THREE-AXIS PIEZOELECTRIC VIBRATION ENERGY HARVESTER

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ABSTRACT

This paper reports for the first time a piezoelectric inertial harvester for scavenging vibrational energy in all three dimensions. The harvester is formed of optimized bulk-PZT/Si crab legs such that the first three resonance vibrational modes are in-plane and out-of-plane translational modes with closely-spaced frequencies (387-398 Hz). Partitioned electrodes on the PZT arms collect mechanical energy in the transverse (d_{31}) piezoelectric mode, and have phase difference in their voltage outputs according to the axis of the applied vibration. The harvester is realized using a planar micro-fabrication method, with internal and packaged device volumes of 2.5 and 6.5 cm^3, respectively. The device has generated 5-53 µW from 50 mg acceleration applied in in-plane and out-of-plane directions at the respective resonance frequencies, and has a half-power bandwidth of 8-16 Hz. The normalized power density (0.3-3.2 mW/cm^3/g^2) compares favorably with respect to previously reported multi-axis inertial energy harvesters.

INTRODUCTION

Inertial energy harvesting from ambient mechanical vibrations is a promising technology to enable next-generation wireless sensor nodes, which are self-powered, maintenance free, and thus truly autonomous [1]. There have been a large number of micro and meso-scale inertial harvesters reported up to date. Most can only operate at a single vibrational axis. Harvesting electrical energy from vibrations applied along any spatial direction can both improve their power output and extend the practical applications. One way to achieve this goal is by using three individual harvesters aligned along the three different axes assembled in a single package [2]. This will, however, decrease the total power density and increase the overall cost due to the enlarged device size. Previously, single-transducer three–axis energy harvesters were reported only for electrostatic and electromagnetic resonators [3-4], although with very limited performance in terms of power output (16-25 nW) and power density (<125 nW/cm^3/g^2), resonance frequency (1.5-25 kHz), and frequency split (100-1000 Hz). Until now, only 2-axis piezoelectric inertial harvesters have been reported, based on configurations such as asymmetric inertial mass [5], multiple mass-spring combinations [6], three-dimensional (L or U shaped) beam design [7-8], permanent-magnet and ball-bearing combination [9], and non-linear motion of a circular cantilever rod due to surrounding permanent magnet architecture [10]. In addition to the limited number of operational axes, the architectures used in these devices require mostly three-dimensional structures with manual assembly, which prevent further device miniaturization. This paper reports for the first time a piezoelectric transducer that can harvest energy from all three axes (Figure 1). The

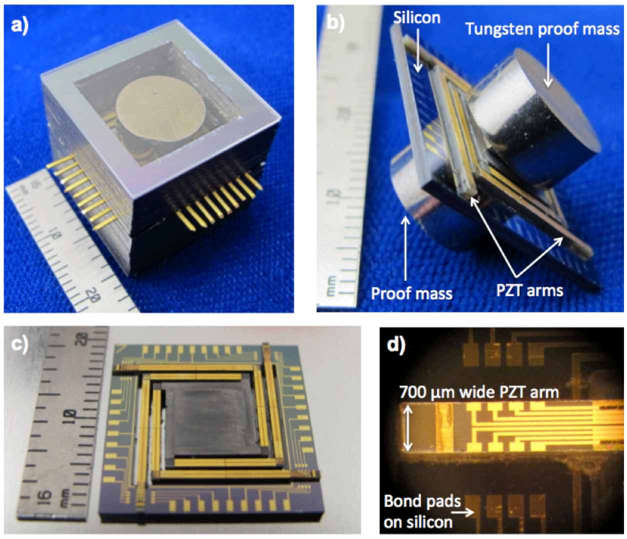

Figure 1: a) Three-axis piezoelectric inertial energy harvester packaged in 6.5 cm^3, b) Device structure with balanced proof mass on both sides, c) PZT-Si unimorph harvester platform, d) Wire-bond pads on PZT & Si.

reported device architecture can be further miniaturized through existing planar micro-fabrication methods.

