MICROMACHINED BULK PZT PIEZOELECTRIC VIBRATION HARVESTER TO IMPROVE EFFECTIVENESS OVER LOW AMPLITUDE AND LOW FREQUENCY VIBRATIONS

Hugo Durou[1,2*], G.A. Ardila-Rodriguez[1,2], A. Ramond[1,2], X. Dollat[1,2], C. Rossi[1,2], D. Esteve[1,2]
[1]CNRS, LAAS, F-31077 Toulouse, France
[2]Université de Toulouse, UPS, INSA, INP, ISAE; LAAS, F-31077 Toulouse, France
*Presenting Author: durou@laas.fr

Abstract: The design, modeling, fabrication and characterization of a silicon/bulk PZT micro machined piezoelectric device are presented. Our miniature device (2.30 cm² × 3mm) consists in 4 micromachined cantilevers made on Silicon substrate sharing the same proof mass. The cantilevers can be used in series or parallel. Each cantilever is a stack of a bulk-PZT ceramic glued on crystal silicon. The frequency can be adjusted easily by tuning the tungsten proof mass from 160 mg to 4 g. Our design permits to produce a sufficient amount of electrical power along with a usable voltage (>1 V) under only 1 m.s^{-2} (50 Hz-90 Hz) which is the vibration level of commercial aircraft mechanical structure. Our design permits to obtain a very good wideband over max electrical power output tradeoff given the vibration spectrum. The fabrication relies on standard MEMS processes. Finally, characterizations under shaker show that we can generate 3.20 µW (1.26 V through a load resistance of 500 kΩ) under 1 m.s^{-2} at 77 Hz, 14 µW (2.64 V) under 2 m.s^{-2} at 76 Hz. Using a new proposed figure of merit, the device compares favorably to other characterized devices in the literature.

Keywords: Mechanical Energy harvesting, MEMS, PZT, Piezoelectric

INTRODUCTION

Remote wireless networks are a very attractive and flexible technology for applications requiring embedded sensors in inaccessible locations. Among various applications of wireless networks, aircraft Structure Health Monitoring (SHM) is a very challenging one to provide effective maintenance schedule. Each wireless sensor of the SHM network must be able to collect and store data during the flight and communicate it when the plane is grounded. The use of batteries still having short lifespan is a high limitation for aircraft SHM wireless sensing networks emergence. One explored option is to harvest the ambient energy (engine vibration, heat, between others) to make the system completely autonomous over a theoretical infinite lifespan. The aim of our work is to propose a microfabricated device capable to harvest the mechanical vibration of the structure to power a sensor device.

The sources of steady mechanical vibration on an aircraft are mainly the engine but the level of acceleration found on large passenger airliner is in the range of 0.01g and 0.2g. The frequencies depend on the engine and we note peaks at low frequencies, between 40 and 80Hz.

Vibration energy harvesting has been studied comprehensively over the past decades. Piezoelectric, electromagnetic and electrostatic transduction mechanisms are commonly used to convert mechanical energy to electrical signal [1]. Due to the specific size restriction in SHM application, a piezoelectric generator is selected as the power source. For more than 15 years many piezoelectric mechanical vibrations harvester prototypes have been reported: a large amount of meso-scale piezoelectric vibration harvester prototypes have demonstrated the capacity to produce a usable electrical power from mechanical vibrations but they could not meet our miniaturization requirement. Then research has focused on micromachining technology to propose millimetric harvesters that can be integrated with sensor networks. To date, the emergence of practical micro machined piezoelectric harvester faces two main difficulties: the fabrication of high-quality piezoelectric thin films and the too high resonant frequency of the device imposed by the material stiffness and low vibrating mass. No micromachined device has a resonant frequency in the range of 40Hz-80Hz which is the frequency range of aircraft vibration sources [2]. Due to the low mechanical to electrical conversion yield with piezoelectric thin film (Zn0, AlN, PZT sol-gel, sputtered-PZT), most of the fabricated devices are characterized under unrealistically high mechanical input (>0.5g), which is not relevant for our application.

This paper proposes an innovative design of a silicon/PZT micro machined piezoelectric device capable to produce a sufficient amount of electrical power (> 1 µW) along with a usable voltage (> 1 V) under 0.1g (at 40 Hz-80 Hz) vibrations.

