PZT THICK SHEET ON FLEXIBLE PLASTIC SUBSTRATE FOR VIBRATION ENERGY HARVESTING

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Abstract: From design, simulations to experimental measurements, this paper describes the proof of concept of a low-cost, low-complexity piezoelectric energy harvester. Thick Lead Zirconate Titanate (PZT) sheet is used as active material and transferred on flexible polyethylene terephthalate (PET) substrate. The design of the cantilever structure was carried out by using COMSOL software. Simulated results were verified to correlate with experimental data. The results reveal that a conventional shape cantilever can be optimized to be used in the moderate frequency range and achieves a power density of 1.4µW/cm². This flexibility concept targets large scale easy implementable power-generation surfaces for vibration-energy harvesting.

Keywords: piezoelectric, harvester, flexible, PZT, PET, vibration, foil

INTRODUCTION

Harvester on foil has gained interest for flexible smart labels or disposable systems with realistic power outputs. To name a few, first flexible nanowire-based piezoelectric generators that can harvest sufficient mechanical energy to power small devices were demonstrated by Zhu et al. [1]. By the mean time Qi et al. have shown to be able to print piezoelectric ribbons onto rubber to make a stretchable energy conversion device [2]. Choi et al. reported a solar and mechanical, touch-sensitive harvester base on zinc oxide nanostructured thin film [3]. Pan et al. presented a piezoelectric thin film deposited on PET flexible substrate. The use of various piezoelectric materials such as polyvinylidene fluoride (PVDF) films [4], zinc oxide (ZnO) films and nanowires [1, 5] and PZT nanoribbons [2] and fibers, is very promising in this field of interest. PVDF foil has a good flexibility but this advantage is offset by the weak electromechanical coupling. The sputtering process of ZnO layers on flexible substrate makes warping effect due to thermal deformation [6]. In this work we have been investigating on a less complex and lower cost process to obtain piezoelectric material transferred on a plastic foil. PZT were chosen as piezoelectric material throughout this work due to its high piezoelectric coefficient and its best conversion efficiency [7]. Furthermore in the $d_{31}$ mode configuration (i.e. the PZT layer is sandwiched between two electrode layers), this material has shown to generate suitable power levels [8-10]. Thick piezoelectric sheet were laminated on flexible substrate using dry resist as bonding layer. Despite the lower power density (which still can be optimized) of flexible technology compared to the silicon one [9], the advantages of using a lower density polymer material is that it allows lower resonant frequencies for the same volume, wider bandwidth and easier manufacturing process, since it doesn’t required clean room instrumentation and infrastructure.

Three different topologies were realized and characterized in order to understand the relation between geometry and first resonant peak. The aim is to be able to harvest energy from periodic vibrations at moderate frequencies (50-400Hz).

The results demonstrated the transfer of thick PZT sheet on a flexible PET substrate. It shows that by increasing the length of the PET cantilever, it reduces the frequency by two and by laminating a mass sheet on the top of the cantilever it naturally decreases the frequency again by two and increases the output power as well.

Finally the paper reports also on the dependence of the first resonant peak on the ratio of the PZT length over the PET length and the relation between the power and the dynamic coupling coefficient of the structures.

DESIGNS

Referring to Table 1 the first A-type topology consists of a simple conventional-shape cantilever design. This design exhibited a first resonant peak at around 1.2 kHz, relatively far from the low frequency range of interest for us. Then optimization of the topology was done using COMSOL simulation tool. The computed results show that by increasing the length of the PET cantilever compared to the PZT part, the resonant frequency of the devices went down in the range of 500-600Hz. Fabricated and characterized B-type devices confirm the first optimization. The second optimization step brought its resonant frequency down to around 260Hz. This was done by adding a metal
Table 1: The characteristics and experimental values of PZT/PET harvesters with different designs

