A MEMS Piezoelectric Vibration Energy Harvesting Device

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Abstract
This paper presents the design and fabrication of a piezoelectric micro power generator to be used as a power source for a wireless sensor node. The device scavenges environmental vibrations and converts it into electrical power through a piezoelectric transduction. The device, that measures 2x2x0.5mm is a resonant structure composed of a seismic mass attached to a cantilever. The device has been built with a MEMS process. The paper presents modelling and simulation of devices using either AlN or PZT piezoelectric layer. The measurements made on a first prototype using an AlN layer have shown a power output of 38nW for 0.5g of excitation at frequency of 204Hz.

Keywords: wireless sensor network, MEMS, piezoelectric, vibration energy scavenging, AlN.

1 Introduction
With the emergence of MEMS sensors, Ultra Low Power electronics and RF communication systems, it is now possible to create small sized microsystems that need ultra low amount of power, in the range of µW. These microsystems are designed to be spread in environments such as buildings, industrial equipment or even in a human body. With a specific telecommunication system, they create an ad-hoc network of sensing nodes. Typical size of these devices is in the range of 1 to 100 mm³. One of the main problems for these microsystems is the power source. For the moment, most of them use a non rechargeable battery, characterised by a finite amount of stored energy, an important volume and mass that dominates the entire system.

Harvesting of ambient energy is a possible solution to power these nodes. Energy can be scavenged from light (photovoltaic effect), temperature difference (thermoelectric effect), mechanical vibrations or kinetic motion. Previous studies [1] indicate that mechanical vibrations are a very promising source of ambient energy with estimated densities of 300µW/cm². Furthermore, the vibration energy can be easily extracted using an electromechanical transducer based on electromagnetic induction, capacitive transduction or piezoelectric effect.

In this paper we present a MEMS device dedicated to harvest vibrations imposed to its body by the environment. The generator is intended to be part of a microsystem to be used in a wireless sensor network[2]. The microsystem, in development in the laboratory is designed around an asynchronous ultra low power processor which runs dedicated software and manages several functions such as monitoring sensors, data storage and RF module driving. Around this processor, several devices take place as illustrated in Figure 1.

Figure 1: Schematic of the architecture of a wireless sensor node. COTS modules appear in dark grey.

We can also notice:
- A power module (or Energy Harvesting Circuit, EHC) to manage the incoming power coming from the generator and to dispatch the energy to the different modules.
- Energy storage units such as Li-ion micro batteries or super capacitors will store electrical power provided by the generator.
- A RF communication module is composed of a module that complies with actual standard like IEEE 802.15.4.
- MEMS sensors like accelerometers or gyroimeters.
- A Clock from the watch industry is used both for its low power consumption and low volume.

In this project, several modules will be Commercial Off the Shelf (COTS) devices. However the asynchronous processor, the energy harvesting circuit and the micro power generator (presented here) will be developed specifically.

## 2 Piezoelectric micro power generator

The micro power generator, as shown in Figure 1, is composed of a seismic mass made of silicon (1.57µg) connected to the substrate by a rounded shape cantilever. The cantilever is composed of monocristalline silicon (5µm) acting both as a mechanical support and bottom electrode, an aluminium nitride piezoelectric layer (1µm) and an aluminium upper electrode. The device fits into a 2mmx2mm square of a silicon on insulator (SOI) wafer.

The ambient vibrations induce movement of the mass, according to its mode shapes, and therefore deformation of the cantilever. The compression – elongation (first mode) of the piezoelectric layer creates electric charges that are collected by the electrodes (Silicon beam and Al layer) and transferred to the load. The latter must be tailored to maximise the power transfer.

![Figure 2: Schematic of the piezoelectric micro power generator.](image)

As the device is a resonant system, the incoming vibration spectrum must close to the resonance frequency of the device (~200Hz in our case).