CONCEPTION

As our inertial vibration harvester has to be set on an aircraft, it must be thin (<5 mm) to avoid aircraft aerodynamics alterations. The harvester design consists in unimorph cantilevers made of single-crystal silicon and bulk PZT-5H bonded with a thin layer of electrically conductive epoxy glue. Each cantilever is attached at one end and a proof mass is set at the remaining free end (see figure 1). The proof mass is a tungsten piece of 15.35×5 mm². Its thickness is adapted as function of the mass required to tune the frequency. Bulk PZT-5H was chosen as piezoelectric material since we look for the highest electromechanical coupling. The PZT-5H thickness is imposed at 200µm by the supplier. The epoxy bonding layer is set to 10 µm, according to earlier SEM measurement we made [3]. The goal of our modeling is to find the dimensional features L_{beam}, w_{beam} and t_{Si} (beam length, width and silicon beam thickness respectively) to produce the maximum electrical power at 50Hz and under 0.1g harmonic vibration.

To do so, we implement a coupled FEA (mechanical coupled with piezoelectric) and SPICE model capable to predict the beam frequency response, strain and stress and the piezoelectric electrical power output. This model is similar to the model used by Yang and Tang in [4]. It is run through a scripted COMSOL/Matlab routine: a geometry is generated with dimensions L_{beam}, w_{beam} and t_{Si} (taken within their respective optimization range) and sent to COMSOL model where materials and boundary conditions are set and simulation run; resulting power output and Eigen frequency for the tested geometry are saved. All geometric combination of L_{beam}, w_{beam} and t_{Si} are simulated.

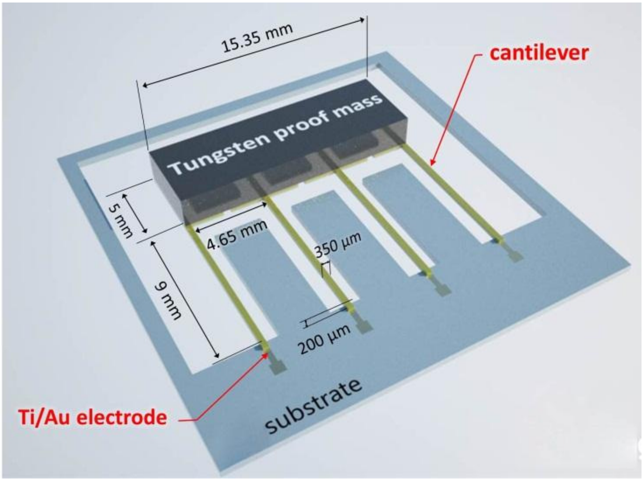

Fig. 1: schematic 3D view of optimized design.

As given in figure 2, the resulting optimized cantilever is:

- 15 mm long: 1 mm is attached to the silicon base, the active part of the beam is 9 mm long and the last 5 mm supports the proof mass.
- 350 µm wide
- 333 µm thick: 125 µm thick silicon, 10 µm thick epoxy glue and 200 µm thick PZT-5H.

According to our model, this beam should provide 0.76 µW under 0.1g at 50 Hz harmonic vibrations. Four of these optimized beams will be integrated into a single device to be serial connected to provide 3.04 µW and sufficient voltage (1.94 V) under 0.1g - 50 Hz harmonic vibrations. The device surface is 2.30 cm² and the total weight is estimated at 0.7 g without the proof mass.

FABRICATION

The fabrication process starts from a 4 inches and 500 µm thick silicon substrate (Si). It uses simple MEMS process steps combined with a conventional packaging process and laser etching technologies. It was first proposed and developed by our group in [5], [3] and has been slightly modified as follows (figure 3-a). The Si wafer is first covered with Si_3N_4 (LPCVD 80 nm, for electrical isolation and KOH masking) then this layer is patterned on the backside with RIE, and then the exposed area is wet etched with KOH for 375 µm (figure 2-a). The second step is the evaporation of thin film Ti/Au (100/800 nm) on the front side, then etched with KI + I_2 solution to make the current collectors (figure 2-b). The third step is the placement and bonding of a 200 µm thick PZT film previously metalized with Cr/Au (500 Å/5000 Å) (610-HD supplied by TRS Technologies) (figure 2-c).

