Comparison of Piezoelectric MEMS Mechanical Vibration Energy Scavengers

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ABSTRACT

This paper presents a design, fabrication and experimental test results of MEMS mechanical vibration energy scavenging devices for micro power generation. There is a growing need for such structures in the field of wireless sensor networks, where increasing the autonomy of nodes is a crucial issue. In our case, the transduction is performed using the piezoelectric effect and the devices are entirely made using microfabrication techniques. Two different piezoelectric materials are used for fabrication: PZT that shows high coupling coefficient, but very complicated fabrication process and AlN, not generating as much power but much easier to deposit, compatible with standard CMOS process and not toxic. We present a comparison of performances of these two types of devices.

Keywords: micro power generation, piezoelectric MEMS, vibration energy scavenging, wireless sensor nodes

1 INTRODUCTION

In recent years, a growing interest has been put into the subject of autonomous microsystems. These devices are commonly used as nodes in wireless sensor networks, where small size and extended autonomy are crucial [1]. In fact, until recently, the only solution was to use an electrochemical battery that would supply power to the system. Nevertheless, this solution has a main drawback – the life span of the device is directly linked with the capacity of the energy reservoir and therefore with its size. A trade off has to be made between the miniaturization and longevity of the device. An alternative solution for powering the nodes lies in scavenging of ambient energy. In fact, the recent progress in low power electronics has made possible to run entire systems with power so low that it can be harvested directly from the environment in which the device operates. An overview of ambient power sources can be found in the works presented by Roundy [1] and Mateu [2]. A conclusion can be made from these studies, that in many environments, mechanical vibrations propose very interesting power densities and furthermore, this kind of energy can be transferred to the device by the means of a simple mechanical coupling. We propose in this paper such an approach consisting in an electromechanical transducer using the piezoelectric effect to convert mechanical vibrations into useful electrical energy. Furthermore, we implement these devices using the microfabrication techniques (MEMS structures) what permits a batch fabrication and may lead to creation of self powered systems on chip (SoC) and systems on a package (SoP).

We have analyzed the power requirements of a simple wireless node, containing a 4bit RISC microcontroller, temperature and acceleration sensors and a wireless transceiver. In the case of very low duty cycle operation of about 1% it would require less than 400nW of continuous power supply. The goal of this work is to analyse the possibility of generating this power from the energy of ambient vibrations using a MEMS device.

This is a continuation of work already presented [3][4] that proposes improved devices and use of new materials.

2 DESIGN OF THE STRUCTURE

2.1 Application

We have specified a direct application for our devices – powering a sensor node placed in a head of an industrial milling machine that generates high amplitude vibrations (up to 20g) at the frequencies around 900Hz. In this case, installation of wireless sensor nodes is very interesting in the view of machine health surveillance. There are two main issues that should be taken into account: the first concerns the main frequency generated and the other the vibration amplitude. It would be energetically advantageous to create a device with its natural frequency exactly matching the frequency generated, but on the other hand, there is enough vibration amplitude that even a device operating not at resonance should create enough power. Furthermore, designing a microscopic device that would have its first resonance frequency around 900Hz and capable of withstanding accelerations up to 20g at resonance is quite demanding. Also, given the uncertainties in layer thicknesses and material properties in MEMS, it is impossible to fabricate a structure that would have its resonance frequency exactly matching the value wanted. Therefore we decided to build a device that would be excited only near its main resonance frequency.

2.2 The transduction method

The previously presented works make comparison of three main methods of energy conversion from the mechanical domain into the electrical domain. These are the electrostatic (capacitive), electromagnetic and piezoelectric ones. It has been proven that the piezoelectric method has many advantages if a miniature device is aimed [1][3]. It provides high theoretical power densities, simple design and relatively high output voltages. The only inconvenience lies in the use of exotic piezoelectric thin layers, the deposition of which is not yet mastered. In the recent years however, many research teams reported successful fabrication of high quality Aluminium Nitride (AlN) thin layers [5] and Lead Zirconate Titanate (PZT) thin layers [6]. We have decided to create microfabricated structures that use these two materials. The first one is interesting because of the relatively simple and CMOS compatible deposition process by means of DC reactive magnetron sputtering and its environmentally friendly composition. On the other hand its coupling coefficients are quite low. The other material – PZT, is known to have very elevated coupling factors, but its deposition requires a complicated layer composition, high temperature treatment and high voltage polarization. Furthermore it contains Lead, which reduces its potential applications. While in macroscopic realisations, the piezoelectric material can be separately prepared and then combined with the rest of the device, in the case of microsystems, the thin piezoelectric layer must be created directly on the device. High temperature treatment and elevated voltages are problematic in such realisations.

