Low-cost Out-of-plane Vibrational Electret Energy Harvester

Y.C. Lee and Y. Chiu*
Dept. of Electrical Engineering, National Chiao Tung University, Hsin Chu, Taiwan, R.O.C.
*Presenting Author: yichiu@mail.nctu.edu.tw

Abstract: This paper reports the design, fabrication, and testing of an out-of-plane electret energy harvester. The energy harvester was fabricated without photolithography to reduce the production cost. The measured output power was 67.4 µW at 190Hz with 2g acceleration. The material of electret was SiO₂/Si₃N₄ double layers. The measured surface charge density was 13.6 mC/cm², which could be improved by multiple corona charging cycles.

Keywords: electret, energy harvesting, vibration

INTRODUCTION

Low power CMOS VLSI technology has enabled the development of applications such as wireless sensor networks or personal health monitoring. In these applications, lifetime and maintenance of the power supply are critical. Recently, energy scavenging from ambient natural sources, such as vibration and ambient heat, is attracting much interest as self-sustainable power sources. Among various approaches, electrostatic vibration-to-electricity conversion is promising due to its compatibility to IC processes and the ubiquity of vibration source in nature. The bias sources in electrostatic energy harvesters include batteries, initial charge, work function difference, and electret. Electret is a dielectric with quasi-permanent charge; therefore, it can be used as a self-sustaining bias source for electrostatic power generation. In recent years, there have been many research activities on electrostatic energy harvesters using electret [1-7].

Conventionally, fluorinated polymer electrets, such as PTFE and FEP, have been used as the electret materials. In recent years, more materials have been found for electret applications, including CYTOP [2], Teflon AF [3], Parylene HT⃝ [4], and SiO₂/Si₃N₄ double layer [5]. SiO₂/Si₃N₄ double layer has the advantage of IC process compatibility and high dielectric strength; its thickness can be accurately controlled by the deposition process. Therefore, the SiO₂/Si₃N₄ double layer is used in the energy harvester in this paper.

Most of the reported electret harvesters have in-plane motion and microfabricated inter-digit electrodes. We propose in this paper a simpler fabrication process by stacking structural layers for an out-of-plane electret harvester to reduce the fabrication cost.

PRINCIPLE AND ANALYSIS

The operation of the electret energy harvester is shown in Fig. 1. The circuit is composed of a bias charge \( \sigma \) which is supported by the electret, a vibration-driven variable capacitor \( C_v \) and an external load \( R_L \). The movable electrode causes capacitance change and variation of the induced charge on the electrodes. It leads to an AC current flowing through the external load resistor.

CORONA DISCHARGING

In this research, the SiO₂/Si₃N₄ double layer was charged by corona discharging [8]. The thickness of the double layer was 1 µm and 50 nm, respectively; SiO₂ was first deposited on the silicon wafer, then Si₃N₄ was deposited on SiO₂ by PECVD.

The corona discharge setup is shown in Fig. 2. Negative voltage is applied to the needle electrode and grid electrode, and the back electrode is connected to ground. The sample is placed on a hot plate to maintain specific temperature conditions during the charging. When the voltage at the needle tip exceeds a threshold, the high electric field causes electric breakdown of the air. The negative charge in the ionized air around the needle tip will then be accelerated by the electric field and deposits on the electret surface.
The discharge experiment was conducted in atmospheric environment. The gap between the needle tip and grid electrode was 8 mm; the distance between the grid electrode and back electrode was 4 mm; and the hot plate was set to 80°C. The sample was prebaked on the hot plate for 30 minutes before the charging process; the charging time was 30 minutes. In our research, higher needle voltage did not improve charge density significantly in the SiO₂/Si₃N₄ double layer; therefore the range of the needle voltage was from -4 kV to -5 kV. The surface charge density was measured by an electrostatic voltmeter (Monroe Electronics Model 279). The baking and charging cycles were repeated multiple times to improve the charge stability [9]. Fig. 3 shows the improved charge stability under various corona discharge conditions due to the additional charging cycles.

In Fig. 4, the sample was charged with a needle voltage of -4.5 kV and a grid voltage of -500 V. The current through the needle electrode and the grid electrode were 16 µA and 6 µA, respectively. The charge cycle is 2 to improve the charge stability, the surface potential was measured once per day after charging.

**MODELING AND SIMULATION**

Fig. 5 shows a simplified model of the electret energy harvester, where g, d, σ are initial gap distance between the electret and the movable electrode, thickness of the electret film, and surface charge density, respectively. The external load is assumed as a pure resistance R.

From conservation of charge,
\[ \sigma = \sigma_1 + \sigma_2, \]  
where \( \sigma \) is the charge density on the electret surface, \( \sigma_1 \) is the induced charge density on the movable electrode, and \( \sigma_2 \) is the induced charge density on the fixed electrode. From Gauss’s law, the boundary condition at the charge layer can be written as
\[ -\varepsilon_0 E_a + \varepsilon_0 E_b = \sigma, \]  
where \( E_a \), \( E_b \), and \( \varepsilon \) are the electric field in the air gap, electric field in the electret layer, and relative permittivity of the electret material, respectively. With Kirchhoff’s law, one can write the following equation,
\[ V + dE_b + gE_a = 0, \]  
where \( V \) is the output voltage on the resistor. Assume there is no current through the resistor \( i = 0 \), then
\[ dE_b + gE_a = 0. \]

From Eq’s (1), (2) and (4), the initial charge density on the electrodes are
\[ \sigma_1 = \frac{\sigma}{1 + \varepsilon g / d}, \]  
\[ \sigma_2 = \frac{\sigma}{1 + d / \varepsilon g}. \]

Therefore, the current \( I \) through the resistor can be calculated from the following expression,
\[ I(t) = \frac{-dQ_1(t)}{dt} = \left( \frac{Q_c(t)}{C_g(t)} - \frac{Q_c(t)}{C_e} \right) \frac{1}{R}, \]  
where \( Q(t) \) is the charge on the movable and fixed electrode, and \( C_g(t) \) and \( C_e \) are the capacitance between the charge layer and the movable electrode and capacitance between the charge layer and fixed electrode, respectively. Eq. (6) can be rewritten as
\[ \frac{Q_c(t)}{RC_g} + \frac{Q_c(t)}{RC_{eq}(t)} = \frac{dQ_1(t)}{dt}, \]
where \( C_{eq}(t) \) is the effective capacitance between the movable electrode and the fixed electrode.