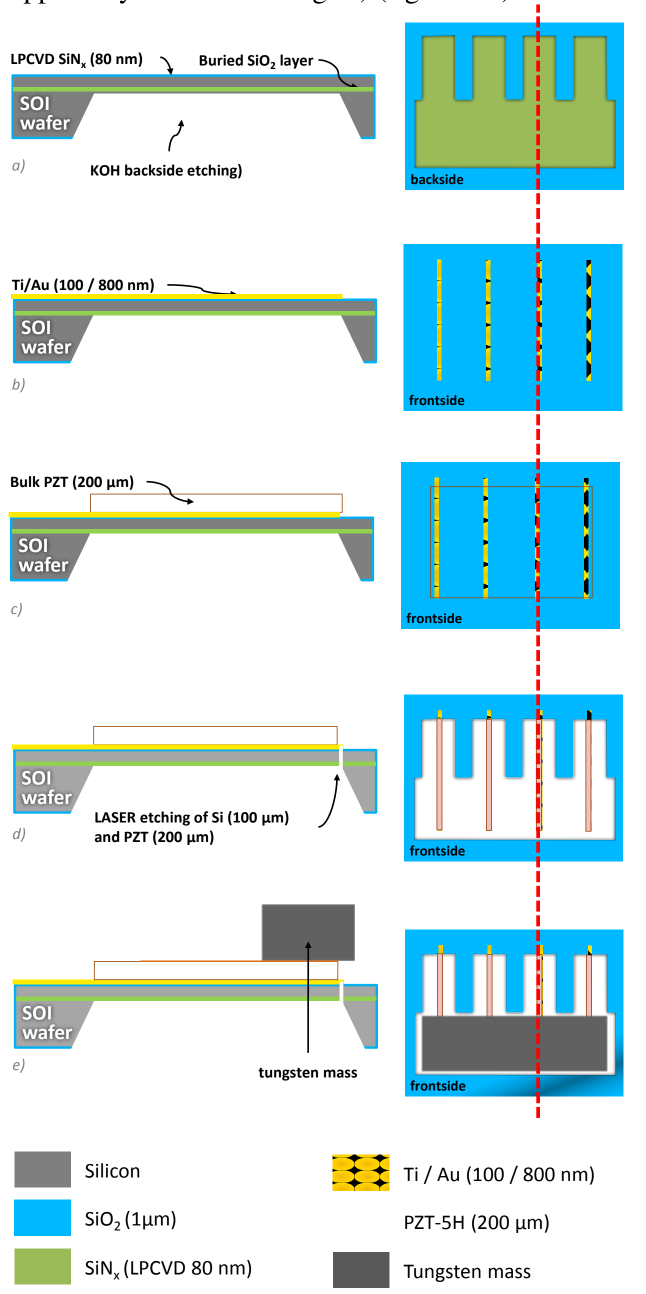

Fig. 2: Fabrication steps

This PZT features relatively high d_{33} and d_{31} coefficients (690 pC/N and -340 pC/N respectively)

[5], relatively low stiffness (c_{33}^{E}= 120 GPa) for low resonance frequency and good machinability, and low mechanical quality factor (Q=46) for broadband frequency response. The placement of the PZT film is performed using a Tresky 3000; the bonding is made using a conductive thermal curing epoxy from Epotek (H20E) with silver filler to ensure electrical contact between PZT lower electrode and evaporated Ti/Au layer on Silicon. Curing of the epoxy bonding layer is done at 100 °C, and a static pressure of approximately 100 MPa ensures that the bonding layer is as thin as possible. The thickness of this layer has been measured using SEM (**Erreur ! Source du renvoi introuvable.** 4) and found to be 10 µm with less than 10 % thickness variation between beams. In the fourth step, the 200 µm-thick PZT and 125 µm thick Si are etched around the cantilevers using a femtosecond LASER (figure 2-d). This type of laser was chosen for its low temperature characteristics caused by an instantaneous ablation [6]. The fifth step is the electrical serial connections between the cantilevers, and manual placement and bonding of the tungsten proof mass over the cantilevers (figure 2-e).

CARACTERIZATION

The fabricated device has been mounted on a printed circuit board; a proof mass of 2.248g has been glued on the free end of the beams and PZT outputs are connected to a resistive load to characterize the device under different harmonic vibration conditions: frequency and amplitude of vibration can be set easily and controlled.