2.3 Geometrical structure

We propose one basic mechanical structure with two possible piezoelectric materials. It is a cantilever beam with a big seismic mass, as presented in the figure 1.

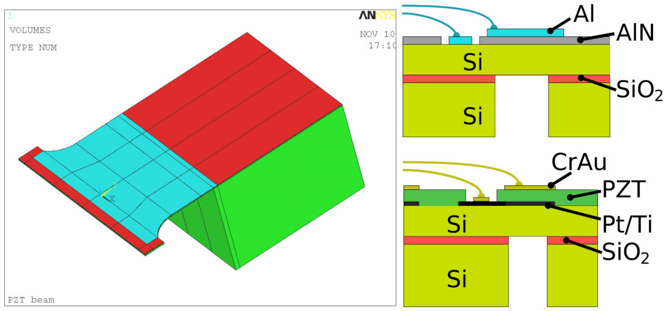

Figure 1 : Piezoelectric micro power generator and the layer composition in the case of using the AlN layer and the PZT layer.

It is an outcome of optimisation process, using analytical models already presented [4]. The seismic mass should be maximised keeping at the same time the value of resonance frequency wanted by adjusting the beam rigidity. The maximal mass volume is defined by the space available and the minimal supporting beam length that guarantees good back side DRIE uniformity. In our case, the maximum length of the device was fixed at 1.5mm and the minimal length of the beam is equal to 400µm. The difference in technological process and material composition of the two approaches using PZT and AlN materials impose a difference in resonance frequency of the two devices.

The device dimensions are as follows: the thickness of the seismic mass is imposed by the thickness of the silicon wafer employed, equal to 525µm. The thickness of the beam is defined by the thickness of the top silicon layer in the SOI wafers used, 5µm in our case. The width of the structure is equal to 800µm, as well the length of the seismic mass. The length of the beam equals 400µm. The AlN layer is 1µm thick and the PZT layer is 2µm thick.

3 FABRICATION PROCESS

Both structures are made out of an SOI wafer. Its use facilitates the definition of a thin supporting beam and a big seismic mass at its end by both face deep reactive ion etching (DRIE). Thanks to the high selectivity of SiO_2 against monocrystalline Silicon, the buried oxide layer is used to stop the etching. The layer composition for the two cases is presented in the figure 1.

3.1 AlN device

For the AlN device, the piezoelectric layer is directly deposited on the top silicon layer, which is highly doped with Boron (p+) in order to increase its conductivity and enable its use as the bottom electrode of the piezoelectric capacity. The AlN layer is deposited using DC magnetron sputtering and a thickness of 1µm is aimed. An Aluminium layer is finally deposited on a patterned AlN layer in order to create the top electrode for the piezoelectric capacity and to make contacts with the silicon layer acting as the bottom electrode. The use of the top silicon layer as the bottom electrode (always on ground) facilitates the fabrication process but introduces parasitic capacitances below each metallic pad and every connection. Furthermore, it makes impossible the connection of multiple devices in series in order to raise the generated voltage.

The AlN devices used in this study were elaborated by the MEMSCAP Company. A special study was performed in order to reduce the built in stress that would cause deformation of the structures.

3.2 PZT device

In the case of the PZT devices, the layer composition is much more complicated. Ti/TiO_2 layer on SiO_2 layer are required as diffusion barriers in order to prevent Lead atoms from penetrating and reacting with Silicon. A Platinum layer is used as the bottom electrode. The PZT film is prepared using the sol-gel technique on a seed layer of $PbTiO_3$. The sol-gel technique may guarantee good uniformity of the layer and elevated thickness (up to 4µm) but requires high temperature treatment and multiple annealing/crystallization steps. Gold layer with chromium seed layer is used to create the top electrode on the piezoelectric capacity. After its creation, the PZT layer needs to be polarized in order to gain piezoelectric properties. The pooling process aligns the domains in the ceramic structure of the layer creating a global polarisation and making the material ferroelectric and piezoelectric.

The devices with PZT piezoelectric layer were elaborated at the ceramics laboratory of the Ecole Polytechnique Federale de Lausanne. The resulting layer was of very good quality without cracks and with relatively low built in stress. The figure 2 presents an SEM photograph of the fabricated PZT device.

