Powering autonomous sensors with miniaturized piezoelectric based energy harvesting devices operating at very low frequency

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Abstract. Harvesting energy from ambient mechanical vibrations is a smart and efficient way to power autonomous sensors and support innovative developments in IoT (Internet of Things), WSN (Wireless Sensor Network) and even implantable medical devices. Beyond the environmental operating conditions, efficiency of such devices is mainly related to energy source properties like the amplitude of vibrations and its spectral contain and some of these applications exhibit a quite low frequency spectrum where harvesting surrounding mechanical energy make sense, typically 5-50Hz for implantable medical devices or 50Hz-150Hz for industrial machines. Harvesting such low frequency vibrations is a challenge since it leads to adapt the resonator geometries to the targeted frequency or to use out-of-band indirect harvesting strategies. In this paper we present a piezoelectric based vibrational energy harvesting device (PEH) which could be integrated into a biocompatible package to power implantable sensor or therapeutic medical devices. The presented architecture is a serial bimorph laminated with ultra-thinned (ranging from 15µm to 100µm) outer PZT “skins” that could operate at a “very low frequency”, below 25Hz typically. The core process flow is disclosed and performances highlighted with regards to other low frequency demonstrations.

1. Introduction
Piezoelectric MEMS is one of the smartest energy harvesting solution which can efficiently convert mechanical energy into electrical energy. These devices can indeed exhibit various shapes and principle of operations but their intrinsic quality lies on the piezoelectric component used to perform such a conversion and the affordable energy source. Piezoelectric materials for MEMS can be deposited using physical or chemical processes on various substrates. Such deposition processes are quite reliable and can be considered as mature technologies since it is widely used in standard inertial sensors. Piezoelectric MEMS also offers a high integration degree through common microelectronic interconnection and packaging solutions. As a result, piezoelectric MEMS are considered as an essential component in electromechanical energy harvesting and has been tested through numerous important and serious studies. [1]

However, piezoelectric MEMS based on thick or thin films cannot address every vibrational energy harvesting applications. At very low frequency, typically between 25 and 50Hz, it starts to be difficult to properly design a performant piezoelectric MEMs. At low frequency, the geometrical dimension became larger and are directly related to the overall beam stiffness which is mainly driven by the substrate mechanical properties and thickness. Thinning silicon or glass substrate below 50µm become challenging in terms of yields and costs limiting the interest for such nice and sophisticated MEMS
construction. There is two main strategies enabling to overtake these limitations, either you design a larger bandwidth vibrating devices that mechanically convert low frequencies into higher frequencies (like beam bashing systems) where piezoelectric MEMs exhibit a better Figure of Merit or you can use very thinned bulk piezoelectric material and even integrate it under a MEMS shape [2]. In this paper, we propose to assess the performances of such a thinned bulk piezoelectric material to harvest mechanical vibrations around 25Hz corresponding to existing vibration in human tissues close to the heart (valve noise) for a relatively low acceleration amplitude, typically around 0.1G where G is the gravitational constant. We will address manufacturing and performance assessment processes to finally conclude on the obtained performances and viability of such approaches.

2. Manufacturing process flow

2.1. Vertical Architecture
Choosing bulk piezoelectric materials instead of deposited piezoelectric material offers to liberate the design from certain MEMS constraints like achievable piezoelectric film thickness, substrate thickness and its mechanical impact, i.e. material type. The most important one is the vertical cantilever architecture which can be a unimorph like most of the Piezoelectric MEMS, a bimorph (see Figure 1) or a multilayered architecture. In this paper, we have decided to focus our efforts on a bimorph architecture electrically connected in serial. We have not yet investigated parallel piezoelectric outer layer connections because at such low vibration amplitude it would be difficult to pass over rectifiers threshold values but it is technologically doable and would only require few developments.

![Figure 1](image1.png)

Figure 1: Schematic of a clamped/free serial bimorph architecture for energy harvesting

2.2. Design
Clamped free cantilever beams is without any doubt the most known mechanical structure [3]. Its vibrating behaviour has been widely described using standard or more sophisticated computation tools. However, such a structure dedicated to low frequency energy harvesting using d31 piezoelectric coefficient push us into a complex world where tip displacement can be up to ten times the overall structure thickness generating both mechanical and piezoelectric non-linearities.

| Table 1: Bimorph architecture description |
|-------------------------------------------|
| Piezo outer layer | Inner shim | Piezo outer layer |
| Type | Hard PZT | Copper | Hard PZT |
| Thickness | 45µm | 10µm | 45µm |
| Electrode | Gold plated | | Gold plated |
| Beam length | 25mm | | |
| Beam width | 4mm | | |
More, to keep a relatively small device that could be implemented within an implantable medical device, we decided to limit the beam length to 25mm, leading us to grind down PZT layer between 80µm and 20µm according to the internal shim layer thickness. As a result, we have defined the optimized vertical architecture as disclosed in Table 1.

