Abstract: This paper presents design optimization for increasing power output of in-plane vibrating electrostatic energy harvesters. With a fixed gap length between charged stripes and counter electrodes, $g$, an optimal degree of parallelization for a unit harvester exists. With a freestanding electret configuration, the maximum performance can be obtained with the optimum ratio of $L/g = 5.84$, where $L$ is the periodicity of parallelized electret stripes.

Keywords: Electret, Design optimization, vibration harvester

INTRODUCTION

There has been a growing interest in environmental energy harvesting, where low density energy sources, such as light, vibration, thermal gradient, etc., are utilized to generate electricity, especially in the field of so-called sensor network societies [1]. In sensor networks, a large quantity of small sensor nodes are distributed, and often communicate with each other, to enhance the quality of the information network. A key example is a health monitoring system for large structures, including buildings and bridges. In such a system, powering each node would be problematic, considering its distributed nature. Using batteries is not practical, since replacing or recharging batteries in each of the distributed sensor nodes is unacceptable due to both economical and environmental concerns. Thus, self-powering sensor nodes is a key technology to achieve a sensor network system.

Vibrations are a ubiquitously available energy source. While numerous research approaches have been dedicated to this area, electrostatic harvesters have some advantages in micro-scale applications, mainly because of greater flexibility via the ability to design mechanical and electrical features separately [2].

Electrets, which can hold electric charge quasi-permanently, are often used in electrostatic energy harvesters. Figure 1 shows the schematic of an electret-based vibration energy harvester. The electret generates an electric field, which induces charges in the surrounding electrodes. Introducing relative movement between the electret and counter-electrodes by utilizing external vibrations causes the amounts of induced charge in the electrodes to change. This charge variation can be converted into electricity by connecting the harvester electrodes to an external circuit with loads. The relative displacement can be either perpendicular or parallel to the surface of the electret, which corresponds to capacitance changes due to gap length or overlapping surface area, respectively. The latter case is further explained in Fig. 2, and often called in-plane type electret harvesters.

There are several strategies to increase the output power of electret-based vibration energy harvesters. The basic idea is simple: increase the induced charges in the work electrodes. The simplest method is to reduce the gap length between electret and counter electrodes [3].

Fig. 1: Schematic of an electret-based vibration energy harvester.

Fig. 2: Operation principles of an in-plane type electrostatic vibration energy harvester.

Fig. 3: Schematic of a parallelized in-plane energy harvester.
In the case of in-plane type harvesters, the use of a freestanding electret film, in which the electret film is removed from its backing plate so that the electric field generated by the electret is efficiently used to induce countercharges in a work electrode rather than in a backing plate, is reported to also enhance output power [4]. In this report, we use this freestanding configuration.

The other approach in in-plane harvesters is parallelization. In MEMS applications, size (volume or mass) is always a consideration, so output power is usually evaluated in power density. In-plane harvesters exploit capacitance change due to variation of overlapping area. Thus, if the effective electret area is too large compared to the area change driven by external vibrations, the vast majority of electret charge does not contribute to countercharge induction. Parallelizing an electret/electrodes unit, as shown in Fig. 3, is often used to increase output power density by effectively utilizing the available area. However, too much parallelization of electret stripes, in other words a striping period \( L \) that is too small compared to \( g \), results in smoothing out the electric field near the counter electrodes. Consequently, given the gap length, there exists an optimum degree of parallelization, or optimum \( L/g \). Similar optimization research has been reported [5], but it dealt with the optimization of harvesters with a unit of one work electrode for one charged stripe, while this study addresses the optimized geometry of a unit of two work electrodes for one charged stripe.

Theoretical analysis predicts that the optimum ratio of \( L/g \) is 5.84 for a freestanding configuration. The details of the theoretical calculation will be reported elsewhere.

**EXPERIMENTAL VERIFICATION**

A macro model was developed to verify the theoretically obtained optimum ratio, as shown in Fig. 4. Since experiments using electret may involve uncertainties in reproducibility, we use voltage-biased metallic electrodes backed by a glass epoxy substrate to simulate a freestanding electret film. Figure 5 shows (a) upper electrodes simulating electret stripes, and (b) work electrodes. \( L \) is fixed at 10 mm throughout the experiments, and \( L/g \) is varied by changing \( g \). Thus, output needs to be evaluated in normalized values: a normalized current in \( I_g^2 \), and a normalized power in \( P^2 g^4 \). The bottom work electrodes were oscillated by a piezoelectric actuator at its resonant frequency of 647 Hz, with an amplitude of 3 µm. Only the middle two out of four output electrodes were connected to an external circuit to ensure that the periodic boundary condition was satisfied.

