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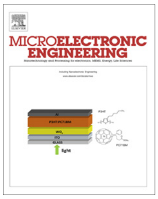

Design and implementation of an out-of-plane electrostatic vibration energy harvester with dual-charged electret plates

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ABSTRACT

This paper presents the design, simulation and implementation of an out-of-plane electrostatic power generator with dual-charged electret plates for low-level ambient kinetic energy harvesting. The rotational symmetrical resonator includes one movable disk-shaped circular mass and a series of spiral springs for suspension. The whole device is fabricated by CMOS compatible silicon micromachining technology with an overall volume of about 0.12 cm^3. The two-plate device has both positive and negative charged electret plates. Experimental analysis shows that the present prototype is able to achieve an output power of 0.34 μW at a low resonance of 66 Hz at 0.5*g*, which corresponds to a normalized power density of 11.67 $\mu\mathrm{W\,cm}^{-3}\,g^{-2}$. With an acceleration changing from 0.1 to 0.5*g*, it is observed the operating half-power bandwidth increases by 2.6 times from 2.5 to 6.5 Hz. This may be attributed to the spring softening nonlinearity induced by the strong electrostatic force. The results could potentially provide an intriguing design methodology for developing nonlinear MEMS devices for broadband random energy harvesting.

1. Introduction

Energy harvesters from ambient natural sources, such as environmental vibrations and ambient heat, have generated great interest amongst both scientific and industrial communities in past decade. Such harvesters may pave the primary step forward to actualizing of self-autonomous devices and performing of intelligent monitoring activities [1–3]. Typical vibration-based energy harvesters normally make use of either electromagnetic [4], piezoelectric [5,6], or electrostatic transduction mechanism [7]. Among these, electrostatic energy harvesters have the advantages in micro-scale applications as they are more compatible with the silicon CMOS processes offering greater flexibilities in the design of mechanical and electrical features separately [8,9]. Specifically, an electrostatic energy harvester mainly operates on the capacitance change of biased variable capacitors to initiate the conversion. The bias source can be either provided by pre-charged electret material or an external voltage. Electret-based electrostatic vibrational energy harvester (EVEH) is one where the sustainable voltage source is based on a special electret material. An electret is a dielectric with quasi-permanent electric charge or dipole moment, which can maintain an electric field for tens of years.

A conventional EVEH usually has an in-plane movable proof mass patterned with parallel-interdigital electrodes and the corresponding stripe-shaped electrets. The electrical current is generated when the overlapping area varies in response to an external horizontal vibration source. In order to enhance the performance, the values of electret pattern width are usually designed in ten to hundred micrometer level to be compatible with the tiny displacement of the proof mass [10]. This, however, gives rise to problems in terms of low charging efficiency and rapid charge decay [11,12]. Furthermore, the optimal working condition for such harvester is when two electrodes have precisely alignment to each other. Even small scale of misalignment may affect or lower its output performance. In order to overcome these problems, Chiu et al. [13] proposed an out-of-plane EVEH with a non-patterned negative-charged plate that operates on the variation of the air gap, where neither precise alignment nor micro-patterning of the electret film is necessary. Boisseau et al. [14] also introduced an out-of-plane EVEH with cantilever beam–mass system with a positive charged electret plate as permanent voltage source. However, the fabrication of these devices is based on manual cutting process that is neither practical for mass-production nor compatible to integration with other electronic devices. These out-of-plane EVEHs are only based on single-charged electret plate.

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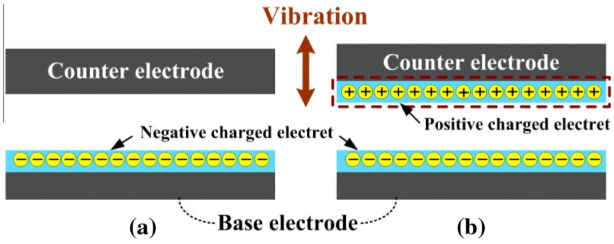

Fig. 1. Schematic of the conventional single-charged out-of-plane gap closing EVEH (left) compared with the new designed concept with double-charged plates (right).

On the other hand, typical energy harvesting devices tend to operate within narrow bandwidths where the vibration energy can only be scavenged when the resonance matches with the frequency of the external vibrations. Various nonlinear techniques have been exploited to broaden the operation bandwidth, such as utilizing mechanical prestress [15], special spring design [16,17], stopper impacts, electromagnetic force [18] or a combination of prestress and stopper impacts [19]. However, none of these works have attempted to use the electrostatic force created by the electret field to harvest energy over a wide operating bandwidth, which is practically more advantageous and compatible with MEMS/CMOS micromachining technology process. This paper presents an out-of-plane EVEH structure that combines both positive and negative charged electrets into single resonant system. Schematic of the conventional single-charged out-of-plane gap closing EVEH compared with the new designed concept with double-charged plates is demonstrated in Fig. 1. By adding positive charged electrets into the new concept device, as shown on right side of Fig. 1, the enhanced electric field within two plates will give rise to an increased electrostatic force, which would induce a stronger soft spring effect of spring–mass system as well as a higher output voltage. These aspects will be introduced in the following sections.

