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ASYMMETRIC QUAD LEG ORTHOPLANAR SPRING FOR WIDEBAND PIEZOELECTRIC MICRO ENERGY HARVESTING

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Abstract- **Piezoelectric energy harvesters (EH) generate their highest energy levels at the resonant frequencies of the transducer devices. To provide a wide-band EH solution, nonlinear mechanical resonators with multiple resonant modes can be used. We present a new asymmetric quad-leg orthoplanar spring (QOPS) EH microstructure to increase the harvesting bandwidth. The proposed design is implemented in CMOS compatible microfabrication processes. Finite element analysis show that the asymmetric designs increases the bandwidth by maximum 27% compared with symmetric designs. In order to measure the electrical output, one symmetric and three asymmetric piezoelectric devices implemented on the same microchip are exposed to mechanical vibrations over a wide frequency bandwidth. Experimental results approve the increase in the frequency bandwidth of resonators introduced by asymmetries added to the spring, as compared to the symmetrical configuration.**

Keywords: Piezoelectric Energy Harvester, Micro-electromechancial Systems (MEMS), Orthoplanar Spring.

INTRODUCTION

MICROELECTROMECHANICAL SYSTEMS (MEMS) provide a reliable and low-cost solution for integration of energy harvesting (EH) devices and sensor transducers. Vibration-based EH have demonstrated higher energy outputs compared with other mechanisms [1], such as radio frequency or pyroelectric approaches with similar transducer dimensions. Wireless power transfer [2], despite its straightforward implementation may have limitations in electromagnetically shielded environments. These EH systems have been implemented using piezoelectric, electromagnetic and capacitive transducers. Piezoelectric transducers have gained higher popularity among the other approaches since they offer the potential for high efficiency and autonomous solutions. In addition, compatibility of some piezoelectric MEMS processes with Complementary Metal Oxide Semiconductor (CMOS) processes offers a great advantage for integration of EH system within sensor nodes.

At the microscale, piezoelectric resonators generate high-quality factor (*Q*) vibrations, so that the power spectrum of the electrical output is concentrated at sharp resonance frequencies. However, the mechanical vibration sources to be harvested often have a wide frequency spectrum. Therefore, applying such wideband vibrational inputs to piezoelectric transducers results in low efficiency and output energy levels, due to the limited range of resonance frequencies.

Time-domain multiplexing of mechanical impacts, recently suggested in [3], increases the output energy of harvesters exposed to random vibrations by applying low frequency mechanical input to sequentially spaced multiple cantilever beams. However, most of the previous works are focused on frequency-domain approaches. Bandwidth widening of meso-scale piezoelectric transducers have been investigated by introducing a variety of nonlinearities, which leads to additional resonant modes [4]. At the micrometre-dimension, a low frequency cantilever resonator can be used as a mechanical stopper against another high frequency cantilever beam [5]. This increases the bandwidth of the second resonator by a *scrape-through* effect. However, the reliability and repeatability of such an approach for fragile MEMS devices needs to be addressed. Permanent magnets in close vicinity of the free end of piezoelectric cantilever beams can also introduce nonlinearity by the magnetic coupling between the vibrating tip of the beam and stationary magnet in meso/macro systems [6]. However, the integration of permanent magnets in standard microfabrication processes is challenging [7]. In an alternative approach, a proof mass suspended from several linear cantilevers provide nonlinear behaviour [8-11]. For example in [11], a three-leg ortho-planar spring (OPS) system has been used with a suspended proof mass at the meso-scale. A comprehensive review of vibration energy harvesters with focus on planar spring systems is presented in [12]. The OPS system is best suited for smaller scales due to its compact size and planar structure, which is highly compatible with standard microfabrication processes.

We introduce here an alternative solution, where equal-sized asymmetries in a Quad-leg piezoelectric OPS system is introduced to further increase the bandwidth of an EH system. In the following sections we investigate the effect of asymmetric weight and stiffness added to specific sections of the OPS legs in a commercially available microfabrication process (Pz-MUMPS). The finite-element piezo-electromechanical analysis and measurement results are presented for different combinations of these asymmetrically located masses and a broadband response is demonstrated.

DEVICE MICROSTRUCTURE

The inherent wide bandwidth of OPS systems as a result of multiple resonant modes at close distances from each other, is

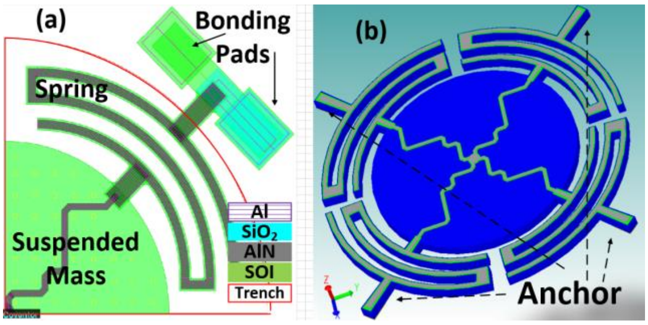

Fig. 1:. The proposed symmetric QOPS microsystem, (a) one leg layout that is rotated 90° four times to generate the full device layout, (b) 3D meshed model for symmetric structure in Coventor without the boning pads and the

a popular feature for EH applications. We show that shifting the resonance frequencies by adding asymmetric suspension beams in the microstructure can further increase the operational bandwidth. The proposed symmetric quad-leg ortho-planar spring (QOPS) system is illustrated in Fig 1. The quarter layout and the process cross-section are shown in Fig. 1(a). The active piezoelectric layer (AlN) is sandwiched between the metal (Al) and silicon (SOI) layers in this microfabrication process. The circular disc-shaped mass is etched out of the SOI layer and coupled to the substrate by S-shaped springs, which are anchored to the substrate by four cantilever beams. Etching the substrate (handle wafer) from the back-side leaves the mass suspended on the trench as shown in the three dimensional (3D) model in Fig 1(b). Coupling the mechanical vibration of the substrate to the suspended mass applies stress to the springs. The piezoelectric layer deposited on the springs converts this stress to a piezo-electric charge that can be collected from the bonding pads. The mechanical features of this structure are determined mostly by the silicon layer, which is an order of magnitude thicker (10µm) than the two other layers (<1µm).

