Performance enhancement of an out-of-plane electret-based vibrational energy harvester with dual charged plates

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Abstract. This paper presents a novel out-of-plane electret-based vibrational power generator (EVPG) that has both negative and positive charged electret plates integrated into a single seismic mass system. Compared with the conventional single-charged two-plate configuration, the proposed device not only exhibits an enhanced output voltage magnitude but also has a wide operational bandwidth due to spring softening nonlinearity according to the experimental analysis. With the acceleration changes from 0.1g to 0.5g, the operating 3-dB bandwidth can be increased 2.6 times from 2.5 Hz to 6.5 Hz, which indicates higher energy conversion efficiency than a linear energy harvester in the practical scenario of broadband random vibrations.

1. Introduction

In recent years, the energy harvesting devices draw a lot of attention as a promising power source for wireless sensor networks (WSNs), which are attractive in many potential fields, such as healthcare, infrastructure and transportation intelligent monitoring[1, 2]. Such energy harvesting technology could offer viable solutions to the maintenance and replacement of battery in WSN to meet the vast and impending demand. Mechanical vibration sources are ubiquitous and readily available in the ambient environment. Several techniques have been proposed in the past decade to perform the electromechanical energy conversion such as piezoelectric, electromagnetic and electrostatic methods. Among these, the electrostatic/electret energy harvesting systems have the advantages both of compatibility with silicon CMOS processes and miniature size [3-5].

A conventional type EVPG generally has a laterally movable seismic mass integrated with parallel interdigital electrodes and stripe-patterned electret [4, 6]. The electret films are normally designed with tens or hundreds of micros to be compatible with the small movement of the spring-mass system. They are first micro-patterned, etched and then charged. However, these processes may harm the performance and charge stability of the electret films [7, 8]. The existence of strong fringe effect caused by small-dimension electret stripes also plays an important role in limiting the change of overall capacitance change[9]. Furthermore, the harvesters can only perform optimally when the two electrodes are precisely aligned with each other; slight misalignment may severely deteriorate the performance of the EVPG[10].
In this paper, a new EVPG with an out-of-plane gap closing scheme is proposed, where both negative and positive charged electret plates are integrated into a single spring-mass system. Since the capacitance change of the proposed EVPG mainly relies on the variation of air gap between the two electrodes, micro-patterning of the electret thin film and precise alignment are not required. Figure 1 shows the schematic diagram of the new concept with dual charged plates compared with the conventional out-of-plane gap closing EVPG. By introducing another positive charged electret plate, the increased electric field between the counter and base electrodes not only leads to an enhanced output voltage magnitude but also gives rise to a stronger nonlinear effect of the spring-mass system. These aspects will be further investigated in the ensuing sections.

![Figure 1. Schematic diagram of the new concept compared with the conventional two-plate out-of-plane gap closing EVPG](image1)

2. Device design and fabrication

Figure 2 shows the schematic structure of the EVPG that seeks to harvest kinetic energy with an out-of-plane gap closing scheme. It consists mainly of two parallel-silicon plates. The top plate composes of a movable spring-mass structure with gold electrodes on it. The seismic mass with a height of 300 µm and a diameter of 6 mm is suspended by three sets of spiral springs. Each spiral beam is with a height of 300 µm and a width of 50 µm at a beam spacing of 250 µm. The electrets mounted on top and bottom plates can be charged and used as a positive/negative permanent voltage source. When the mass with top electrode is driven by an external vibration, the air gap between the electrode and electret would change, causing a variation of the capacitance and thus generating an alternating current in the external circuit.

