Design, modelling and optimisation of integrated piezoelectric micro power generators

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ABSTRACT

This paper presents a mechanical vibration energy scavenging solution for micro power generation. The transduction is performed using a novel resonant cantilever beam SOI structure with a piezoelectric Aluminium Nitride layer. FEA simulation and optimization of such a device is detailed. The simulation results will be compared with experimental data obtained using devices fabricated using a special MEMS process.

Keywords: ambient energy harvesting, piezoelectric MEMS, micro power generation

1 INTRODUCTION

During recent years, a growing interest in the field of wireless sensor nodes could be seen. These are devices that contain numerous sensors for environmental data collection and a wireless communication device that allows data exchange with a base station. It is planned that they will be used to monitor crucial values over large or inaccessible areas. Possible fields of application range from sensors embedded into buildings or machinery, to human implants. There are two major features that decide about the utility of such a device: the first is the capability of collecting data in hard to reach places and sending them wirelessly to a base station, the second is the device autonomy. Until now, power was supplied to these devices by means of an electrochemical battery. However, there are numerous disadvantages of such solution. Firstly, the size of the entire device is dominated by the energy source [1] and furthermore its autonomy is limited by the battery capacity.

Recently, thanks to the development of very low power consumption electronics, it has become possible to run wireless sensor nodes using ambient energy. There are two main advantages of using the ambient energy – firstly, the working time of a node is limited only by the intrinsic lifetime of its components and by the presence of ambient energy source and secondly, the size and weight of the device can be significantly decreased. Several approaches have been presented for scavenging of environmental energy. It was the solar and thermal (temperature difference) energy that received most attention and this field is now well explored. This work focuses on another possibility – harvesting of mechanical ambient energy, most precisely energy of mechanical vibrations. Previous studies [2][3] indicate that mechanical vibrations are a very promising source of ambient energy, with estimated densities of 300μW/cm^3 versus 10μW/cm^3 for interior light and 40μW/cm^3 for a temperature difference [2].

2 VIBRATION ENERGY SCAVENGING

2.1 The method

There are three main methods of converting energy of mechanical vibrations into electrical energy:

- → Capacitive method [4]
- → Electromagnetic method [5]
- → Piezoelectric method [2][6]

The problem with capacitive method is that an external power supply is needed and that very high voltages must be processed [4]. The electromagnetic method, widely used in macroscale, suffers from relatively high complexity of fabrication (integrated coils and magnets) and from low output voltages that are obtained. This work presents exploration of the third method that consists of using the piezoelectric effect. Piezoelectricity, it is a capability of certain materials to develop electrical charges as a reaction to mechanical stress excreted on them. This method of energy harvesting was widely examined [2][6] but creation of micro power generators in MEMS technology has not yet been well explored. Recent developments in MEMS technology permit fabrication of micro machines with high quality piezoelectric layers, like Aluminium Nitride and Plomb Zirconate Titanate (PZT).

Energy density that can be obtained from a piezoelectric material can be calculated from equation 1 [2], where σ is the yield stress, k is the coupling coefficient and c is the elastic constant.

$$\frac{\sigma^2 k^2}{4c} \qquad (1)$$

For a PZT 5-H material the maximum energy density of 35.4mJ/cm^3 can be obtained. This value depends on the proprieties of the material used and on the maximal strain that it can withstand.

2.2 Design of the power harvester

The size of the energy harvesting device must be limited, in order to be useful in demanding applications, like human implants. On the other hand, several studies [2] have shown that the spectrum of environmental vibrations reaches its maximum for low frequencies, below 1kHz. The design of the micro power generator must then take into account these two constraints, in order to create a system with low resonance frequency that fits into a small volume.

The proposed device is a harmonic resonator composed of a mass suspended at the end of a cantilever beam. It occupies less than $2mm^3$ and resonates at 300Hz. The flexure movement of the beam induces tensile and compressive stress to the active piezoelectric layer. The beam is composed, as shown in the Figure 1, of Aluminium Nitride and Aluminium deposited on a SOI wafer and patterned with DRIE on both sides.

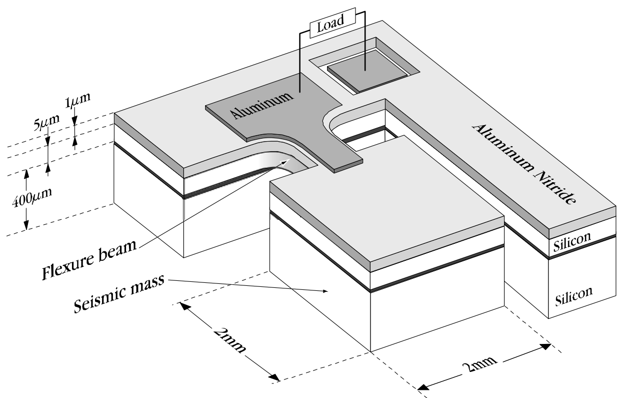

Figure 1: Cantilever beam composition.

