power slope depends on the input acceleration, and its evolution matches well the experimental results, which confirms the importance of both the thermally induced stresses and the increase in damping as the two main causes behind the power drop at elevated temperatures up to 160 °C. The remaining unexplained difference between the experimental and theoretical power drop is going to be investigated in further work.

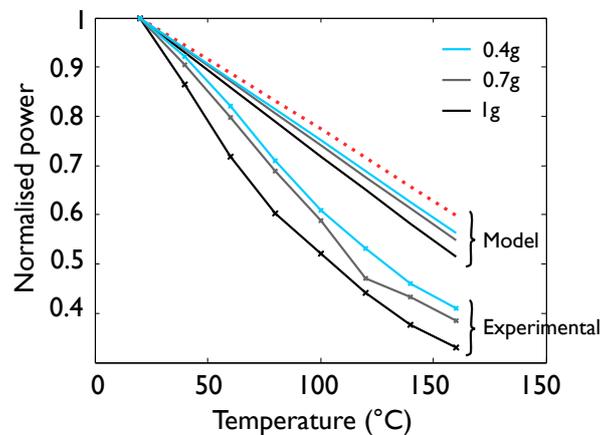


Figure 7. Normalized power as a function of temperature, modeled and experimental data for three different input acceleration.

4. Conclusion

This study experimentally and theoretically studies the evolution of the harvested power of a classical MEMS cantilever under vacuum, as a function of the ambient temperature. When the working temperature is increased to 160 °C, a power drop of almost 70% is experimentally measured. Simulations with a classical lumped parameters model confirm that the quality factor causes the biggest decrease in power, accounting for 59% of this decrease. Thermal stresses appearing in the composite cantilever are the second largest cause for power drop. Those stresses could be further reduced by optimizing the electrode shape, which has the largest thermal expansion coefficient among the cantilever materials. Future work aims at completely understanding and modeling the effect behind the quality factor drop in order to anticipate and reduce its effect on the power decrease at elevated temperatures.

References

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