DESIGN OF THREE-AXIS HARVESTER

The harvester is formed of four 700-µm wide and 1.5 mm thick PZT/Si unimorph, crab-leg suspensions that symmetrically hold an 8×8 mm^2 sized center platform and enable its in-plane and out-of-plane motions. There is a common ground electrode underneath the piezoelectric layer, while each crab-leg suspension has 8 partitioned top electrodes to harvest energy in the transverse (31) piezoelectric mode (Figure 2). Depending on the applied acceleration direction, and thus the created mechanical strain on the beams, the outputs from these top electrodes have different voltage polarity. This is unlike a conventional piezoelectric cantilever beam, where a single top and bottom electrode is used to harvest only from out-of-plane vibrations. The challenges introduced by these partitioned electrodes on the required power management circuitry are the decreased capacitance of (and collected charge from) each electrode, need for a full-wave rectifier and load matching circuitry for each electrode, and the cost of increased IC chip area to accommodate the number of input pads. The partitioned electrodes enable the presented harvester to be utilized for harvesting energy from not only translational but also rotational periodic motions (tilting around X, Y, or Z axes), although these are not studied in this paper due to the required test setup.

For maximum efficiency, the presented multi-axis harvester is designed for resonant operation within a

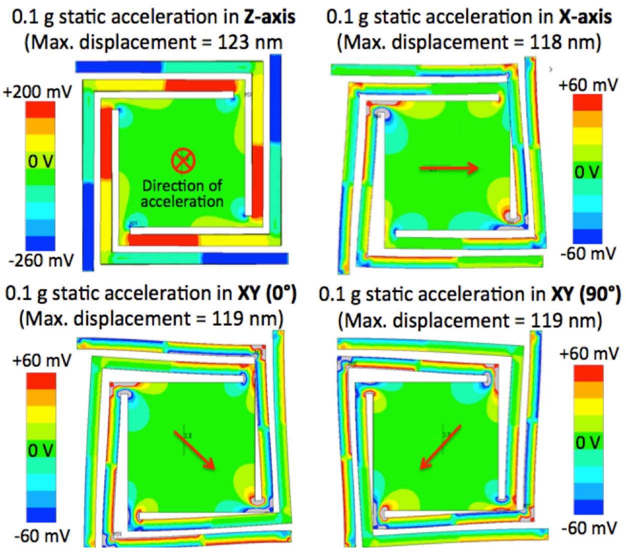

Figure 2: Finite element simulation results for open circuit output when a static acceleration of 100 mg amplitude is applied in different axes.

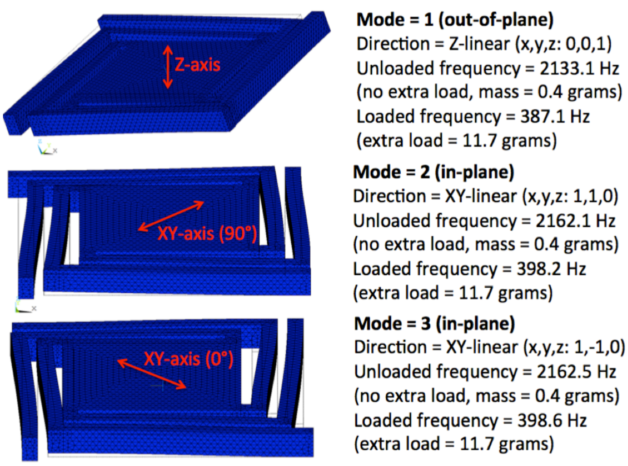

Figure 3: FEA simulation results for modal analysis.

limited frequency range. Therefore, the beam dimensions are optimized via finite element modeling (ANSYS) such that the resonance frequencies for translational motion in both in-plane (XY-axes) and out-of-plane (Z-axis) directions are closely matched (Figure 3). Without any additional mass, the center stage has a weight of 0.4 grams, and the frequencies associated with the considered modes of the platform are simulated to be in the range of 2.1 kHz. These values are calculated to decrease down to 385-400 Hz when an external proof mass of 11.7 grams is attached, which is in a more practical frequency range for industrial applications.

DEVICE FABRICATION

The fabrication process is summarized in Fig. 4. After e-beam evaporation and lift-off patterning of Cr/Au metal electrodes on a 500 µm thick polished bulk-PZT substrate, a ~4 µm thick parylene film is evaporated and RIE-patterned as an electrical isolation layer. Next, the electrical interconnects are deposited and patterned on this

