Multi-Axis Inertial Energy Harvester Based on Piezoelectric Crab-Legs with Partitioned Electrodes

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Multi-Axis Inertial Energy Harvester Based on Piezoelectric Crab-Legs with Partitioned Electrodes

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Abstract. This paper reports a microfabricated piezoelectric MEMS inertial energy harvester that can scavenge high-frequency mechanical vibrations in all three dimensions with an active inner volume of only 55 mm³. The device can generate 0.1 to 10.5 μW from out-of-plane vibrations (365-465 Hz), and 0.1 to 3.2 μW from in-plane vibrations (680-930 Hz) at 0.5 g acceleration input. The reported harvester is demonstrated to be effective for multi-axis operation, with a favorable power density of 0.2-2.2 mW/cm³/g² (at 0.1-0.5 g) with respect to previously reported microfabricated multi-axis vibration harvesters.

1. Introduction
Harvesting vibrational energy from all spatial directions can both enable higher power output from an energy scavenger, and also extend its practical applications in real-life situations. Previously, three-degrees-of-freedom energy harvesting in a single transducer has been reported only with electrostatic and electromagnetic devices [4-5], but with limited power density (<125 nW/cm³/g²). On the other hand, piezoelectric inertial energy harvesters have been reported with only up to 2-axis operation, based on asymmetric inertial mass [1], coupled mass-spring combinations [2], and three-dimensional beam designs [3]. In addition, the employed device architectures mostly require unconventional three-dimensional structures with manual assembly, which hinder further device miniaturization. Recently, we reported for the first time a meso-scale piezoelectric device (6500 mm³) that can be used for 3-axis inertial energy harvesting [6]. In this paper, a highly miniaturized (100×) and batch-mode microfabricated version of this structure and its detailed experimental results are demonstrated.

Figure 1. Micro-fabricated piezoelectric energy scavenger for multi-axis vibration harvesting.
2. Design of the Three-Axis Harvester

The harvester design is based on three key aspects (Figure 1). First of all, in order to create a balanced inertial force during both out-of-plane and in-plane excitations, two proof masses with equal sizes and weights are attached to the top and bottom surfaces of a center platform. Secondly, this center platform is suspended by four piezoelectric unimorph crab-legs in a symmetric layout (Figure 1). As the inertial proof mass is coupled to ambient vibrational accelerations, this crab-leg beam structure allows its motion in both in-plane and out-of-plane directions (Figure 2a-b). Finally, depending on the direction of applied acceleration, the mechanical strain created on the piezoelectric layer of a crab-leg beam has different polarities at different sections of the beam. The conventional method of using a single monolithic electrode on top of the piezoelectric layer would cause charge cancellation on the surface, and thus lower the power output substantially. Instead, the presented design utilizes partitioned surface electrodes (Figure 2c), such that charge outputs with varying phases from these sections can be harvested efficiently with respect to a common ground electrode in the transverse piezoelectric mode.

![Figure 2. a-b) Simulated electrical output and polarity on the piezoelectric layer at different vibration modes, c) Partitioned top electrodes and the common ground electrode on one arm of the crab-stage.](image)

3. Microfabrication

A 10-mask wafer-level fabrication process is developed, based on a previously reported and further advanced “bulk-PZT on Si” technology [7]. The process involves diffusion solder bonding, precision lapping, and dry-etch patterning of a bulk-PZT substrate on a Si wafer. The fabricated piezoelectric unimorph beams have a cross-section of 35-μm thick high-quality PZT film on top of 160-μm thick Si. The piezoelectric layer is covered with two layers of metallization buried in between electrical isolation layers, of which the first layer forms the energy-harvesting partitioned top electrodes, and the second layer forms the electrical interconnects. The overall harvester structure, excluding the wire-bonding pads and support frame but including empty space for packaging, occupies only 55 mm³.

4. Experimental Setup and Results

The harvester is wire-bonded to a dual in-line package with electrical connections to the 16 partitioned top electrodes and the common ground, and all electrodes are connected to individual loads of equal resistivity for electrical damping (Figure 3a). A custom-made jig is utilized to attach the device to a shaker table in different spatial orientations, and test its response for each vibration axis (Figure 3b-d).