3 SIMULATION

In order to validate the concept of a piezoelectric power harvester, simulation in the ANSYS FEA environment was performed. Evaluation of power that can be obtained from this kind of device, was made my means of harmonic simulations for different acceleration excitations with a matched resistive load connected between the electrodes. Figure 2 shows simulated power dissipated on the load versus sinusoidal acceleration amplitude at the first resonance frequency.

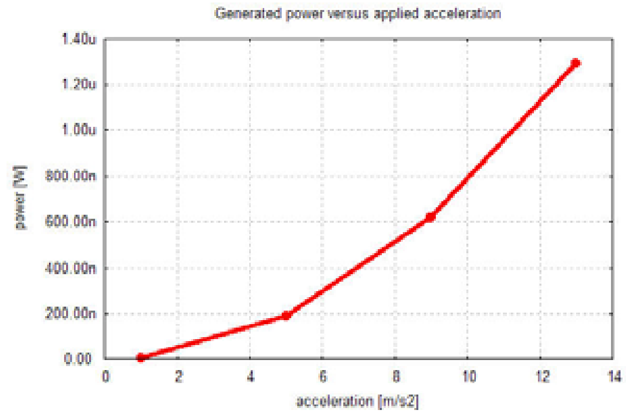

Figure 2: Power dissipated on the resistive load versus acceleration amplitude.

3.1 Design optimization

The standard cantilever beam structure is composed of a rectangular supporting beam and a seismic mass attached at its end. The common problem of such a configuration is the fact that induced stress is concentrated at the clamping and therefore limiting the device performance. In order to equally distribute stress along the beam during vibration, an optimization study was performed. Structures with different angles of curvatures at the clamping and at the mass (Figure 3) were simulated and later fabricated in order to confirm taken assumptions.

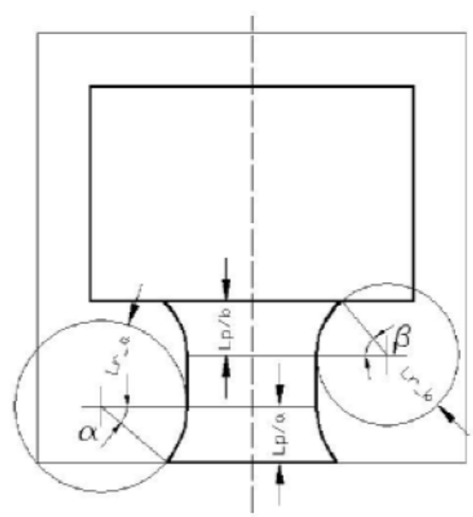

Figure 3: Cantilever beam shape variation using alpha and beta angles.

Figure 4 shows stress distribution along the beam for different angles of the curvature at the clamping (alpha angle from the Figure 3). It can be seen that for a straight beam (alpha=1) stress is concentrated at the clamping, while for rising alpha angle (curvature) stress distribution is becoming uniform. Figure 5 shows normalized maximum stress variation along the beam and normalized power for different angles at the clamping. It can be seen that simply by adding a curvature, the maximum stress can be decreased by 50% while lost in harvested power is only 20%. The lost in the harvested power is due to rise of the capacity value and therefore decrease of voltage.

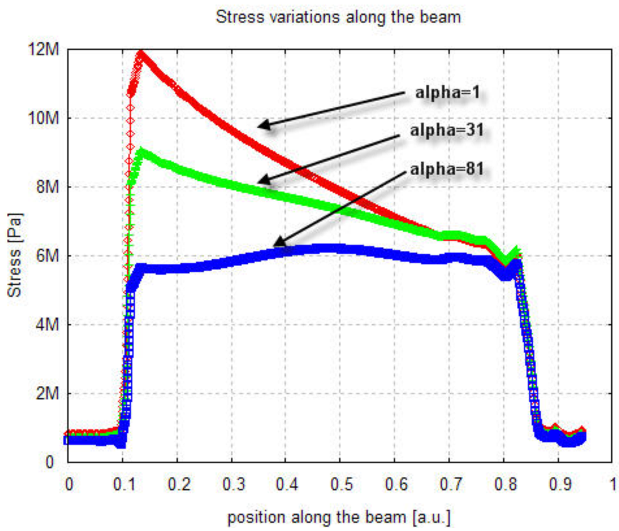

Figure 4 Stress distribution along the beam for different angles.

