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High-performance piezoelectric thick film based energy harvesting micro-generators for MEMS

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Abstract

Energy harvesting, known also as energy scavenging, covers a great body of technologies and devices that transform low grade energy sources such as solar energy, environmental vibrations, thermal energy, human motion into usable electrical energy. In this paper vibrations are used as energy source and are transformed by the energy harvesting micro-generator into usable electrical signal. The micro-generator comprises a silicon cantilever with integrated InSensor® TF2100 PZT thick film deposited using screen-printing. The output power versus frequency and electrical load has been investigated. Furthermore, devices based on modified, pressure treated thick film materials have been tested and compared with the commercial InSensor® TF2100 PZT thick films. It has been found that the structures based on the pressure treated materials exhibit superior properties in terms of energy output.

Keywords: piezoelectric; PZT; thick film; energy harvesting; MEMS

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1. Introduction

The continuous miniaturization of electronic mobile devices has for a number of years been a driving force for the development of small, high energy density power sources in the form of batteries. In this context mobile devices can be both consumer electronics or wireless sensor systems for remote monitoring of industrious machinery. Recently, advances in IC technology has lead to a decrease in power consumption of mobile devices and along with progress in material development it has sparked an increased interest in energy harvesting for powering such mobile devices. Ambient heat [1], light or vibrations [2] may be subject to energy harvesting, in this paper we will focus on vibrational energy harvesting by use of a piezoelectric vibration energy harvester. The high coupling coefficient of

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PZT makes it a preferred choice of piezoelectric material for use in a vibrational energy harvester. Several piezoelectric cantilever based energy harvesters with bulk PZT have been presented [3].

MEMS based energy harvesters with sol-gel deposited PZT have previously been presented [4] where the thickness of the PZT layer is in the range of 1-2 µm. Typically piezoelectric thin films have been used for energy harvesting devices but these films have thicknesses below the optimal thickness [5]. To harvest the highest amount of energy with a MEMS based energy harvester we aim at using PZT films with a thickness in the tens of micrometer range. For this purpose screen printing of PZT on silicon substrates is used for deposition of PZT [6].

For the most part applications for PZT thick film and MEMS technology are based on the bending mode where the planar piezoelectric coefficient d_{31} is used. However, in PZT thick film the planar coupling coefficients are generally lower than for bulk. The main reason for this is that the thick film has a porosity of about 20 %. In this paper, work with PZT thick film prepared using high pressure in order to decrease the porosity in the thick film material is presented.

2. Sample preparation and measurement setup

Insensor® PZT thick film based structures have been manufactured using the screen-printing technique combined with standard MEMS processing of the silicon substrate. The 30 µm PZT thick film has been deposited by screen printing on 350 µm thick silicon substrates with Pt based diffusion barrier layer. The barrier layer served also as the bottom electrode and its thickness was lower than 1 µm. The PZT layer has been sintered at temperatures of above 800 ºC. The Al top electrode has been deposited by PVD. To make a good comparison, half of the samples were exposed to high pressure treatment at a certain point of manufacturing. Fig. 1a and 1b show SEM cross sections of PZT thick films produced using the standard processing and PZT thick film exposed to the high pressure treatment.

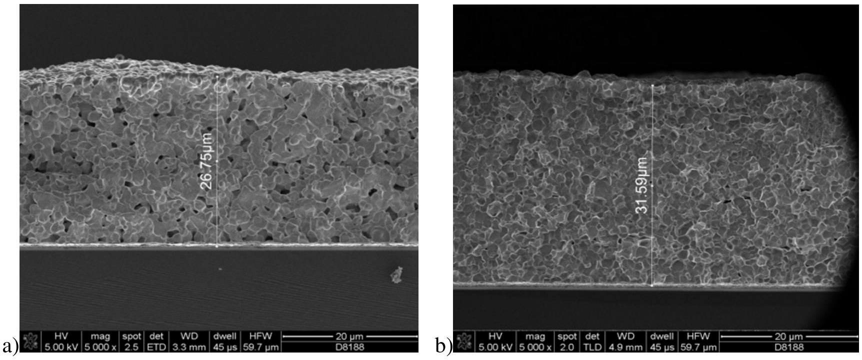

Fig. 1. (a) SEM image of PZT thick film not exposed to high pressure treatment; (b) SEM image of PZT thick film treated with high pressure

The bending structures have been diced out of a wafer after the fabrication. The general structure of the cantilevers together with the dimensions are given in Fig. 2a. Three different kinds of structures of different planar dimensions have been manufactured and tested: 12.5x2 mm^2 12.5x3 mm^2 and, 25x3 mm^2. The active film (PZT) has been polarized at elevated temperature with a high electric field.

Before the measurements the devices were glued to PCB fixtures such that one end of the cantilever was clamped and the other was freely moving as depicted in Fig. 2a. The whole fixture was mounted on a shaker (TIRA S51110), imposing a sinusoidal acceleration. A reference accelerometer (PCB 301A11) was fixed to the vertical axis of the shaker, in order to measure the vertical acceleration. All the electrical measurements were performed using a digital oscilloscope DSO8064A. In-house designed digitally controlled resistive load has been used in the tests. Fig. 2b shows the test fixture mounted on the shaker. A set of clip-on proof masses attached to the cantilever was used in the experiments.