The experimental setup consists in an aluminum holder attached to a voltage controlled shaker V101 from LDS. The acceleration amplitude and frequency are measured using a 3-axis accelerometer (MMA7260QT from Freescale Semiconductor) integrated into the holder to ensure equal base vibration amplitude over the whole frequency regardless of the damping of the harvester.

The adapted resistive load is set to 500kΩ for all the experiments. Figure 3 shows the power spectrum (output power-frequency diagram) of the 4 cantilevers serial-connected under vibration amplitude of 0.1g and 0.2g, and these results are presented in table 1.The harvester exhibits the frequency response of a linear damped oscillator. Measured resonance frequency is different than what we expected after the model simulation, but we found a good agreement when we run the model with the measured dimensions (slight variations from LASER etching).

Table 1: characterization results.

Input [g]	Natural Frequency [Hz]	Voltage [V]	Output electrical Power[µW]	Power density [µW.cm^{-3}]
0.1	77	1.26	3.20	9.22
0.2	76	2.64	13.9	40.1

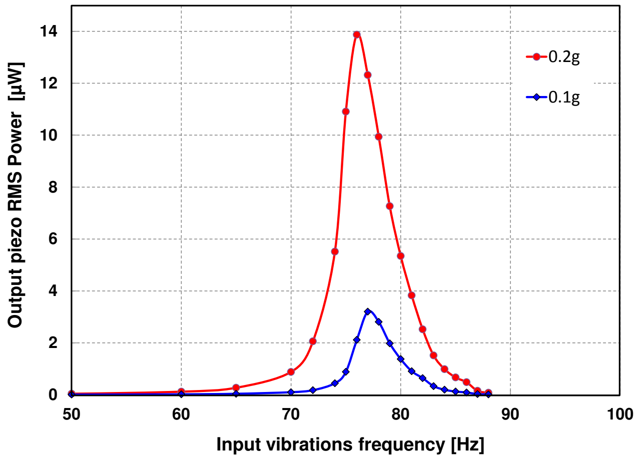

Fig. 3: RMS power output versus frequency for 0.1g and 0.2g input vibrations

DISCUSSION

Several drawbacks on the fabrication scheme presented elsewhere ([3], [5]) were solved for this article: First, concerning the laser etching process; the laser energy and time exposition were increased, and at the same time, multiple lines over the undesirable PZT parts were patterned to easily remove them. Secondly, considering the cantilever liberation; a wet etching (KOH) was used instead of plasma etching process (DRIE), as the latter technique led to over-etching of the cantilevers, and thus low device power output.

We designed the device with 4 cantilevers to have the ability to serial connect them in order to have an output signal high enough so it can be rectified without too great loss. This requires keeping phase between signals to a minimum to avoid signal cancelation, so we used a shared proof mass in our design. Despite variation in amplitude of each beam output signal, the phase between all signals was always under 15 °.

Performance comparison

Comparing the performance of inertial harvesting devices is a key issue: power output alone is not a relevant figure since it strongly depends on the input vibrations (both amplitude and frequency). The volume of the devices is also relevant since most of the applications require miniaturized autonomous sensing systems. We have calculated the figure of merit (FOM), as reported in [6] for the most effective devices reported in [7] and for commercial devices; comparison is made in table 3. We provide here an additional FOM, defined as the integration (using a trapezoidal integration method with MATLAB) of the FoM_v over the normalized frequency. It appears to be a more fair comparison method since it accounts for the input energy, the volume of the device and the output energy over the whole tested spectrum.

Table 2: performance comparison.

Author	Ref.	Acceleration [m.s^{-2}]	Frequency [Hz]	Amplitude [µm]	Power out [µW]	Volume [mm^3]	FoM_v [%]	FoM_{int} [ppm]
LAAS		1.96	76	8.6	12.3	464	0.303	258
LAAS		0.98	77	4.2	3.20	464	0.156	205
Soliman	[8]	4.91	95	13.78	2 083	9 337	0.300	145
Wischke	[9]	10.00	296	2.9	68	800	0.041	88
Perpetuum PG17	[10]	0.98	100	2.48	5000	537 067	0.0154	10.4
Arevni	[11]	4.91	50	49.75	44 800	190 080	0.220	145

Among the 23 references reviewed in [7] and 4 commercial devices, we are only able to make a comparison with 4 devices since our figure of merit requires a record of the frequency response (power output versus input frequency), the input vibration amplitude, and the system volume. To illustrate the meaning of the figure of merit (FOM) we propose, we plotted in figure 4 the FOM proposed by Mitcheson in [6] versus the normalized input vibration frequency. Thus for a given device the FOM we propose can be seen as the area under its frequency response curve Our harvester presented in this paper compares favorably to other devices in the literature in terms of maximum FoM_v. It also provides very good sensitivity to broadband vibrations as reflected by its FoM_{int} value.