<table>
<thead>
<tr>
<th>Sample</th>
<th>Cross section</th>
<th>Frequency (Hz)</th>
<th>k&lt;sup&gt;2&lt;/sup&gt; (%)</th>
<th>PZT length (mm)</th>
<th>PET length (mm)</th>
<th>Width (mm)</th>
<th>Power @ 1g (µW)</th>
<th>Optimal load (Ω)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>PZT</td>
<td>1236</td>
<td>0.21</td>
<td>8.5</td>
<td>8.5</td>
<td>2.9</td>
<td>0.25</td>
<td>26.6k</td>
</tr>
<tr>
<td>B</td>
<td>PZT</td>
<td>517</td>
<td>0.27</td>
<td>9.5</td>
<td>15</td>
<td>2.9</td>
<td>0.18</td>
<td>39k</td>
</tr>
<tr>
<td>C</td>
<td>PZT</td>
<td>268</td>
<td>0.51</td>
<td>11</td>
<td>11</td>
<td>11</td>
<td>0.6</td>
<td>118k</td>
</tr>
</tbody>
</table>

sheet on the top of the cantilever acting as a mass (C-Type). Consequently, the output power increased as well.

**First optimization**

The three different types of devices were modeled using finite-element-method (FEM) simulations with COMSOL Multphysics. The material properties input parameters are faithful to values reported in the datasheets provided by the manufacturer. From bottom-up the references of the materials used are; for the PET: 125µm-thick Melinex ST506 polyester film, then a 14µm-thick dry photoresist film, PerMX3050 from DUPONT, and 130µm-thick piezoelectric sheet of PZT (PSI-5A4E) exhibiting piezoelectric coefficient as d<sub>31</sub> ~190 pC/N and an relative dielectric constant at 1 kHz of 1800. The A-type cantilever has a length of 8.5 mm and a width of 2.9 mm. The first peak resonant frequency obtained for these dimensions is around 1 kHz.

**Second optimization**

The previous optimization brings the frequency of the structure from ~1 kHz down to ~550 Hz. Although the frequencies of the ambient vibrations in our environment range from 60 to 200 Hz [11]. Therefore the second optimization allows us to get close to these frequencies. By adding a 100 µm-thick sheet of metallic foil on the top of the cantilever, having the same size than the cantilever itself, it will act as a mass. The computed frequency value of this C-type device is around 260 Hz.

**EXPERIMENTAL Fabrication**

Figure 3 shows an illustration of one of the B-type devices. As aforementioned the base material is a 125 µm-thick PET substrate. The latter was first patterned using a Computer Numerical Control (CNC) drilling machine to make the cantilever’s shape and also a small opening for the bottom contact. Laser machining could also be used and etching could be done as the last fabrication step to form the cantilever. The 130
µm-thick PZT was diced into the desired size and shape using a standard dicing saw. Then the dry photo resist is used to bond the bulk PET pieces on the PET substrate. This bonding process involved:

- cutting the dry resist film to fit to the size of the cantilever;
- fixation of the dry resist film first on the PZT pieces using a roller laminator;
- UV exposure and post-lamination bake at 100°C for cross-linking purpose of polymers [12];
- surface treatment to improve adhesion;
- bonding of PZT/dry foil to the PET substrate;
- finally hard cure of the structures in an oven.

For the measurements, the devices were mounted on a rigid PCB, which was put on the shaker (Figure 3b). The 100 µm copper sheet of C-type devices was fixed using a dedicated adhesive tape.

To obtain these frequencies, power versus frequency were measured with an acceleration of 1 g and the open circuit is simulated with a 1 MΩ resistor, while short-circuit is simulated with a 100 Ω resistor. Typical values of $k^2$ for all three types of devices are reported in Table 1. Better the coupling coefficient higher will be the output power. Afterwards, its performances including effects of resistive load, vibration frequency, acceleration and output power, are characterized.

