Improvement of effectiveness and output of electret energy harvester by symmetric comb-drive structures

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Abstract. In this paper, we experimentally demonstrate a new method to improve the effectiveness of energy harvester that is based on solid-state electret. A symmetric three-ports electrostatic comb-electrode mechanism is used to reduce the binding electrostatic force that constraints the movable electrodes, thereby allowing a formation of a higher electret potential without electrostatic collapse. Two energy harvesters having different electret potentials are prepared to compare the harvester effectiveness and the electrical damping. The harvester effectiveness is increased by 4 times by increasing the electret potential from the -60 V to -250 V. At the same time, the electrical quality factor is also decreased from 700 to 500. Therefore, this new mechanism provides the energy-harvesting device for a wireless sensor node which can compatibly be made compact and can generate large output.

1. Introduction

Energy harvester is a vital component for Internet-of-Things (IoT) applications [1] that must operate without batteries to be free from frequent replacement. Amongst various harvesters, vibration type is thought to be a most potential for powering wireless sensor nodes that are deployed in various areas such as monitoring system for social infrastructures, where further of miniaturization and high power are needed to drive wireless sensor nodes. Amongst various principles, electret-based energy harvester can effectively convert the ambient vibrational energy owing to the flexibility in MEMS design to adapt to the environmental frequency range. Use of a large stroke of a moving mass and improvement of conversion effectiveness are a straightforward method to increase the output power [2, 3]. In general, the output power of the electret-based energy harvester increases by increasing the electrical damping [4]. However, electrostatic constraint force also increases with increasing the electret density, resulting in small mechanical amplitude of the moving mass in a small acceleration range [5].

To solve this problem, we newly introduce a symmetric electrodes layout that cancels the binding electrostatic force despite a high-density electret. At the same time, the output current under low acceleration condition is increased [6] owing to the large force factor. In this paper, we experimentally demonstrate the improvement of the harvester effectiveness by adopting a three-port comb-electrode mechanism. Performance is studied on two different electret potentials to compare the harvester effectiveness and the electrical damping.
2. Design and fabrication

When the vibrational energy harvester operates at resonance, generating power is given by [7, 8]

\[ P_{\text{rms}} = \frac{1}{4} m \omega^3 X_{\text{lim}} y E_H, \]  

(1)

where \( m \) and \( \omega \) are the mass and the resonance angular frequency of the movable electrode, respectively. Variables \( y \) and \( X_{\text{lim}} \) are the oscillation displacements of the movable electrode and the chip, respectively, and \( E_H \) is the energy conversion efficiency defined by

\[ E_H = \frac{1}{1 + \frac{Q_e}{Q_m}} \]  

(2)

which depends on the mechanical \( Q_m \) and electrical \( Q_e \)-factors [7].

The harvester effectiveness is increased because the electrical Q-factor is also reduced with the increase of the electret potential [4]. At the same time, large displacement of the oscillator mass is required to convert kinetic energy into high electrical power.

Figure 1 shows the schematic structure of the energy harvester based on the symmetric three-ports mechanism to cancel the electrostatic binding force. The electret formed by potassium doping is deployed on the comb fingers [9], while the moving shuttle is electrically grounded. Figure 2(a) shows a developed energy harvester. Scanning electron microscope (SEM) images are shown in Fig. 2(b) and (c).

Table 1 shows measured displacements of the moving shuttle. Total 900 pairs of comb-fingers are made in a 100-\( \mu \)m thick SOI, and finished with the electrets charged at -60 V and -250 V with respect to the moving shuttle [6]. The suspensions are designed at a resonant frequency of 125 Hz. Maximum displacements are almost equal, 347 \( \mu \)m and 348 \( \mu \)m for the electrets of -60 V and -250 V, respectively, thereby the design of the mechanical and electrical damping is independently performed by the symmetric structure.

![Figure 1](image1)

![Figure 2](image2)

Figure 1. (a) Schematic structure of the electrostatic energy harvester based on the three-ports comb electrode mechanism. (b) Schematic picture of the electret formed on the side wall of comb fingers. (c) The relationship between the mechanical operation and the inductive charge in the electret-based energy harvester.
Figure 2. (a) Developed energy harvester composed of the three-ports comb-electrode mechanism. (b) SEM image of the electrode layout, and (c) close-up view of the comb electrodes.

Table 1. Experimentally observed displacement of the energy harvesters prepared with two different electret potentials.

| Electret Potential (V) | Maximum Displacement (µm) |
|------------------------|---------------------------|
| -60                    | 346.8                     |
| -250                   | 347.5                     |

3. Experimental results
The developed energy harvesters were put on the vibration-testing equipment and mechanically shaken at a constant acceleration and oscillation stroke. At the same time, the oscillation displacement of the moving electrode was measured by the high-speed camera.

Figure 3(a) shows the experimental setup to measure the output power by using the induction current when the device is shaken. Figure 3(b) is the harvester effectiveness as a function of the load resistance. The moving mass was operated at the maximum operating condition. Maximum effectivenesses at the resonance were 23% and 86% for the electret potentials of -60 V and -250 V, respectively. From this measurement, use of the higher electret potential effectively improves the harvester effectiveness in a small acceleration range. Figure 3(c) shows the experimentally obtained displacement of the moving mass as a function of the load resistance. The input displacement of 0.1 µm is used to keep the oscillator mass at a constant amplitude at resonance. Depression of stroke was 10 µm and 36 µm for the electret potentials of -60 V and -250 V, respectively. The electrical Q-factor was also decreased from 700 to 500 by increasing the electret potential value.
Figure 3. (a) Harvester effectiveness of the electrodes charged at -60 V and -250 V with respect to the moving mass. (b) Harvester Effectiveness as a function of the load resistance at the maximum operating condition in resonance. (c) Measured stroke of the moving shuttle as a function of the load resistance under the input displacement of 0.1 µm in resonance.

4. Conclusions
In conclusion, a symmetric comb-electrode structure was found to have improved the electret potential while maintaining the stable mechanical operation of the energy harvester. A use of higher electret potential was also found to increase the electrical damping, which also increases the power converted into electrical output. Therefore, maximum output power was further increased by using higher acceleration for input.

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