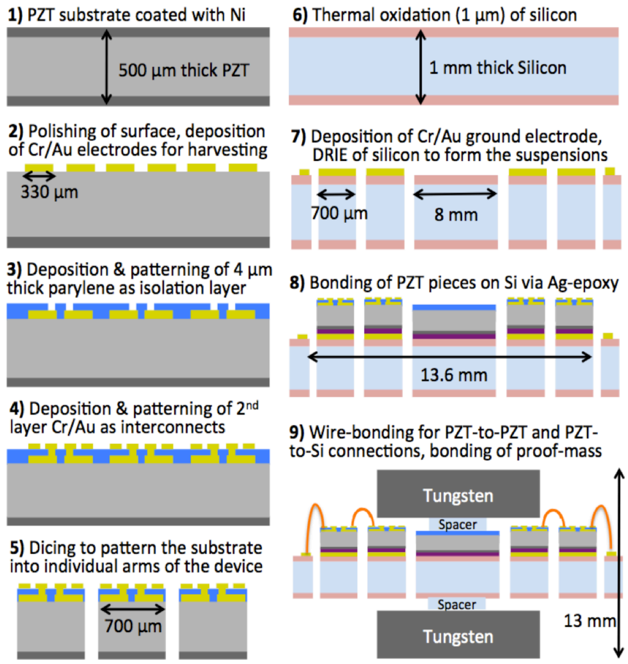

Figure 4: Fabrication process of the piezoelectric three-axis vibration energy harvester.

parylene layer allowing individual connections to the partitioned energy-harvesting electrodes underneath. Finally, the piezoelectric substrate is diced into individual pieces to be utilized as the suspension arms, which are manually aligned and assembled via conductive epoxy on a 1 mm thick, oxidized, metallized and DRIE-patterned silicon die (Figure 1c).

Electrical connections from one PZT piece to the adjacent piece on the same crab-leg suspension are achieved via ball bonding between pads on these arms. Similarly, the electrical connections from a crab-leg suspension to the silicon die are achieved via wire bonding (Figure 1d). The wire bonds are covered by epoxy to provide mechanical protection during vibration tests. Two similarly sized tungsten proof-masses with 10-mm diameter (11.7 grams in total) are attached to the top and bottom sides of the center platform with 0.7 mm thick spacers in-between (Figure 1b). Compared to the case of using a single proof mass at either side of the platform, this configuration prevents unbalanced motions due to unequal weight distribution. For instance, without this measure, a translational vibration input along X-axis would also create tilting motion around Y-axis since the centroid of the proof mass is not located at the center of the moving platform.

For handling and testing purposes, the harvester is packaged in a non-hermetic silicon frame with glass covers on its top and bottom sides (Figure 1a). The packaged device volume is 6.5 cm^3, while the internal device consumes 2.5 cm^3 (13.6×13.6×13.6 mm^3). Since the presented piezoelectric device architecture is planar, it can be further miniaturized via a previously reported microfabrication method, which involves solid-state bonding, lapping, and etching of a bulk-PZT substrate on silicon [11].

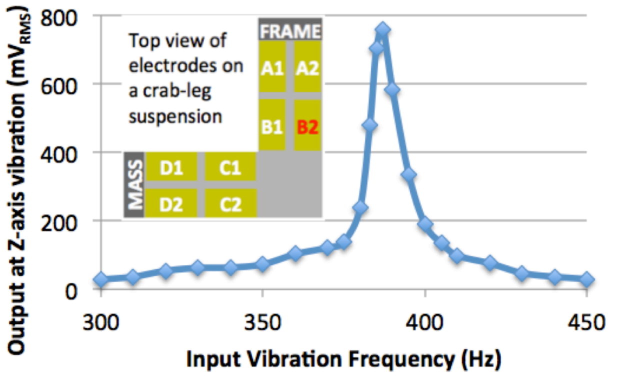

Figure 5: Measured frequency response from a top electrode (B2) when harvester is excited out-of-plane (Z).

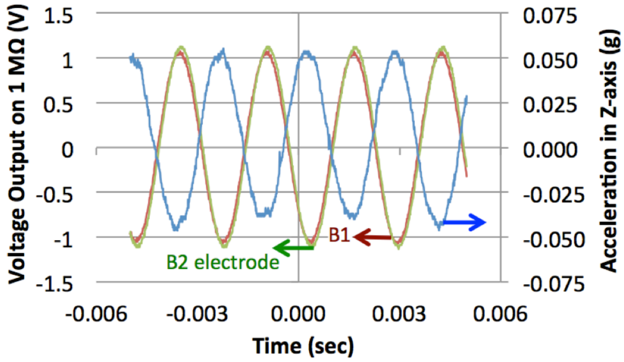

Figure 7: Measured voltage outputs from two electrodes on 1 MΩ loads for 50 mg acceleration amplitude at 387 Hz in the Z-axis direction.