Figure 4 shows the output power versus resistive load at 1g for all three types of devices and the optimal load was determined to be 26.6 kΩ, 39 kΩ and 118 kΩ for A-, B-, and C-type devices respectively. It has been roughly verified that the optimal doesn’t change in the range of 0.1 to 1 g. Then the experimental power as a function of frequency and acceleration at the optimal load was measured. Figure 5 summarizes the results obtained from the overall sets of measurements done with A-, B-, and C-type devices. This picture shows that not only we were able to reduce the resonance frequency of A-type devices, but the output power was increased using a longer PET cantilever (B-type).

Characterization

The fabricated devices were fully characterized. First, impedance versus frequency measurements are done to obtain the resonant and anti-resonant frequencies. More than 10 measurements were done on different A-type and B-type devices and it is summarized in Figure 2. Once the resonant frequency known, the dynamic electromechanical coupling coefficient $k^2$ is determined using the method described in [13]. The equation is as follow:

$$k^2 = \frac{f_{oc}^2 - f_{sc}^2}{f_{oc}^2}$$  \hspace{1cm} (1)

where $f_{oc}$ and $f_{sc}$ are the open circuit and short circuit resonant frequencies, respectively.

Furthermore, by adding a metallic sheet as a mass (C-type) the first resonant peak goes down to around 260 Hz and the output power reaches 0.64μW, which corresponds to an power density of 1.4μW/cm². However as prospective work the authors believe that the design still can be optimized to reach higher output power levels.

Figure 6 is used to estimate the quality factor and the bandwidth of C-type structures. In average, the experimental quality factor is found to be around 22 with a relatively large bandwidth of 12 Hz. In comparison with silicon-based devices the quality factor is lower but larger bandwidth is obtained.

Fig. 3: Illustration of one B type device, a) computed 3D view, b) one fabricated device mounted on the test bench.

Fig. 4: Experimental powers versus load resistance for the three types of devices vibrated at 1 g and at its corresponding resonant frequency.

Fig. 5: Experimental power vs resonant frequency of all three types harvesters for accelerations ranging from 0.1g up to 1g.
**Fig. 6:** Experimental powers versus frequency with accelerations from 0.1 to 1 g of C-type devices.

**DISCUSSION**

In Figure 7 the relation between the experimental output power and the dynamic electromechanical coupling coefficient $k^2$ is reported. It should be borne in mind that this is not the coefficient of the piezoelectric material itself $k_{11}$. This $k^2$ coefficient qualifies and takes into account the overall structure behavior, therefore it varies depending on the topology of the structure and also the quality of the bonding interface between the PZT part and the plastic foil. Hence the output power is determined to be power law dependent on this coefficient. In spite of the moderate output power of these test structures, the proof of concept for transferring thick PZT pieces on flexible substrate is hereby validated. Indeed optimization is still possible. Few devices with bigger mass volume (119.3 mg of stainless steel) have shown to be able to generate power up to 15μW (at 75Hz) as reported in Figure 7. In this case if we calculated the volume figure of merit $FoM_v$ proposed by Mitcheson et al. in [14, 15] we obtained a $FoM_v$ of 2%. Or if we use the definition of the bandwidth figure of merit $FoM_{bw}$ [14, 15], we obtained a value of 10.88 (mW.Hz/cm$^2$/g$^2$), which becomes very interesting and favorably comparable and competitive to other state-of-art devices reported in the literature [10].

**Fig. 7:** Experimental power versus the dynamic coupling coefficient $k^2$ (at 1 g).

**CONCLUSION**

This communication presented simulations and experimental results of planar piezoelectric harvester made on a plastic sheet. A new lamination process for transferring PZT sheet on flexible substrate has been successfully demonstrated. The results show that this technology has a great potential for large scale easy implementable power-generation surfaces for vibration-energy harvesting due to the low cost and low complexity of the process. However the reliability of those structures i.e. the stability over time is still under investigation. The outlook for further improvement for this technology is to design a structure with a higher $k^2$ coefficient, which will allow an increase in the output power.

**REFERENCES**