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**Fig. 4:** Experimental setup of a macro-model to verify the analytical solutions.

**Fig. 5:** Electrodes configurations, (a) upper electrodes simulating freestanding electret stripes, and (b) bottom work electrodes connected to external circuit for measuring output power. A piezoelectric actuator was used to apply external vibration.

**Fig. 6:** Normalized output power for different \( L/g \) ratio.
Figure 6 shows measured normalized output as a function of $L/g$. The dotted line indicates a theoretical prediction. The measured value peaks at $L/g = 7.14$, which is 20% larger than the theoretical value. Reasons for the discrepancy are twofold. In the large $g$ region, which corresponds to a small $L/g$, the actual output was very small, and a deteriorated signal-to-noise ratio ended up with larger error bars in Fig. 6. The other reason is that upper electret-simulated electrodes and bottom electrodes were not perfectly in parallel. This resulted in both smaller $g$ regions and larger $g$ regions than the prescribed value. Since the normalized output power is proportional to $g^4$, output increases due to a smaller $g$ region are more dominant than output decreases due to a larger $g$ region.

Fig. 7: Design of a micromachined device.

**MICRO MODEL PROTOTYPE**

Prototypes of a micromachined device were also fabricated, and consist of two parallel wafers: an electrode wafer containing patterned Al and an electret wafer with patterned CYTOP, as shown in Fig. 7. Electrode wafers were fabricated via deposition of Al ($\sim 225$nm) onto glass wafers and patterning of the Al using photolithography, with wet-etching (NMD-3) of the Al / exposed photoresist (OFPR-800). The fabrication process for the CYTOP wafers is depicted in Fig. 8. First, CYTOP was spin-coated on silicon wafers up to $\sim 8 \mu m$. Then, patterning of the CYTOP was performed using photolithography (development of Al masks) / plasma-etching ($O_2$) of the CYTOP. Finally, positive ions were implanted in the CYTOP using corona discharge to complete the electret wafer fabrication.

The device size was $20 \, \text{mm} \times 20 \, \text{mm}$. We examined four different configurations for $L$ as summarized in Table 1.

The device was oscillated with a shaker, as shown in Fig. 9. The external vibration applied was sinusoidal wave of $2 \, \text{mm}$ peak-to-peak at $75\, \text{Hz}$. Output power was measured on a $1 \, \text{M} \Omega$ external load. Red lines in Fig. 10 show measured output for three different gap lengths, 0.2, 0.3, and 0.6 mm. In contrast to the macro model experiments shown in Fig. 6, $L/g$ values were varied by changing $L$ as shown in Table 1.

In this case, the measured power does not peak at the predicted value of $L/g$ of 5.84, and rather shows monotonous increase with increasing $L/g$. This result can be attributed to non-uniform surface potential for different wafers. Table 1 shows surface potentials for each wafer with different $L$, measured at $0.5 \, \text{mm}$ above the surface. Although, available surface area for charge implantation is same for all four patterned wafers, the measured surface potential decreased with decreasing $L$. The reason for this is not clear, though increasing corners and side edges on striped electret surfaces is likely to reduce implanted charges when corona discharge conditions are the same. Genda et al. [6] reported that micropatterned electrets show lower surface potential and lower charge stability with smaller striped patterns. They developed a new technique using contact elec-

Fig. 8: Process chart for electret wafer fabrication.

Fig. 9: Experimental setup of a micro-scale device.
<table>
<thead>
<tr>
<th>L (mm)</th>
<th>Surface Potential (V)</th>
<th>% of Max. Potential</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>7.29</td>
<td>2.49</td>
</tr>
<tr>
<td>1.0</td>
<td>9.27</td>
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<td>2.0</td>
<td>20.6</td>
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<td>4.0</td>
<td>65.7</td>
<td>22.4</td>
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<tr>
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<td>293</td>
<td>100</td>
</tr>
</tbody>
</table>

CONCLUSION

We present an optimized geometry for electret based in-plane vibration harvesters. The theoretical calculation predicts the optimum value of $L/g = 5.84$ for a free-standing electret configuration. A series of experiments using both macro and micro scale devices verified the theoretical prediction. It is also shown that, however, $L$ optimization is valid when other parameters, such as $g$ and surface potential, are fixed. Thus, as a design strategy, $L/g$ optimization should be considered in conjunction with other design optimizations.

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REFERENCES


