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Micro electrostatic energy harvester with both broad bandwidth and high normalized power density

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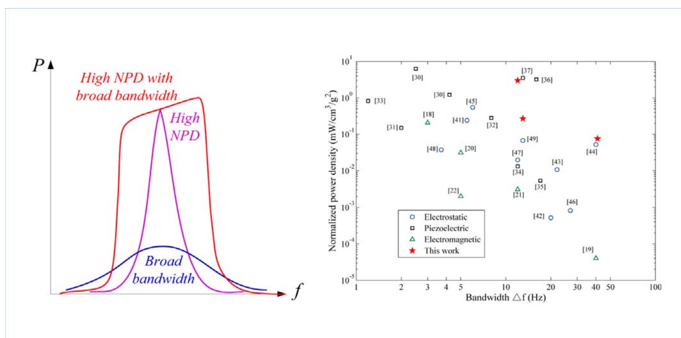
HIGHLIGHTS

- Both broad bandwidth and high normalized power density are achieved resulting in excellent overall performance.
- Energy harvesting from random sources and multi-devices stack are feasible for wireless sensing networks.
- Mechanical collision and air damping effect on electrostatic energy harvesting has been investigated.
- MEMS compatible process flow has been developed for system integration with sensors and IC.

GRAPHICAL ABSTRACT



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ABSTRACT

In this paper, an electrostatic vibration energy harvester is proposed and fabricated with both broad bandwidth and high normalized power density (NPD, harvested power/volume/acceleration^2). The device is made up of two parts, top movable plate and bottom fixed plate, both of which are fabricated from silicon wafers using advanced micro-electro-mechanical system (MEMS) technology. A CYTOP polymer layer is spray coated for an electret material as well as an adhesive layer for low temperature wafer bonding. The air damping effect in energy harvesting has been investigated. At a low pressure of 3 Pa in a vacuum chamber, maximum power output of 4.95 µW has been harvested at low vibration amplitude of 0.09 g, resulting in a bandwidth of 12 Hz and NPD of 3 mW/cm^3/g^2, which outperforms most of the previous harvesters. A high harvester effectiveness of 67.9% is therefore achieved. The response on random vibrations is also tested. An average output power of 2.22 µW is harvested when random vibration is applied at a frequency range of 160 ± 12.5 Hz with RMS acceleration of 10.5 m/s^2. The excellent overall performance gives promising application for energy harvesting from random sources and multi-device stack for wireless sensor networks.

1. Introduction

In recent years, self-sustainable power sources have attracted much attention from both academia and industry for their potential applications on the personal health monitoring, micro systems, and wireless sensor networks [1–3]. The energy harvesting technologies from

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ambient sources, like mechanical vibration [4,5], wasted heat [6,7] and triboelectricity [8–13], provide a promising way to replace the traditional chemical batteries with micro-scale devices. For instance, based on the periodic contact/separation between polydimethylsiloxane (PDMS) film and human skin, peak power density up to 4.8 mW/m^2 was harvested, which is attractive for self-powered and portable devices [11].

Many vibration-based energy harvesters have been designed based on the electromagnetic [14–22], piezoelectric [23–37], and electrostatic [38–49] transduction methods for vibration-to-electricity conversion. The electromagnetic energy harvester is basically designed on the Faraday's law of induction. Using an array of alternating north and south-orientation magnets, Zhang and Kim have harvested 263 mW from vibration at low frequency, which is high enough to light an incandescent light bulb [15]. The bottleneck for electromagnetic method is the bulky size since the power output is dependent on the number of coil turns and the magnet. In piezoelectric energy harvester, some certain materials with piezoelectric effect, such as PZT [23–26] and PVDF [28,29], are utilized. Jung et al. developed flexible energy harvesters with PVDF films, which could harvest 0.2 W with power density of 8 W/m^2 for roadway applications [28]. One challenge for this method is that most of the piezoelectric materials are not compatible to IC fabrication.

Among the transduction types above, electrostatic energy harvester has become more attractive thanks to its good compatibility to integrated circuit (IC) and micro-electro-mechanical system (MEMS) processes. It is mainly based on a variable capacitor structure which is biased by either an external voltage source [50] or pre-charged electret materials [51–53]. For instance, the capacitance of the device would change when the gap distance between the two electrodes is changed due to the relative movement of proof mass according to vibration source. Based on this out-of-the-plane scheme, a cantilever based energy harvest was developed by Boisseau et al. [39]. A maximum power of 50 μW was harvested from an active chip size of 4.2 cm^2. In 2014, IC compatible process flow was developed for the electret based energy harvester, where four-wafer stack was batch fabricated and fully packaged at wafer scale [42]. Energy harvesting from in-plane vibration can also be accomplished by switching the counter electrode [38,41] or varying the overlapping area [46,47]. Based on the advanced MEMS technology, electrostatic micro energy harvester takes the advantages of small size, high sensitivity, high energy density and conversion efficiency [54]. And thanks to the compatible processes, it is feasible in the future to fabricate and package the electrostatic micro power generator together with the wireless sensor into a self-powered system.

