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High-performance energy harvester fabricated with aerosol deposited PMN-PT material

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Abstract. This paper reports a high-performance piezoelectric energy harvester (EH) fabricated with xPb(Mg₁/₃Nb₂/₃)−(1−x)PbTiO₃ (PMN-PT) by aerosol deposition method. The result indicates that PMN-PT based EH owns 1.8 times output power which is higher than traditional PbZrₓTi₁₋ₓO₃ (PZT) based EH. In order to compare the output performance of EH fabricated with PMN-PT compared with PZT, the similar thickness of PMN-PT and PZT thin film is deposited on stainless steel subtracted. The experimental results show that PZT-based EH had a maximum output power of 4.65 µW with 1.11 V_p-p output voltage excited at 94.4 Hz under 0.5g base excitation, while the PMN-PT based device has a maximum output power of 8.42 µW with 1.49 V_p-p output voltage at a vibration frequency of 94.8 Hz and the same base excitation level. The volumetric power density was 82.95 µW/mm³ and 48.05 µW/mm³ for the device based on PMN-PT and PZT materials, respectively. All the results demonstrate that PMN-PT has better output performance than PZT.

1. Introduction

In past years, researchers keep trying to improve the output performance of EH from the optimization of the design of device and the improvement of process. The performance of EH power output has gradually reached the limit of the chosen materials. In our previous research results [1,2], the significant increase of the power output and the improvements of durability were achieved by the change of the EH substrate material. In this study, we tried to improve the overall EH performance by replacing PZT with PMN-PT which has better piezoelectric performance. In several investigations, PMN-PT exhibits high piezoelectric coefficient and electromechanical coupling factor compared with PZT. However, there are still very few studies related to PMN-PT based EH [3,4]. Therefore, this study focuses on introducing PMN-PT material as the active material. And PMN-PT are deposited on stainless steel substrate with aerosol deposition method with the same design and fabrication process as the PZT that we have done before. The comparison of output performance of the devices which is based on two different piezoelectric materials will be completely analyzed.
2. Device Fabrication Process

Figure 1 shows a schematic illustration of the piezoelectric energy harvester device. Based on microelectromechanical systems (MEMS) fabrication process [5], the lithography and etching are processed as the flow chart shown in Figure 2.

For better mechanical ductile property [6], 301 stainless steel is chosen as the substrate for device fabrication and the metal substrate also acted as the bottom electrode of the fabricate EH device. The fabrication process steps are described as follows. First of all, metallic oxide and organic residues on the surface of substrate are removed with acid solution. After the cleaning process, a piezoelectric layer is then deposited onto the stainless steel substrate using the aerosol deposition method [7]. The schematic diagram of aerosol deposition equipment is shown in Fig. 3. In order to compare the output performance of the piezoelectric EH based on different materials, PMN-PT and PZT with the thickness of 2.8 um are both deposited on stainless steel substrates. THB-151N photoresist is used for patterning the piezoelectric layer with lift-off process which is shown in Fig 2(c). After patterning the piezoelectric layer, an annealing process with 600 ºC is then applied. The upper electrode is then deposited with a 20 nm titanium and 200 nm platinum onto the piezoelectric layer by using E-gun evaporation. Lift-off process is again adopted for patterning the electrode shapes. The beam shape is defined and release with wet etching by using aqua regia. Afterwards, thin epoxy layer is applied on the upper electrode as the protective layer shown in Fig. 2(f). Finally, a tungsten proof mass is glued on the beam tip with epoxy. The tungsten material is selected here because of high density so as to increase the power output at low base excitation level and lower the resonance frequency (Fig. 2(g)).
3. Experimental Setup

