COMPARISON OF DIFFERENT BEAM SHAPES FOR PIEZOELECTRIC VIBRATION ENERGY HARVESTING

Maxime Defosseux1*, Marjolaine Allain1, Skandar Basrour1
1TIMA, UJF-CNRS-Grenoble INP, Grenoble, France
*Presenting Author: maxime.defosseux@imag.fr

Abstract: This paper reports the comparison of different beam shapes of piezoelectric vibration energy harvesters in regards to their stress level and power harvestable. We proved that trapezoidal and circular shapes allow to reduce the stress level in the material for a low decrease of the power harvested at a given resonance frequency, which increases the reliability of the device. The reliability of the piezoelectric harvesters and in particular their tolerance to high accelerations are an important problematic. We are also developing a process to fabricate home made MEMS piezoelectric harvesters, and the first devices have been fabricated.

Keywords: energy harvesting, piezoelectric, reliability

INTRODUCTION
There is nowadays a huge interest for wireless sensor networks in industrial or natural environment. It is now possible to create small nodes for these networks with the development of MEMS sensors, low power electronics and RF communications systems. These nodes can be spread in an environment, which will allow having a high density of information.

However, powering these nodes is still a challenge. The power source needs to be nomad. Usually, each network’s node is powered by a battery. After use, a battery needs to be charged or changed. As a consequence, maintenance is needed, and can be difficult and costly depending on the environment. A way to improve these networks is to replace batteries at each network’s nodes by ambient energy harvesters, to have energy sources without maintenance. The use of energy harvesters is getting possible by the development of low power electronics and RF communication, with which the energy needed by node is much less important. Piezoelectric vibration energy harvesters are a promising solution to this problem ([1], [2]), and this is the solution we will use in our studies.

If ambient vibration energy harvesters are used, then the lifetime of each node will depend of the lifetime of the energy harvester, and so of its reliability. A harvester is designed for a specific resonance frequency and a specific acceleration of vibrations, depending on the application, to optimize the power harvested. However, during a real use, the amplitude of vibration can change. If the amplitude becomes too important, the device can break, and a node of the network will be lost. As a consequence, an important issue of these scavengers is reliability, and in particular their tolerance to high acceleration input. The tolerance of the device to high acceleration can be improved by reducing the maximum stress level in the device. We will propose a solution to this problematic based on a specific geometric design of the piezoelectric harvester.

Another problematic for wireless sensor network is the miniaturization. It is very interesting to have very small nodes, as they would not interfere with the environment for sensing. Moreover, if they are very small, it would allow to have a high density of nodes, and so a high density of information. The ideal would be to have a system on a chip with the sensors, the energy harvesters, the RF communication system, a microcontroller and the electronic of conditioning. A process to fabricate micro piezoelectric energy harvester will be presented, as the first fabrication results.

CONCEPT
Usually, the piezoelectric energy scavenger structure is a clamped free beam, with a piezoelectric thin layer deposited on top, and a seismic mass at the end of the beam to reduce the resonance frequency. The beam is rectangular, as we can see on Fig. 1.

![Fig. 1: Usual structure of a piezoelectric vibration energy harvester with a rectangular beam with a piezoelectric layer, and a seismic mass.](image-url)
It is interesting to reduce the maximum of stress in the device, so that the device tolerates higher accelerations. To reduce this maximum, we have to widen the beam at the clamping, to spread spatially the maximum of stress. However, as it was mentioned before, a piezoelectric harvester is designed for a specific resonance frequency. Widening the beam at the clamping increases the resonance frequency. As a consequence, to keep the same resonance frequency we have to thin down the beam far from the clamping.

Two structures have been proposed to reduce the maximum of stress: trapezoid shaped-beam [3] and circularly filleted beam [4] (Fig. 3), but their efficiencies were not compared. In this paper, we will compare the stress reduction and the power harvested of both kinds of beams.

SIMULATIONS

We have done some finite elements simulations to compare the behaviours of the beams. For a rectangular beam, the stress is concentrated close to the clamping. For trapezoid-shaped or circularly filleted beams, the stress is spread spatially, as we can see on Fig. 4. We can see that the maximum of stress is located much further of the clamping for a circularly filleted beam than for a rectangular beam. The maximum of stress has also decreased, due to this better spreading. As a consequence, trapezoid-shaped and circularly filleted beams can support higher acceleration than rectangular beams, as the maximum of stress is further from the failure stress at a given acceleration.

Fig. 2: Stress level in a rectangular beam depending on position (0 is the clamping).