2. Design and modeling

2.1. Device configuration

Fig. 2 exhibits 3D EVEH structure that enables to scavenge vibrational energy using an out-of-plane scheme. The device is mainly constructed with two parallel Si plates with gold electrodes. The spring–mass resonant structure has a circular mass with 6 mm in diameter at the center and three parallel suspension spiral beams around with 50 μm in width and 300 μm in height. The spacing between each adjacent beam is 250 μm. Electret thin films, acting as permanent charge voltage source are mounted on the both sides of electrodes. When the device is excited by out-of-plane vibration, the relative movement of the two electrode plates would generate an alternating current through the external load due to the capacitance change between top and bottom electrodes.

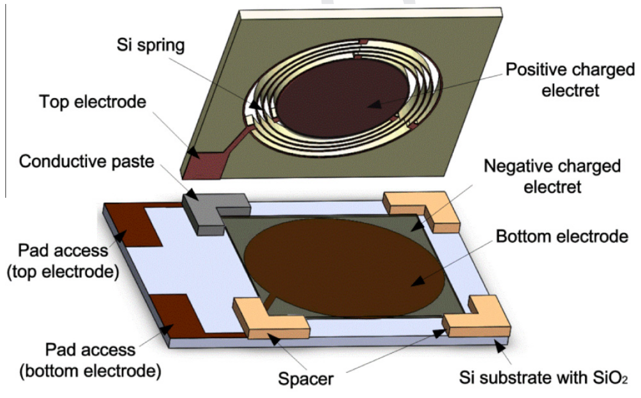

Fig. 2. 3D schematic view of the energy harvester.

2.2. Mechanical model

Finite element method is employed to analyze the stress distribution and dynamic behavior of the spring–mass system of the generator. Static structure and modal analyses performed by ANSYS simulation are used to determine the stress and the vibration mode, respectively. Fig. 3(a) shows the shape and resonant frequency of the primary vibration mode. It can be found that the spring–mass resonant structure vibrates at a low resonant frequency of about 95 Hz in an out-of-plane direction at its primary mode. Since the natural frequency of resonator is dependent on the beam geometry and proof mass, resonance of the system can be easily tuned from tens to hundreds of Hz. From our previous investigation [8], the proposed spring–mass resonant structure is not only capable of vibrating in an out-of-plane direction at mode I but also able to oscillate with in-plane directions at mode II and mode III. It is observed that the robustness of the system is mainly determined by the out-of-plane vibration of mode I, since collapse is more likely to take place in out-of-plane direction due to the occurrence of 'pull-in' effect. Although the in-plane oscillation modes could possibly be excited near their resonant frequencies, their maximum oscillation amplitudes are constrained by limited frame space; therefore, the severe damage of device could be avoided. Thus, the robustness of the system is mainly dominated by its primary out-of-plane excitation mode as well as by the high aspect ratio of the micro machined Si structures.

The stress distribution of the parallel spiral springs is further investigated by ANSYS when the proof mass is displaced of 300 μm, as presented in Fig. 3(b). The simulation results show the maximum stress is only about 18.6 MPa occurring around the beam anchors. Although single-crystal Si displays high fracture limit (up to 7 GPa) below a ductile–brittle transition temperature of ~500 °C [20], its fracture strength is more likely to be affected by its intrinsic imperfections such as the size and population of surface defects [21] and extrinsic conditions such as the stress intensity and high-cycle fatigue loading [22]. Previous research has reported that the fracture strength of silicon beam could be diminished by 33–75% by using different grade polish paste [23]. Since the calculated maximum stress is only in MPa level, which would still be substantial less than the high fracture strength reported to be of the order of GPa. One can therefore infer that the device should work adequately under the current circumstances.

2.3. Electro-mechanical dynamic model

Fig. 4 illustrates schematic model of an EVEH where both the mechanical and the electrical parts are incorporated. The behavior of the harvester is governed by a basic nonlinear differential equation and is expressed as:

$$m\ddot{x} + b_m\dot{x} + kx = -m\ddot{y} + Fe \tag{1}$$

where k is the spring stiffness, b_m is the mechanical damping, m is the seismic mass, Fe is the electrostatic force and y is the external vibration excitations ($y = Y\sin(\omega t)$), respectively. As depicted in Fig. 4, $C(t)$ is the overall capacitance between the fixed and movable electrodes, which is consist of three serial capacitances, the variable capacitance $C_1(t)$ and the two fixed electret capacitances C_2 and C_3. g and d denote the thickness of air gap and electret thin film,

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