Fig. 4 shows a schematic diagram of experimental setup for measuring EH output performance. In order to compare the output performance between PZT and PMN-PT based EH, the thickness of film is analyzed by Probe-Type Surface Analyzer. Then, both EH were mounted on the shaker which was driven by a function generator through a power amplifier to simulation ambient vibration sources with different frequency and amplitude. An accelerometer (B&K Type 4381) is mounted on the shaker with the piezoelectric EH to measure the base excitation acceleration level. The output signal of the device is connected to different load resistance in order to investigate the output characteristic. However, the corresponding output average powers are calculated using the following equation,

\[
P = \frac{(V_{pp} / 2\sqrt{2})^2}{R}
\]

, where \( V_{pp} \) is the peak-to-peak output voltage, and \( R \) is the load resistance.
4. Results and Discussion

Fig. 5(a)(b) shows the peak to peak voltage ($V_{pp}$) versus the vibration frequency under an open circuit condition at different base excitation acceleration levels. The resonant frequency increases when excited acceleration increases. The resonance frequency of the $d_{31}$ mode PZT based EH shifts significantly from 93.4 Hz to 94.4 Hz under 0.3 g to 0.5 g base excitation acceleration levels. Due to the similarity of dimension, thickness and mechanical properties of two piezoelectric layer materials, the resonant frequency of PMN-PT based EH is very close to PZT based EH. From the experiment, we found out the resonant frequency shifts from 93.6 Hz to 94.8 Hz. The results indicate that the PMN-PT based EH output voltage under an open circuit condition is greater than PZT based EH.

![Figure 5](image)

Figure 5. (a) PZT (b) PMN-PT device output voltage vs. frequency under the open circuit condition at 0.3 g to 0.5 g.

In order to measure the output power from EH, the devices are connected to resistors with different resistance values in series. Therefore, the output power could be calculated by equation (1). Fig. 6(a)(b) shows the comparison of PZT and PMN-PT based EH output performance. When both excited at a 0.5 g acceleration level, the PMN-PT based EH could provide 8.42 µW output power which is significantly greater than the PZT based EH with 4.65 µW output power.

![Figure 6](image)

Figure 6. (a) PZT (b) PMN-PT device electrical output vs. load impedance at 0.5 g acceleration.
Table 1. Dimension and Properties of PZT and PMN-PT device

<table>
<thead>
<tr>
<th>Material</th>
<th>PZT</th>
<th>0.6PMN-0.4PT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness (μm)</td>
<td>2.67</td>
<td>2.81</td>
</tr>
<tr>
<td>Resonant Frequency (Hz)</td>
<td>94.4</td>
<td>94.8</td>
</tr>
<tr>
<td>$\varepsilon_r$ (@ 1 kHz)</td>
<td>455.08</td>
<td>413.69</td>
</tr>
<tr>
<td>$d_{33}$ (pC/N)</td>
<td>13.5</td>
<td>18.5</td>
</tr>
<tr>
<td>FOM ($10^{-24}$ C/N²)</td>
<td>0.400(1)</td>
<td>0.8273(2.065)</td>
</tr>
<tr>
<td>Voltage (with load) (V_{pp})</td>
<td>1.108 @ 0.5g(1)</td>
<td>1.491 @ 0.5g(1.346)</td>
</tr>
<tr>
<td>Power (with load) (μW)</td>
<td>4.651 @ 0.5g(1)</td>
<td>8.423 @ 0.5g(1.811)</td>
</tr>
<tr>
<td>Power density (μW/mm³)</td>
<td>48.05 @ 0.5g(1)</td>
<td>82.99 @ 0.5g(1.727)</td>
</tr>
</tbody>
</table>

5. Conclusion

We summarized the characteristics of PZT and PMN-PT based EH in Table 1. With the same exact specification; the voltage output, power output and power density of the PMN-PT device excel the PZT device performance. We concluded that the figure of merit (FOM) of PMN-PT material is better than PZT material. When both devices excited under a 0.5 g base excitation acceleration level, PMN-PT based EH shows 1.8 times maximum power output of the PZT based EH. The volumetric power density of PMN-PT based EH is 1.72 times larger than PZT based EH. According to the results, it indicates that PMN-PT based EH exhibits better output performance than PZT based EH.

References

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