![Figure 2. 3-D schematic view of the proposed out-of-plane EVPG with dual charged electret plates](image2)

The presented out-of-plane micro EVPG is fabricated using MEMS micromachining technique based on silicon substrate. The surface of the silicon is deposited with 1 µm SiO₂ as an insulation layer by plasma-enhanced chemical vapour deposition (PECVD). The fabrication of spring-mass structure adopts a two-mask process. The electrode is fabricated through a lift-off process with an adhesive film of reactive metal Cr of 50 nm followed by a 300 nm metallic film of non-reactive metal Au. An Al thin film with 600 nm thickness is sputtered on the backside of the top plate that facilitates heat dissipation.
dispassion. Then the wafer is bonded with a carrier wafer by a 5 µm thick thermal grease. Reactive-ion etching (RIE) and deep reactive-ion etching (DRIE) are used to remove the exposed SiO$_2$ and Si layer to define the geometry of the spring-mass structure, respectively. A commercial-grade film of LDPE (GOODFELLOW, USA) thin film with a thickness of 15 µm is used as electrets in the prototype fabrication. The electret thin film is mounted on both the top and the bottom electrodes and then charged with a surface potential of 800V and -800V by the corona charging, respectively, which can serve as a constant voltage bias. After all the components are prepared, the EVPG prototype is finally constructed by assembling the top spring-mass plates and the bottom plates with charged electrets by a flip-chip package. Figure 3 shows optical photograph of an assemble out-of-plane EVPG prototype and a fabricated spring-mass structure. The overall size of the prototype is only about 10×12×1 mm$^3$.

3. Power generation characterization
The fabricated EVPG prototype is characterized using the experimental setup as shown in Figure 4. It mainly consists of a shaker, an accelerometer, a power amplifier, a function generator, and a data acquisition system. The prototype is attached to a linear piezoelectric shaker that mimics the external ambient excitations. The harmonic excitation signal is created by the function generator, adjusted by the power amplifier and finally fed to the piezoelectric shaker. The motion of the central seismic mass is captured by a high speed camera. An acceleration sensor is fixed on the base of the holder to monitor the excitation acceleration. A data acquisition system (DAQ NI USB-6289 M series) is utilized to record the electrical output of the prototype.

Figure 3. Optical photographs of an assemble out-of-plane EVPG prototype and a fabricated spring-mass structure

Figure 4. Block diagram of the experiment setup
During the experiment, the characterizations are carried out with excitation frequencies manually swept from 60 Hz to 90 Hz at different acceleration levels from 0.1g to 0.9 g having a load resistance of 50 MΩ. The testing is performed twice before and after the top electrode is positively charged. Figure 5 shows the comparison of output voltage responses with different excitation accelerations for dual-charged and single-charged electret plates with a load resistance of 50MΩ. It is found that the output voltage amplitudes increased from 0.35V to 1.92V for single-charged type and from 0.62V to 3.5V for dual-charged type when accelerations increase from 0.1g to 0.9g. The voltage magnitudes in both types are almost proportional to the excitation accelerations, while the increase rate of the dual-charged type is almost twice than that of single-charged plate and has a much larger magnitudes. This phenomenon also accompanies with a stronger spring softening phenomenon occurred in dual-charged type that the resonant frequencies shift from 77.9 Hz at the acceleration of 0.1g to 73.4 Hz when the acceleration increased to 0.8g in an frequency-up sweep process.

This phenomenon is further investigated and illustrated in Figure 6, which shows the frequency responses with excitation accelerations increased from 0.3g to 0.5g. The frequency-up and frequency-down curves at the accelerations of 0.3g, 0.4g and 0.5g are recorded as shown in Figure 6(a), (b) and (c), respectively. The 3-dB bandwidth has been increased from 2.6 Hz to 6.5 Hz when the acceleration increases form 0.1g to 0.5g due to the spring nonlinearity caused by the electret/electrostatic force. This indicates that this type of EVPG can be further exploited for scavenging low-level ambient energy from broadband random vibrations.

Figure 5. Comparisons of the output voltages with different excitation accelerations for dual-charged and single-charged electret plates in the frequency-up sweeps

Figure 6. Measured frequency responses of the output voltage in up and down frequency sweeps at different excitation acceleration levels: (a) 0.3g; (b) 0.4g; (c) 0.5g
5. Conclusion
In this paper, a novel out-of-plane MEMS EVPG with dual-charged electret plates is designed, fabricated and tested. By the merit of this configuration, the proposed device not only exhibits an enhanced output voltage magnitude but also has a wide operational bandwidth due to spring softening nonlinearity induced by electret/electrostatic force. Spring softening nonlinearity and wide band frequency response were also investigated, where the spring softening effect was observed to be stronger with increase in the acceleration levels.

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