![Figure 3. Experimental setup to test the harvester for sinusoidal vibrations in the X, Y, and Z axes.](image)
In order to obtain maximum power transfer, the electrical load on the harvester should be optimized, such that the induced electrical damping equals to the existing mechanical damping in the system. When the device is tested for sinusoidal vibration at its first resonance frequency (433 Hz), the optimum resistive load on a single electrode is measured to be ~800 k\(\Omega\) (Figure 4a). However, as the excitation frequency is swept from 300 Hz to 850 Hz covering different vibration modes, the optimum load is observed to range between 400 k\(\Omega\) and 1.5 M\(\Omega\) (Figure 4b). This suggests that, an impedance matching network will be required to be included in the power management circuitry of this transducer in order to obtain high efficiency in all possible operation conditions.

![Figure 4. a) Output from a single electrode of the harvester with respect to a resistive load for a sinusoidal vibration at 433 Hz, 0.1 g b) Variance of the optimum resistive load for maximum power output when the device is excited at different frequencies and at constant peak acceleration of 0.1 g.](image)

The amplitude and phase of voltage outputs from the 16 partitioned electrodes depend on the direction and frequency of excitation. For instance, the voltage outputs recorded from the electrode pairs 1-2 and 3-4 on a crab-leg, as pictured in Figure 2c, are measured to have similar phase and amplitudes, when the device is tested with an out-of-plane excitation at its first mode at 433 Hz (Figure 5a). However, the phase differences between these electrodes shift, as the direction of input vibration is alternated and an in-plane mode is excited. In this case, electrode pairs 1-4 and 2-3 have similar phase in their outputs (Figure 5b). These results match well with the FEA simulations presented in Figure 2a-2b. The variable phase difference in the outputs demonstrates the effectiveness of using partitioned surface electrodes to prevent charge cancellation across the piezoelectric layer compared to using a single monolithic electrode in a conventional design. One drawback of using multiple harvesting electrodes could be the required number of input channels in a possible power management circuitry connected to this device, and thus a potential increase in the power consumption necessary for active rectification of multiple low-voltage signals. In order to minimize this power consumption and generate a net energy output, a smart circuit architecture could be employed, such that the outputs of only certain electrodes with sufficient voltage levels are actively rectified depending on the vibration mode and amplitude.

![Figure 5. Comparison of voltage outputs and phases of partitioned electrodes in a single arm, when the device is excited at resonance in the a) out-of-plane (Z-axis), and b) in-plane (X-axis) directions.](image)
When the harvester is tested for its maximum total power output for an input vibration with 0.1 g acceleration amplitude, it is found to generate 1.2 $\mu$W and 0.3 $\mu$W from out-of-plane and in-plane excitations, respectively (Figure 6-7). At 0.5 g acceleration, the power output increases about 10×, to 10.5 $\mu$W and 3.2 $\mu$W for the same excitation modes, respectively. For an unpackaged device, these values correspond to a normalized power density of 0.2 to 2.2 mW/cm$^3$/g$^2$. This result compares favorably with respect to previously reported three-axis microfabricated energy harvesters based on electrostatic and electromagnetic transduction (<0.1 mW/cm$^3$/g$^2$) [4-5].

![Figure 6. Total power output from all 16 partitioned electrodes of the multi-axis harvester as it is excited in the a) out-of-plane mode (Z-axis) with a resistive load of 767 k$\Omega$ on each electrode, and b) in-plane mode (X-axis) with a resistive load of 450 k$\Omega$, at 0.1 g and 0.5 g acceleration amplitudes.]

5. Conclusions
A three-axis vibration energy harvester is developed based on a novel architecture with piezoelectric crab-legs and partitioned surface electrodes. The presented device is microfabricated with an advanced piezoelectric MEMS technology, and experimentally verified with results matching FEA simulations. The multi-axis MEMS harvester can harvest 0.3 to 10.5 $\mu$W from input vibrations in the X, Y or Z spatial directions with 0.1 to 0.5 g acceleration amplitude at its modal frequencies (430-850 Hz). Although the power density (0.2-2.2 mW/cm$^3$/g$^2$) is lower than the values reported for high-performance single-axis microfabricated cantilever beam energy harvesters (6-10 mW/cm$^3$/g$^2$) [8], the presented device is advantageous for its multi-axis and wide bandwidth operation capability. Future work will focus on decreasing the resonance frequency of in-plane modes, and increasing the power output via optimization of the beam structure for larger in-plane structural flexibility.

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