## 3 Fabrication process

A specific MEMS process has been developed in cooperation with MEMSCAP-ESIEE in France. The process begins with deposition of the AlN layer on a SOI substrate, which is then patterned to define contacts with the Silicon substrate. Then Aluminium layer is deposited and patterned to define the bonding pads, electrical connections and the top electrode. After that the moving structure is defined using Deep Reactive Ion Etching from both the bottom and the front side. Finally the silicon oxide layer is removed by selective etching and the structure is released.

Figure 3 shows an exploded view of all the layers of the device, and table 1 summarizes the physical properties of Aluminium nitride thin film employed for this first prototype. A PZT piezoelectric layer will be used in a forthcoming prototype, its piezo properties are also listed in table 1. These material properties are used for the simulation of the device.

![Figure 3: Exploded view of the microfabrication process](image)

<table>
<thead>
<tr>
<th></th>
<th>AlN</th>
<th>PZT</th>
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<td>$\epsilon_{33}$ [C/m²]</td>
<td>1.55</td>
<td>13.91</td>
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<tr>
<td>$\epsilon_{31}$ [C/m²]</td>
<td>-0.58</td>
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<tr>
<td>$\rho$ [kg/m³]</td>
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<tr>
<td>$\varepsilon$ [F/m]</td>
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<td>1800</td>
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<tr>
<td>$E$ [GPa]</td>
<td>345</td>
<td>100</td>
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Modelling and simulation

In order to evaluate the output power from a vibrating system, a harmonic simulation with sinusoidal excitation with amplitude of 5ms\(^{-2}\) at the resonance frequency was performed. The ANSYS FEM software was used for this task. The simulated model is presented in the Figure 4. The model uses coupled field simulation of the piezoelectric effect. The beam is clamped at one end and the load is a matched resistor. Two piezoelectric materials have been taken into account, AlN and PZT in order to compare the resonance frequency and the output power. The dimensions of both devices were the same, only the piezoelectric layer material was changed.

The simulation results, (Figure 5) show a larger power output for the PZT device which has better piezoelectric coefficients than AlN as well as lower resonance frequency and optimum load resistor. On the other hand the capacity of the PZT device is much higher which complicates design of the electrical circuit of power transfer. Simulation results are listed in Table 2.

The PZT solution is clearly better. The first prototype device has been made using AlN but the piezoelectric layer will be made of PZT in the second prototype.

Mechanical and electrical characterization

For characterizing the generator, the device has been placed on the head of a shaker, as shown in Figure 6. The device is placed near a calibrated accelerometer to monitor the incoming excitation vibration.

The resonance frequency of the device was measured to be 204 Hz. This low value is the result of large silicon mass and a thin cantilever. This value fits the specifications in terms of vibration spectrum of a dedicated application.

Figure 7 shows photos of the micro generator at three different positions of the first mode. The white parts of the images are the Aluminium electrode. The piezoelectric layer, placed beneath is even compressed (Figure 7(a)) or elongated (Figure 7(c)) thus creating electrical charges.

Images have been taken by a high speed APS camera (Pixelink PL-A741) working at 600 fps. The device produces 38 nW into a matched resistive load for a sinusoidal acceleration of 0.5g amplitude. The maximum deflection has been estimated to be around 600µm.

<table>
<thead>
<tr>
<th>Material</th>
<th>Power [nW]</th>
<th>f(_r) [Hz]</th>
<th>Load [Ω]</th>
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<tr>
<td>AlN</td>
<td>40</td>
<td>239</td>
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<tr>
<td>PZT</td>
<td>85</td>
<td>195</td>
<td>24k</td>
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Table 2: FEM simulation results
6 Conclusions

This paper presents modelling, simulation, fabrication and characterization of a piezoelectric resonant micro power generator. The level of power obtained with this kind of device (38nW for AlN and 85nW for PZT at 0.5g) at a very low frequency of 204Hz allows the scavenging of environmental vibration to power a wireless sensor node. The future works within the topic include the use of a PZT layer instead of AlN in order to improve the generated power and also the development of a dedicated electronic circuit [5] to rectify and stabilize the low voltage signal coming from the generator to charge a micro battery or a capacitor.

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References