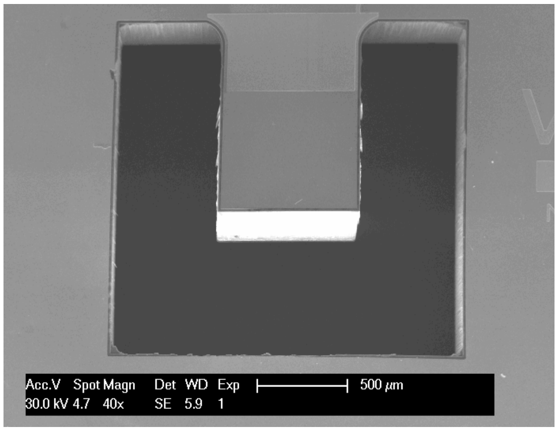

Figure 2 : SEM photograph of a MEMS energy scavenger with a PZT thin layer.

4 HARVESTED POWER

4.1 Analytical modelling

We have used the analytical model of a piezoelectric cantilever beam harvester that we have developed earlier [4] in order to predict the power output of the two devices. We have calculated the power dissipated on a matched resistive load as a function of frequency for the two materials considered: PZT and AlN. In order to perform a comparison, the thickness of the top silicon layer in the devices was adjusted to tune the resonance frequency of the two devices at 900Hz. The resulting thickness is 7.5µm for PZT device and 6.85µm for AlN device. The analytical model does not take into account the influence of electrodes, so in reality the resonance frequencies of such structures would be higher. The quality factors of piezoelectric materials were taken into account ($Q_{PZT} = 135$, $Q_{AlN} = 120$, $\tan\delta_{PZT} = 3\%$, $\tan\delta_{AlN} = 0.1\%$). The silicon layer was supposed to be perfect.

The modelled power outputs of the two devices are presented in the figure 3. The amplitudes generated are almost identical, but thanks to the very low electrical permittivity of AlN (of 10 against 1200 for PZT) the output voltages for these devices are higher, especially at resonance.

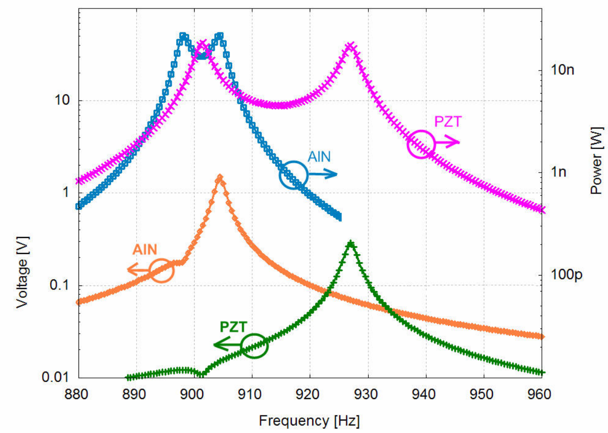

Figure 3 : Analytical modelling results of voltage and output power generated on an optimal resistive load for PZT and AlN devices.

4.2 Experimental results

We have tested the fabricated devices on a controlled vibration source – a DataPhysics V20 shaker controlled by a custom LabVIEW application. The same application provided a closed loop acceleration amplitude control and data acquisition through a National Instruments card PCI-6024E. For each measure a variable load was connected between the electrodes of the generator and the output voltage was observed through INA116 (BurrBrown) high impedance instrumentation amplifier. The output power was calculated from the RMS value of the voltage measured and the resistive load value. In the case of PZT devices, the corresponding resonance frequencies were situated slightly below 900Hz. Power output was observed at antiresonance, on an optimal load of 2MΩ in order to obtain high output voltages. The output power, presented in the figure 4 is equal to 850nW for 2g acceleration and 20nW for 0.2g with voltage amplitudes respectively of 1.8V and 300mV.

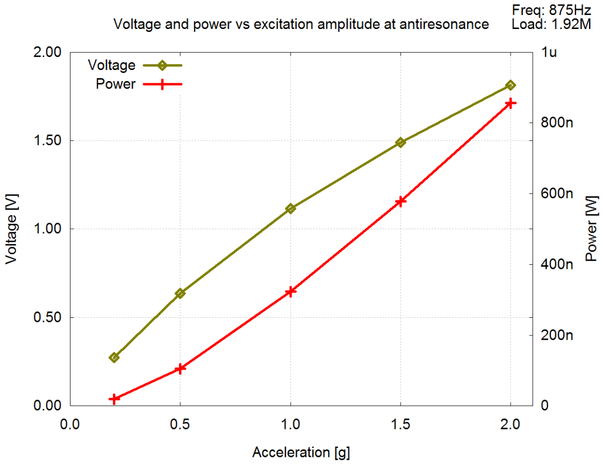

Figure 4 : Experimental results for power dissipated on a matched resistive load at antiresonance for a PZT device.