The motion of the harvesting device can be described by the equation,
\[ m\ddot{x} + b\dot{x} + kx = -m\ddot{y} + F_e, \]  
where the electrostatic force \( F_e \) is a function of the electric charge \( Q_c(t) \) on the movable electrode according to

![Fig. 5 Simplified model of the electret harvester](image-url)
\[
F_e = \frac{Q(t)}{2\varepsilon_0 A},
\]
where \(A\) is the area of the capacitance.

Therefore, the output power can be calculated by Eqs. (7) and (8). The simulation of output power was conducted by using Simulink. The simulation condition is listed at Table 1. The input vibration is 2.25 m/s\(^2\) at 120 Hz, measured from an air purifier. Two design parameters, the initial gap and the external load, were used to find the optimized condition for maximum power. Fig. 6 shows the output power for the initial gap from 100 µm to 600 µm, and the external load from 500 MΩ to 1.5 GΩ. The optimization result is listed in Table 2. The energy harvester can generate a maximum power of 14.23 µW for the load of 800 MΩ.

### Table 1 Parameters of simulation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input acceleration</td>
<td>2.25 m/s(^2)</td>
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<tr>
<td>Vibration frequency</td>
<td>120 Hz</td>
</tr>
<tr>
<td>Spring constant</td>
<td>153.75 N/m</td>
</tr>
<tr>
<td>Mass</td>
<td>0.268 g</td>
</tr>
<tr>
<td>Area of mass</td>
<td>10 mm × 10 mm</td>
</tr>
<tr>
<td>Surface charge density</td>
<td>13.6 mC/cm(^2)</td>
</tr>
<tr>
<td>Thickness of electret</td>
<td>1 µm</td>
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<tr>
<td>Quality factor</td>
<td>35</td>
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</tbody>
</table>

### Table 2 Simulation result

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optimized initial gap</td>
<td>250 µm</td>
</tr>
<tr>
<td>Optimized external load</td>
<td>800 MΩ</td>
</tr>
<tr>
<td>Maximum output power</td>
<td>14.23 µW</td>
</tr>
</tbody>
</table>

### FABRICATION

The proposed fabrication process is shown in Fig. 7. In Fig. 7(a), 1-µm-thick SiO\(_2\) and 50-nm-thick Si\(_3\)N\(_4\) layers were sequentially deposited on a 4" silicon wafer by PECVD. Next in Fig. 7(b), a spacer layer with thickness of 250 µm was bonded onto the silicon wafer. Then the sample was placed in the corona discharging setup to charge the SiO\(_2\)/Si\(_3\)N\(_4\) double layer. The prebake time was 30 min at 80 ºC, the charging time was 30 min. To improve the charge stability, the charging cycle was repeated twice. In Fig. 7(c), a copper top electrode was prepared by stacking two copper plates together. The larger plate had an area of \(1 \times 4 \text{ cm}^2\) and thickness of 50 µm; the smaller plate had an area of \(1 \times 1 \text{ cm}^2\) and thickness of 300 µm. They were cut from standard copper sheets and served as the spring and mass, respectively. Finally in Fig. 7(d), the copper electrode and the charged electret sample were bonded together. Fig. 8 shows the prototype harvester thus fabricated.

### POWER GENERATION EXPERIMENT

Fig. 9 shows the power generation experiment. The harvester was fixed on an electromagnetic shaker and tested in the out-of-plane direction with an external load of 800 MΩ. The input acceleration was 2g, and the vibration frequency was scanned to find the maximum output voltage.

The output voltage was measured from a small resistor of 1 MΩ in series with load resistor of 800 MΩ. The voltage drop on the small resistor is shown in the Fig 10 and the maximum output power on the load...
resistor can be calculated as 67.4 µW at 190 Hz. Fig. 11 shows the frequency response of the output power. The resonance frequency is 190 Hz, which is different from our design of 120 Hz due to different bonding conditions.

![Fig. 9 Measurement setup](image)

![Fig. 10 Time trace of measured voltage at resonance frequency 190 Hz](image)

![Fig. 11 Frequency response for the electret harvester](image)

**CONCLUSION**

This paper presents the design, fabrication and measurement of an out-of-plane electret energy harvester. The mathematical model was transformed into a Simulink model. The optimum design of initial gap and external load was found. The experiment showed the electret energy harvester generated a maximum output power of 67.4 µW with a 2g acceleration at the vibration frequency of 190 Hz for an external load of 800 MΩ. The experimental result is different from our simulation due to the difference in the bonding conditions and the initial gap. The electret charging result of the SiO₂/Si₃N₄ double layer is also presented. The charge stability can be improved by multiple charging cycles.

This project was supported in part by the National Science Council, Taiwan, R.O.C., under contract no. NSC 98-2220-E-009-040. The authors were grateful to the use of facilities at the National Center for High-performance Computing and the National Nano Device Laboratory, Taiwan, R.O.C..

**REFERENCE**