There are a few general considerations for the energy harvesting devices. The resonant frequency and the maximum power output of the device are of the highest concern, since the size and mass of the device should be comparable to the conventional battery. A low resonant frequency around 10–200 Hz is preferred for the application on vibration sources from human motion, wind flow and structure motions in our daily life [55,56]. However, the maximum generated power is proportional to the cube of the resonant frequency, which significantly limits the output of the energy harvesters [57]. Mechanical frequency-up converters were designed to harvest energy more effectively from external vibrations at low frequency [58–61].

Furthermore, normalized power density (NPD) and bandwidth are two important technical factors to evaluate the efficiency of the material and the structure of a vibration based energy harvester. NPD, defined as harvested power/volume/acceleration^2, is a factor of merit based on the fact that the harvested power is typically in proportion to the device volume and the square of the vibration amplitude [14]. FWHM (full width at half maximum) bandwidth of the device is defined as the vibration frequency range where the power harvested from the device is higher than half of the maximum output power. Generally, there is a trade-off between the NPD and the FWHM bandwidth of an energy harvester. For linear oscillators, high Q-factor is typically favorable for high NPD. But optimal power output can only be achieved at the resonant frequency with a narrow bandwidth, as shown in Fig. 1(a). This type of device might be applicable to harvest energy from vibration sources with specific resonant frequency. However, broad bandwidth is necessary to harvest energy from the ambient vibrations like human motion and wind flow, which generally exhibit random frequency spectrum. Broad bandwidth can provide another benefit that we can pile up multi devices for high power, which was impractical due to the mismatch of the resonant frequency from the fabrication errors. By reducing the Q-factor of the linear oscillator, a broad bandwidth can be achieved at the cost of the NPD, as shown in Fig. 1(b).

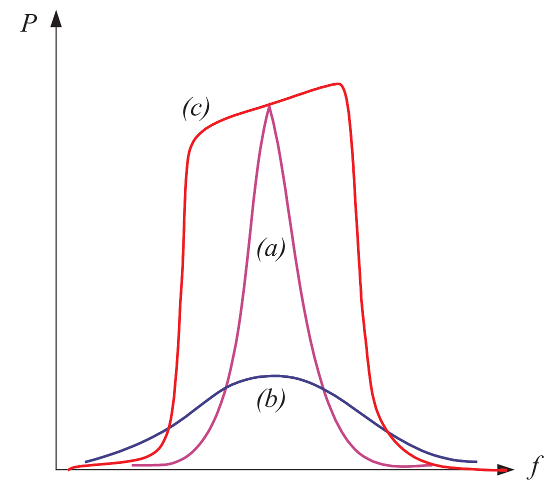

Fig. 1. (a) High NPD with high-Q; (b) broad bandwidth with low-Q; and (c) all-round performance with both decent power output and broad bandwidth can be achieved from a gap-closing scheme with high-Q from low packaging pressure (without increasing the acceleration amplitude).

A few approaches have been recently tried to optimize the frequency response of the device. A broad-band energy harvester with multiple beams was fabricated with a series of separate linear devices at different resonant frequencies [62]. It can harvest energy at multiple resonant frequencies; however, the efficiency of the overall device is in doubt [26]. Other researchers have tried to design double well potential with bi-stable or tri-stable resonant systems, which can be realized by adding external magnets or by buckling a beam with preload [63–67]. These methods have been studied in depth, mainly for the piezoelectric energy harvesters. The bandwidth of electrostatic energy harvesters can be broadened by introducing a repulsive electrostatic force [46], gap-spacing controlling with a mechanical stopper [40], or using nonlinear spring structures [48,68,69]. However, the NPD is generally much lower than piezoelectric devices.

In this paper, we propose an electret based energy harvester with both high NPD and broad bandwidth. Comparing to the conventional devices at atmosphere, the proposed device works with a gap-closing scheme packaged at a low pressure, which reduces the air damping and increases the Q-factor. Therefore, it is feasible to drive the mass to decent amplitude at a low acceleration, resulting in a high NPD as shown in Fig. 1(c). Thanks to the low air damping, high harvester effectiveness could also be achieved. From another aspect, the maximum displacement is restricted by the packaging plate. The squeeze-film damping force (F_d) increases when the gap (g) between the electrodes is small ($F_d \propto g^{-3}$) [70], which would also affect the bandwidth of the device. By tuning the packaging pressure and the vibration amplitude, we have successfully broadened the bandwidth of the device. The broad bandwidth solves two major challenges for the practical application of vibration energy harvesters. One challenge is due to the difficulty of harvesting from random vibration sources; the other one comes from the feasibility to stack multi devices for high power output. The relationship between the output power and the air pressure has been