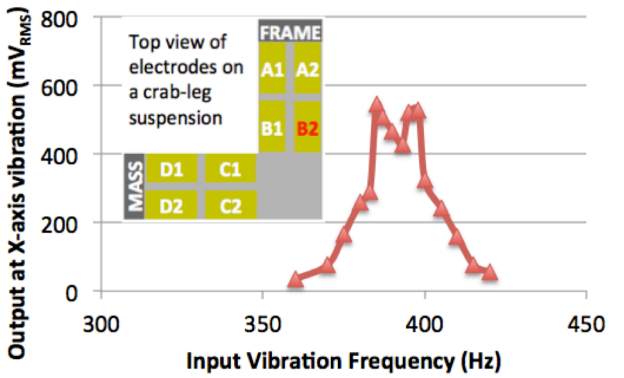

Figure 6: Measured frequency response from a top electrode (B2) when harvester is excited in-plane (X).

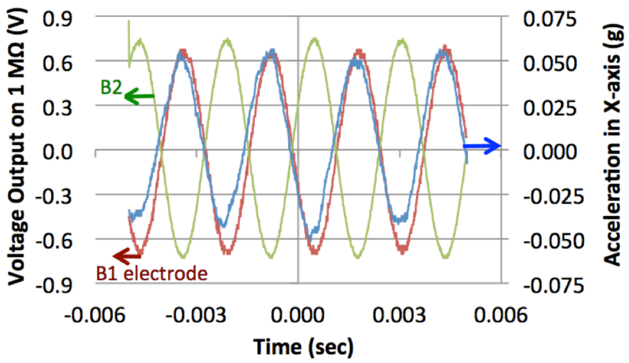

Figure 8: Measured voltage outputs from two electrodes on 1 MΩ resistive loads for 50 mg acceleration amplitude at 398 Hz in the X-axis direction.

EXPERIMENTAL RESULTS

The harvester is fixed on and excited by an electromagnetic shaker table at 50 mg acceleration amplitude in the X-, Y-, and Z-axes individually. The measured resonance frequency for the out-of-plane mode (Z) is ~387 Hz with a half-power bandwidth of 8 Hz (Figure 5). Due to the rectangular shape of the device package and the utilized mechanical clamping method, the harvester had to be excited across X or Y axes to detect its in-plane modes, although the 2nd and 3rd modes are actually 45° misaligned from these directions. In this test, the resonance frequencies are measured as ~385 Hz and ~398 Hz for the in-plane modes (XY-axis 0° and 90°) (Figure 6). Since the in-plane mode resonance frequencies are closely spaced and the tested input vibration has vector components in both directions, this results in an extended bandwidth of 16 Hz.

Depending on the input vibration axis, it is observed that there is amplitude and phase difference between the voltage outputs of individual electrodes as expected (Figures 7-8). The optimum external resistive load to obtain maximum power output from each electrode is measured to be 1 MΩ. The sum of measured power output from 32 individual electrodes is 52.9 µW for Z-axis, and 4.9 µW for X-axis, and 5.1 µW for Y-axis vibration inputs. The calculated normalized power densities (0.3-3.2 $mW/cm^3/g^2$) compare favorably with previously reported multi-axis harvesters, although the values are slightly lower than single-axis, high-performance, microfabricated bulk-PZT cantilever beam energy harvesters (3.5-10 $mW/cm^3/g^2$) [12-13].

The energy harvested from in-plane vibrations is measured as considerably lower compared to the energy obtained from out-of-plane vibration. This is mostly due to the undesired confinement of most of the mechanical stress on the silicon material instead of the piezoelectric layer during lateral bending. This problem can be solved in a future device architecture, where a PZT/PZT bimorph beam cross-section with partitioned electrodes on both top and bottom surfaces is used instead of the presented PZT/Si unimorph beam design. Another cause is that lateral bending creates varying amount of surface charge (and thus electrical potential) from the center of the piezoelectric beam to its lateral edge, while a single electrode is used to cover this region and average out the potential. This results in un-optimized external-load matching and electrical damping on the beam motion. Finally, the 45° misalignment between the actuation direction and the tested in-plane resonance mode causes only one component in the vector basis of the vibration input to be effective in the power output.

CONCLUSION

A three-axis resonant inertial energy harvester, based on transverse-mode piezoelectric crab-leg suspensions and partitioned top electrodes, is presented. For fast prototyping purpose, the introduced planar device architecture is fabricated via individually assembling processed and diced bulk-PZT legs on a patterned silicon die, and forming electrical connections between individual pieces through wire bonding. The multi-axis harvester can scavenge 5-50 μW power from vibrations with 50 mg acceleration amplitude in the X, Y or Z spatial directions at the first three modal frequencies of the device (387-398 Hz). Future work will focus on improving power output in in-plane vibration modes.

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