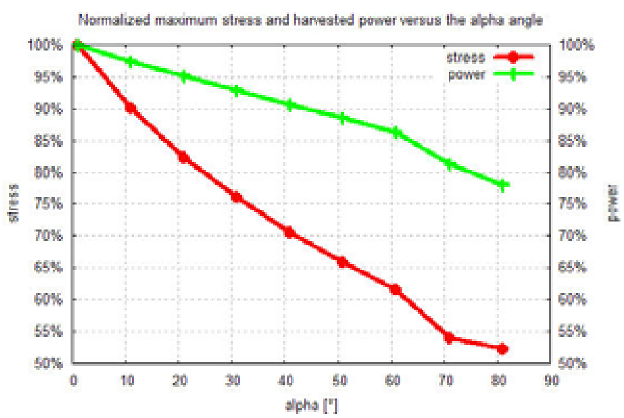

Figure 5: Normalized maximum stress and energy versus angle value at the clamping.

4 FABRICATION

The devices that were simulated and optimized using finite element method were fabricated using a specific MEMS AlN process, developed at ESIEE in Paris in cooperation with MEMSCAP. SOI wafers were utilized to fabricate the devices and heavily doped top silicon layer was used as a bottom electrode for the piezoelectric layer. The process flow, presented in the Figure 7, consists of: 1) deposition of 1µm of Aluminium Nitride 2) wet etching of the piezoelectric layer 3) deposition of 0.5µm of Aluminium 4) wet etching of the aluminium layer – definition of the top electrode 5) DRIE etching of the top silicon layer – definition of the bottom electrode 6) back side DRIE etching of bulk silicon 7) release of structures by wet etching of buried oxide. Devices fabricated using this technique are shown in Figure 6.

Problems with fabrication have caused a significant delay in the characterization process, which is now in progress.

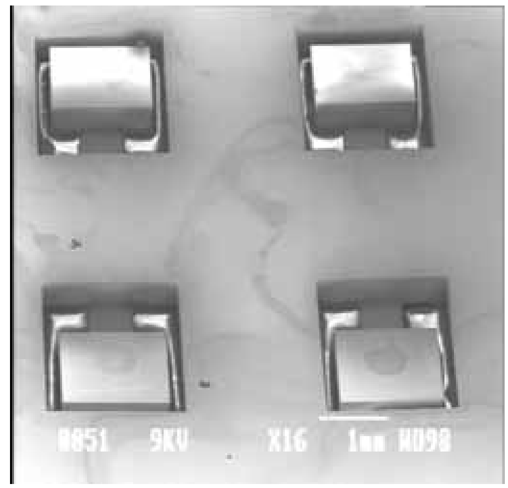

Figure 6: Cantilever beams fabricated using the MEMSCAP AlN process.

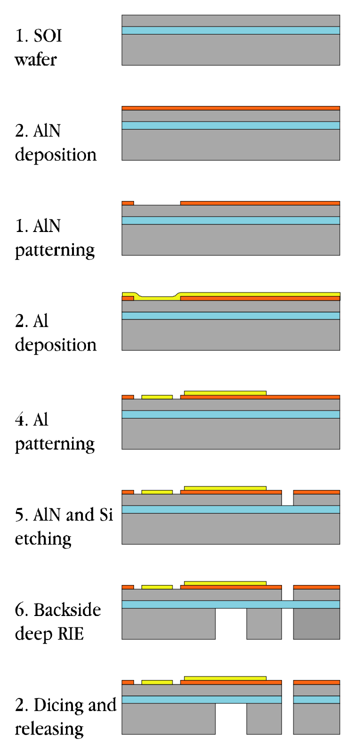

Figure 7: Piezoelectric MEMS fabrication process flow.

5 CONCLUSIONS

This paper presents design, simulation and optimization of integrated piezoelectric micropower generators. The simulations show that one device that occupies less than $2mm^3$ can harvest about 0.8μW from sinusoidal acceleration of $10m/s^2$ at its resonance frequency of 300Hz. By using matrices of such devices, the obtained energy can be sufficient to power up a wireless sensor node. Furthermore, a new idea of using circular shapes for improving reliability of such devices was presented and verified.

6 FUTURE WORK

The fabricated devices will be tested and obtainable power will be measured both with passive resistive load as with adaptive DC/DC converter [3]. It is also planned to implement similar structures using PZT layers that exhibit much higher electro mechanic coupling and therefore can provide more energy.

7 ACKNOWLEDGEMENTS

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