Fig. 3: Top view of: (a) Rectangular-shaped beam, (b) circularly filleted beam and (c) trapezoid-shaped beam. $L_c$ is the non-rectangular length.

Fig. 4: Stress distribution in a rectangular-shaped beam (top) and in a circularly filleted beam (down).

Now that we knew that trapezoid-shaped and circularly filleted beams have better tolerance to high accelerations than rectangular beams, we have decided to compared the performance of both beams, for a given resonance frequency of 200Hz and a fixed acceleration of 0.25g, with given beam length and mass dimensions. For each simulation we changed the non-rectangular length to beam length ratio ($L_c/L_b$), but
we kept the same resonance frequency by changing the beam width. On Fig. 5, we compared the power harvested and the maximum stress level for both kinds of beam. We can see that the stress reduction is very important compared to the power reduction for both beams. Trapezoid-shaped beams showed the best stress reduction with 61% of reduction, but with 18% of power reduction, as circularly filleted beams showed 59% of stress reduction for 7% of power reduction. Therefore, both structures are promising structures for stress reduction and improvement of reliability.

For the same input acceleration, we will get less power harvested for a circularly filleted beam or for a trapezoidal shaped beam than for a rectangular beam, because of the stress reduction. However, as there is a stress reduction, these beams can tolerate higher accelerations than the rectangular ones. And as the stress reduction is much more important than the power reduction, these structures have a much more important maximal power harvestable (the maximal power harvestable is obtained with the maximal input acceleration that the structure can bear without breaking).

**FABRICATION**

Home-made MEMS devices have been fabricated, with a thin piezoelectric layer of aluminium nitride (AIN). Usually, the piezoelectric material used for energy harvesters is PZT (Lead zirconate titanate) as it has the best piezoelectric properties. However, its deposit process is not CMOS compatible, so PZT piezoelectric harvesters can not be integrated with electronics, which is a further goal for energy harvesters, to have a sensor network’s node as a system on chip. We chose to use AIN, which deposit process is CMOS compatible.

The process of fabrication (Fig. 6) has been developed specifically for piezoelectric vibration energy harvesters. This process requires 5 different masks. The process starts with a wafer of SOI (Silicon On Insulator). A piezoelectric stack is then deposited, with molybdenum as a lower electrode, a layer of AIN as the piezoelectric layer and platinum as top electrode. The top electrode is patterned by IBE (Ion Beam Etching). A chemical etching had to be used to etch AIN as the thickness is too important to etch it by IBE. We now have to pattern the lower electrode, which is done in step 5. We then need to have patches of gold on the lower electrode to have easier contacts for electrical characterisation. These patches were patterned by lift off (step 6). All these steps have been done on the front face of the wafer.

We will now pattern the back face of the wafer. We will start by defining a hard mask of aluminium for the deep etching of silicon. Then the critical step (step 9) is the deep etching of silicon, on 500µm. This has been done with Deep Reactive Ion Etching (DRIE). The seismic mass of the device is patterned by the deep etching.

We can now pattern the beam, with an etching of silicon on the front face (step 11). We then only have
to liberate the structure by etching the oxide, and we have our devices liberated.

Different devices are being fabricated, including rectangular, trapezoidal and circularly filleted clamped-free beams. There are several goals for this fabrication: first of all, testing our process and the piezoelectric material used. Then we want to fabricate some new devices as trapezoidal and circularly filleted beams and test their behaviours.

The first run of fabrication is finished, and we get our first devices. We can see on Fig. 7 an SEM (Scanning Electron Microscope) image of a device: this is the first MEMS fabricated with our process. This device is a piezoelectric energy harvester with a circularly filleted beam. However, we can’t characterize our device with vibrations as we are still working on the dicing and the packaging of our harvesters, which are complex as the structure are fragile.

![First MEMS fabricated by our process.](image)

**CONCLUSION**

We showed in this paper the importance of the tolerance to high accelerations for piezoelectric harvesters. Two designs that increase that tolerance have been proposed: trapezoidal shaped beam and circularly filleted beam. We simulated both systems in order to compare them, and we proved 60% of reduction of maximum of stress for a low decrease of the power harvested. Both designs seem to be interesting to reduce the maximum of stress.

Then, we proposed a fabrication process for piezoelectric energy harvesters. We presented the first devices we fabricated and are waiting for the first characterization results.

**ACKNOWLEDGEMENTS**

This work is partially funded by the French National Research Agency (ANR) through the project SESAM (contract JC05-54551). We would also like to thank Paul Ivaldi and Emmanuel Defay from CEA-LETI for their essential help on this project.

**REFERENCES**