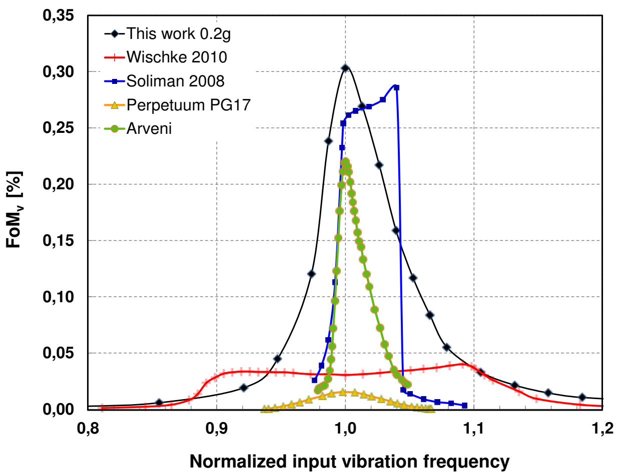

Fig. 4: Comparison of wideband research and commercial inertial vibration harvesters.

CONCLUSION

The design, fabrication and characterization of a bulk PZT piezoelectric vibration harvester are presented. The device has been designed to deliver few micro Watts and voltage higher than 1 V under low level vibrations (typically 0.1g – 50Hz) to be able to power aircraft SHM sensors, and fabricated using femtosecond LASER-machined bulk PZT-5H. This allows significant improvement over up to date literature devices, which used thin piezoelectric layer deposited with sputtering or Sol-gel techniques. The device, which is 0.46 cm^3 large and 2.1 mm thick, has been fabricated relying on standard MEMS processes. Characterizations show that we can generate 3.20 µW (1.26V) under 0.1g at 77 Hz and 14 µW (2.64V) under 0.2g at 76 Hz. All performances are finally compared to other characterized devices in the literature, using a new figure of merit. It is thus shown that this bulk-PZT process allow unachieved levels of performance in micro harvesting devices.

REFERENCES

[1] Priya S, 2007 Advances in energy harvesting using low profile piezoelectric transducers Journal of Electroceramics, **19** 1 165-182

[2] Reilly E K 2009 A study of ambient vibrations for piezoelectric energy conversion Technical Digest PowerMEMS 2009 (Washington DC, USA, December 2009)

[3] Ardila G A 2009 A PZT vibration harvester: Fabrication and characterization Technical Digest PowerMEMS 2009 (Washington DC, USA, December 2009)

[4] Yang Y, Tang L 2009 Equivalent Circuit Modeling of Piezoelectric Energy Harvesters Journal of Intelligent Material Systems and Structures **20** 18 2223-2235

[5] Ardila G A 2008 et al., Fabrication and simulation of a PZT energy harvester MEMS in Technical Digest PowerMEMS 2008 (Sendai, Japan, November 2008)

[6] Mitcheson P D 2008 Energy harvesting from human and machine motion for wireless electronic devices Proceedings of the IEEE **96** 9 1457–1486

[7] Zhu D, Tudor M J, Beeby S P 2010 Strategies for increasing the operating frequency range of vibration energy harvesters: a review Measurement Science and Technology **21** 2 022001

[8] Soliman M S M, Abdel-Rahman E M, El-Saadany E F, Mansour R R 2008 A wideband vibration-based energy harvester Journal of Micromechanics and Microengineering **18** 11 115021

[9] Wischke M, Masur M, Goldschmidtboeing F, Woias P 2010 Electromagnetic vibration harvester with piezoelectrically tunable resonance frequency Journal of Micromechanics and Microengineering **20** 3 035025

[10] http://www.perpetuum.co.uk/. Webpage accessed on November 10, 2008

[11] http://www.arveni.fr/eng_productspe.php. Webpage accessed on June 20, 2010