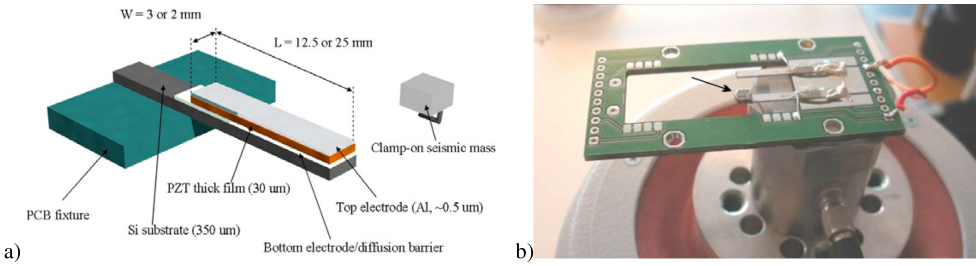

Fig. 2. (a) Schematic structure and dimensions of the tested devices; (b) devices mounted on the shaker system, one device with visible clamp-on seismic mass.

3. Results

A number of test structures have been characterized, by performing a frequency scan around their resonance at different electrical loads. Structures based both on standard (STD) as well as high pressure treated (CIP) materials have been tested at an acceleration of around 1 m/s^2. An example of a typical performance of standard and high pressure treated devices is given in Fig. 3.

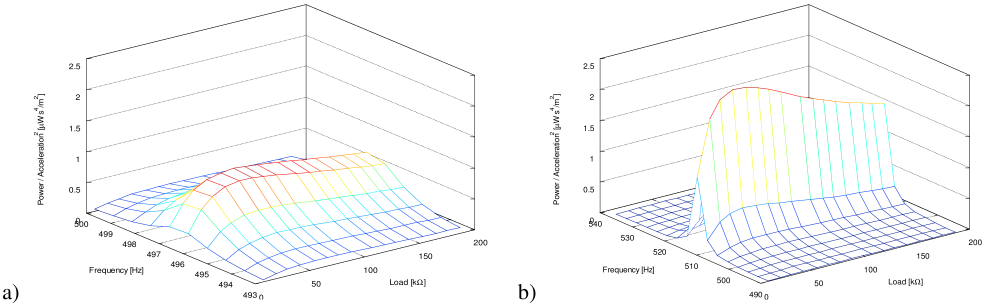

Fig. 3. Normalized power output (RMS) as a function of the excitation frequency and resistive load; (a) 12.5x2 mm^2 structure based on STD TF2100 PZT thick film; (b) 12.5x2 mm^2 structure based on high pressure TF2100 PZT thick film

Output voltage as well as dependence of the output power on the seismic mass is given in Fig 4a and Fig4b, respectively.

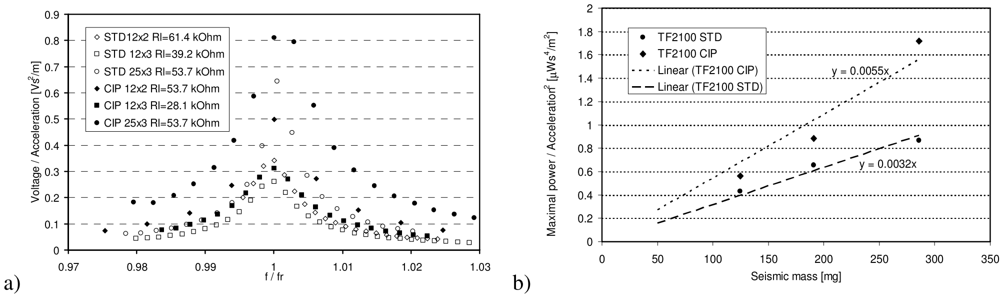

Fig. 4. (a) Normalized voltage output of tested devices around resonance frequency. Dimensions of the tested devices are indicated in the legend; (b) Dependence of maximal measured power (RMS) of 12.5x3 mm^2 devices at different seismic masses for different piezoelectric materials

4. Summary

The maximal output power P_{max} of a vibration generator at resonance frequency can be expressed in the following way: $P_{max} \sim m\, a^2 / f_r$, where m is the seismic mass, a acceleration and f_r the resonance frequency. Therefore one can calculate a figure of merit, which allows a direct comparison of the bending elements regardless the applied conditions according to the following formula:

$$f.o.m. = P_{max}\, f_r / m\, a^2 \,. \qquad (1)$$

Table 1 summarizes the results for tested devices allowing a direct comparison of the structures based on the standard PZT thick film TF2100 (TF2100 STD) and high pressure treated (TF2100 CIP).

Table 1. Summary of the obtained results for selected samples. All values have been measured for seismic mass of 286 mg at matching load

Planar dimensions [mm x mm]	Piezoelectric thick film	Resonance frequency; f_r [Hz]	Maximal measured output power; P_{max} [μW s^4/m^2]	Figure of merit according to *(1)*
12.5 x 2	TF2100 STD	493.2	0.95	1.6
	TF2100 CIP	512.1	2.46	4.4
12.5 x 3	TF2100 STD	617.4	0.87	1.9
	TF2100 CIP	612.6	1.71	3.9
25 x 3	TF2100 STD	191.2	4.18	2.8
	TF2100 CIP	205.0	7.56	5.4

5. Conclusions

It has been successfully demonstrated that high pressure treatment of the PZT thick films improves the performance of the material. This has been indicated by a number of measured parameters such as figure of merit and maximal output power, which doubles for the structures based on the high pressure treated PZT thick film. The actual properties of the high performance material have yet to be determined. It must be pointed out that the devices produce a usable level of voltage (in the range of hundreds of mV up to 1 V) at very moderate accelerations of about 1 m/s^2. Taking into account that the screen printed thick films can be integrated with silicon technology one can conclude that the new high performance PZT thick film material is a very promising candidate for manufacturing of highly integrated MEMS structures for autonomous devices based on energy harvesting principle.

Acknowledgements

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