Micro Energy Harvester with (K,Na)NbO$_3$/Silicon Composite Cantilevers

Le Van Minh$^1$, Motoaki Hara$^1$, and Hiroki Kuwano$^1$
(Grad. School of Eng., Tohoku University)

1. Introduction

Harvesting the electric power from ambient resources, such as sunlight, wind, heat gradient, vibration and so on, is an promising solution for autonomous sensor systems. Vibration based energy harvester becomes a key technology to maintain a stable power supply to the system [1]. Pb(Zr,Ti)O$_3$ (PZT) based energy harvester is actively researched owing to high piezoelectric constant of the PZT. However, it is unlikely to spread such harvesters into environment since Pb has high toxicity.

In our previous work, (K,Na)NbO$_3$ (KNN) instead of PZT was applied as a piezoelectric material for energy harvester [2]. The KNN turns out not only being an environmental-friendly material but also possessing high power figure of merit (FOM) [3]. The previous device, constructed from a silicon proof mass and four clamped-clamped KNN cantilevers, achieved wide band responses due to high nonlinear characteristics. However, output power was not so high.

In this study, the KNN/silicon (Si) composite structure was applied to the harvester. The device fabrication became simplified and the output power was extremely improved.

2. Design and Fabrication

The previous paper reported the harvester using a quatrefoil proof mass suspended by KNN beams as shown in Fig. 1 [2]. However, we could not obtain the adequate output power from this device since both compressive and tensile strains exist in the bending KNN beam and negate the charge each other.

Si support layer was adopted to enhance the device performance. By using this structure, strain in the KNN was redistributed to avoid the negation effect. For 2-μm thick KNN beam and 2-μm thick KNN/10-μm thick Si composite beam, strain distribution was calculated numerically with commercial FEM simulator (ANSYS). Fig. 2 shows the calculation results when the tip displacement, average strain of piezoelectric element along the electrode position for downward deflection of 50 μm cantilever length, and width were set to 50 μm, 1500 μm, and 500 μm, respectively. The strain shown in Fig. 2 was averaged for the thickness direction. From this result, avoiding negation of the strain was confirmed.

The harvester was fabricated using bulk micromachining technologies for KNN/SOI wafer based on the manufacturing flow disclosed in Ref. 2. At first, bottom electrode, KNN piezoelectric film, and top electrode were deposited on SOI wafer and patterned. Finally, proof mass and beams were fabricated by using the deep reactive ion etching (RIE). The SEM image of the harvester is shown in Fig. 3.

3. Results and Discussion

Figure 4 shows the relationship between output power from each beam and frequency under the input acceleration of 5 m/s$^2$. In this result, the load resistance was optimized to 141 kΩ.
Figure 3 shows the maximum output power and $\Delta f$ as a function of input acceleration. The $\Delta f$ was defined in Ref. 2 and was difference between jump up and down frequency. Also the maximum power of the whole micro-energy harvester was defined four-fold larger than output of each beam.

At the acceleration of 6 m/s$^2$, the maximum power and bandwidth were 2.9 $\mu$W and 195 Hz, respectively. The power density, which is quotient of the maximum power for the device volume, was up to 555 $\mu$W/cm$^3$ that was about 4 times larger than the previous result [2].

Table 1 shows the survey of the state of the art in the piezoelectric MEMS energy harvesters using the clamped-clamped beams. The performance of the micro-energy harvester applying lead-free KNN piezoelectric thin film at low input acceleration can be comparable to that of PZT-based energy harvester.

<table>
<thead>
<tr>
<th>Piezoelectric material</th>
<th>$a_0$ [g]</th>
<th>$P$ [\mu W]</th>
<th>$\Delta f$ [Hz]</th>
<th>PD [\mu W/cm$^3$]</th>
<th>PD×BW [mW/cm$^3$Hz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d_{31}$ KNN (This work)</td>
<td>0.6</td>
<td>2.9</td>
<td>517</td>
<td>555</td>
<td>108.2</td>
</tr>
<tr>
<td>$d_{31}$ KNN [2]</td>
<td>1.5</td>
<td>0.7</td>
<td>412</td>
<td>122</td>
<td>14.6</td>
</tr>
<tr>
<td>$d_{31}$ AIN [4]</td>
<td>2.0</td>
<td>0.1</td>
<td>650</td>
<td>34</td>
<td>8.5</td>
</tr>
</tbody>
</table>

PD = Power Density; BW = Band Width

Acknowledgment

We are grateful to Dr. Fumimasa Horikiri and Dr. Kenji Shibata at Hitachi Cable, Ltd. for their excellent advice and support. A part of this work was performed at micro/nano- machining research and education center, Tohoku University, Japan. This work was conducted under the project “Research of a nano-energy system creation” (No.18GS0203), funded by the Ministry of Education, Culture, Sports, Science and Technology (MEXT).

References

1. S. Roundy et al.: Computer Communications, 26 (2013), 1131