The behaviour of the PZT devices is non-linear, which means that the output voltage amplitude do not raise linearly with the input vibration as predicted by the analytical model [4]. This effect limits the maximum power that can be obtained from this type of structures and changes the value of frequency at which the device delivers highest power – figure 5.

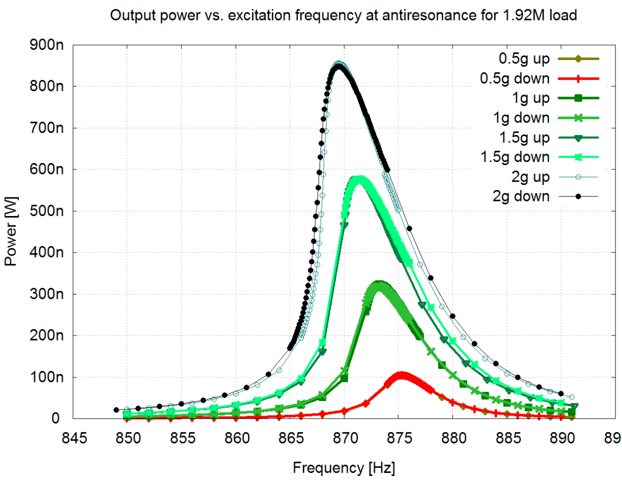

Figure 5 : Experimental results for power dissipated at antiresonance, on a matched resistive load for different input acceleration levels for a PZT device.

The AlN devices have their first vibration frequency around 1400Hz. The big difference is caused not only by the material difference but also by a big variation of top silicon layer thickness in SOI wafers used for fabrication and important under etch of the seismic mass. The higher operating frequency permits to use higher excitation levels. The output power dissipated on a matched resistive load of 650k is equal to about 0.54µW for 2g excitation and 1.96µW for 4g excitation (figure 6).

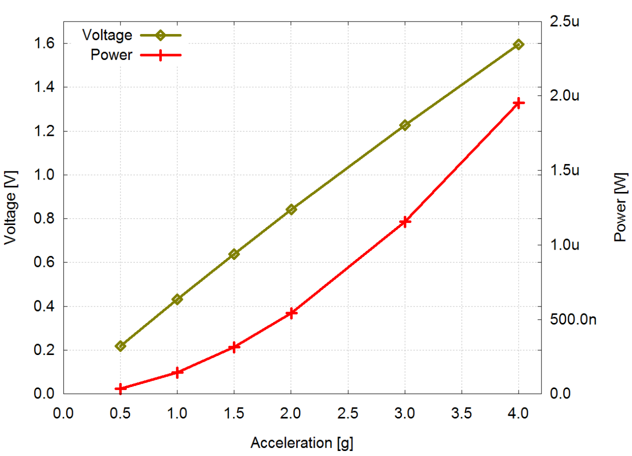

Figure 6 : Experimental power output results for a device with AlN piezoelectric layer, at resonance on a matched resistive load.

The devices are much less non-linear that the previously studied PZT structures. The output power is deteriorated in this case by the presence of parasitic capacitances under the connection pads.

5 CONCLUSIONS AND FUTURE WORK

This paper presents a novel solution for increasing the autonomy of wireless sensor nodes by using MEMS power harvesters. A design, fabrication and experimental results of entirely microfabricated piezoelectric micro power generators have been presented. The results show that one such device can deliver power up to several microwatts into a matched resistive load which is sufficient for the application aimed. A direct comparison of the devices was impossible due to the difference of the resonance frequencies. However, it can be stated that as predicted the PZT structures provide higher power. The AlN structures however, can operate at higher excitation levels and prove to provide sufficient power for the application aimed. We conclude that the AlN devices are better suited for industrialisation thanks to the easier manufacturing process, but the PZT option is much more interesting in the aspect of the output power.

The future work will consist in improving the effectiveness of the devices and further evaluation of the entire power harvesting system including AC/DC and DC/DC converters and a supercapacitor.

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