Based on this first architecture definition, a manufacturing process flow has been defined and iteratively optimized. It has to be noticed that obtaining performant bulk PZT material with a thickness ranging between 20µm and 80µm is already challenging and can be directly compared with PZT thick films. A French research program called LAUREAT is currently assessing both reliability and aging of such piezoelectric structures.

2.3. Manufacturing process flow
A very simple approach has been used. As a first step, each piezoelectric layers are bonded at room temperature using conductive epoxy on a copper foil through advanced chemical and mechanical adhesion improvement processes. Then each face are grinded down and polished to their final thickness. The metallisation is sputtered and mechanically patterned to enable both interconnection and tip mass assembly.

![Manufacturing process flow](image)

**Figure 2:** Manufacturing process flow is disclosed in (a), a microscope photo (X50) of the bimorph cross cut (b) and four bimorphs presenting unplated areas for tip mass assembly (c).

Our process flow, based on seven simple individual steps, is presented Figure 2. A cross section obtained with an optical microscope is also presented and a more general view of the final bimorph beams as well. The process flow is quite reproducible with an accuracy of the thickness over the bimorph surface around 2µm. Internal stresses trapped within the layered structure during the assembly are quite low since no visible deflection has been detected. A Panel of 40x40 square millimeters can be processed. Increasing the panel dimensions should lead to considerably reduce costs and increase the yield.

3. Performance assessment

3.1. Measurement Setup
We also present a fully programmable uniaxial harmonic test bench (presented Figure 3) which enables us to dynamically assess the performances even at non-linear mechanical solicitations. Instead of using a sophisticated shaker, we have built around a loud speaker (SPH-275C from MONACOR) a custom shaker where the membrane is actuated using a waveform generator from TEKTRONIX (AG3001), the displacement is applied to a grip tool through a piston fixed on the membrane where cantilever beam is mechanically clamped on one end at a monitored pressure force ensuring a good clamping reproducibility. A tip mass is fixed on both side of the free end of the beam using cyanoacrylate glue.
An accelerometer ADXL 337 from Analog Devices, with a maximal resolution of 300mV/G is used to monitor the vibration amplitude and spectral contains and generated voltages are acquired through a pure resistive load with an oscilloscope TEKTRONIX TDS3052B.

Figure 3: Uniaxial harmonic vibrating bench enabling the output power measurement on an optimized resistive loaded.

A computer drive the whole acquisition chain enabling an automated scan of the output power for given vibration frequencies and amplitudes at an optimized resistive load determined at the maximum frequency thanks to a custom programmable decade box ranging from 1Ohm to 10KOhms. The internal oscilloscope impedance is taken into account. Through this automated bench, it is possible to get output voltages with regards to vibration frequency, amplitude and parallel resistive load.

3.2. Performances
Using the test bench described above, we have measured with two different tip masses, the RMS output power for an acceleration of 1m.s^{-2} at, when possible, the resonant (blue curve) and antiresonant (red curve) time frequencies.

Figure 4: RMS output power measured for a clamped free cantilever beam of: 4mmx36.2mm with a tip mass of 4mmx7.5mm of 0.5g measured for a resistive load optimized at the resonant (in blue) and
antiresonant (in red) frequencies (a), 4mmx25mm square millimeters with a tip mass of 4mmx7.5mm of 3.7g measured for an optimized resistive load (b). Both measurements have been made for a uniaxial acceleration of 1m.s$^{-2}$ along the gravitational direction.

For the device equipped with a heavier tip mass (3.7g), the mechanical quality factor become very low and it is no more possible to get distinct antiresonant and resonant frequencies. The optimized resistive load is also lower and the maximum output voltage is about 15 Volts pick to pick at 0.1G of acceleration which is already high compared to diode threshold value of a classical rectifier circuit.

4. Conclusion

Our optimized thinned-bulk bimorph PEH device has been fully characterized and has exhibited a RMS output power of up to 60µW at 1m.s$^{-2}$ of acceleration at 23.2Hz along the gravitational direction for a 4X25 square millimetre footprint. The resulting RMS output power density measured at 1m.s$^{-2}$ is up to 6.6mW/cm$^3$/g$^2$ (assuming a capsule of 6x30x5mm$^3$) which is very promising and already competitive to previous works [4] using same design strategy and can already serve batteryless implanted medical devices.

Beyond the performance demonstration, such bimorph architectures can be considered as an alternative to more traditional MEMS energy harvesting devices enabling to address lower frequency applications with large displacements. Another key should lies on the durability of such a construction and a study has been launched to monitor piezoelectric and mechanic constant during mechanical cycling.

References

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