The addition of weights to the symmetric mesoscale three-leg OPS systems is investigated for piezoelectric EH [13]. However, in standard microfabrication processes the only way to introduce asymmetries is to alter the 2D layout. In this work we have added three different asymmetries on the symmetric QOPS system above, where changes in the stiffness of the springs and the effective mass are used to affect the frequency of different resonant modes. The top view of 3D meshed model for these three different asymmetric designs are shown in Fig. 2. The S-shaped spring is widened as shown by arrows in one, two and four points for *Asym1*, *Asym2* and *Asym3*, respectively. Finite element analysis (FEA) has been applied to extract the mechanical resonance behavior of this QOPS system and Fig. 3 shows an animated view of first four resonant modes for the symmetric system. The resonance frequencies associated with each of these microstructures are reported in table 1 for the first four modes. Mode four can be ignored as its frequency is much higher than the others. The difference between first and third resonance frequencies is also reported as Δf_{31} in this table. The frequency difference between the first and third modes increases by adding the asymmetries, which is expected to increase the bandwidth. The addition of asymmetries has a higher impact on the stiffness, rather than the effective mass of the structure, since the dominant suspended mass of this microstructure is determined by the circular disk. The addition of asymmetries has different impacts on the resonance behavior of *Asym1*, *Asym2* and

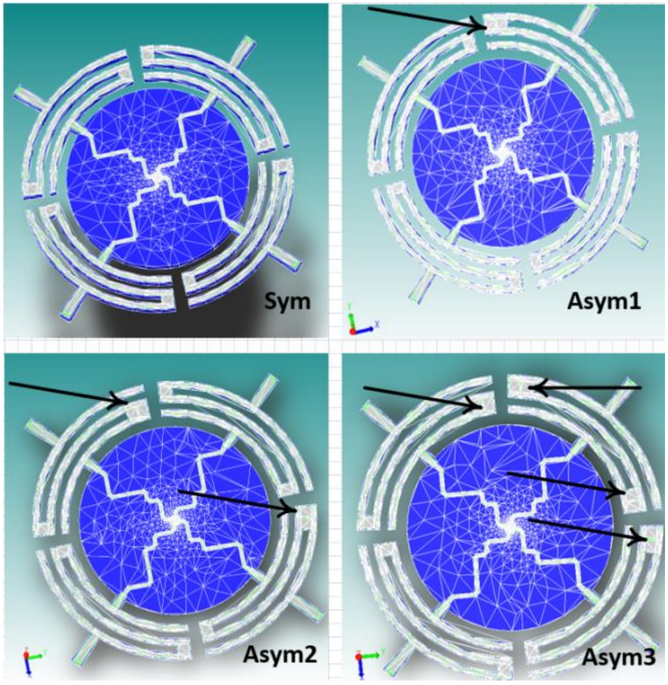

Fig. 2: Meshed model for the symmetric and asymmetric OPS in Pz-MUMP, (a) symmetric, (b-d) Asymmetric configurations with one (Asym1), two (asym2) and four (Asym3) asymmetries shown by arrows.

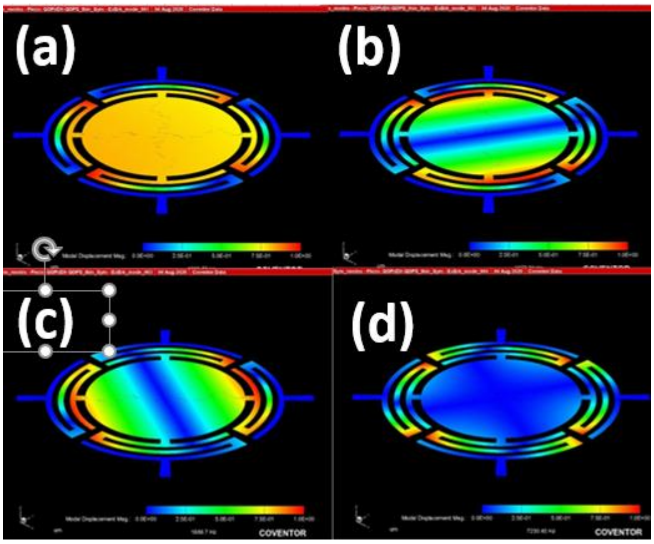

Fig. 3: Finite element analysis of the 3D meshed model for the symmetric COPS systems, (a) vertical mode, (b) and (c) torsion around symmetric access, (d) opposite torsion around the centre

Table 1: Resonant mode frequencies associated with the symmetric (Sym) and asymmetric (Asym) structures

Mode	Sym	Asym1	Asym2	Asym3
1	1209.8	1237.2	1266.1	1315.8
2	1672.4	1675.3	1716.9	1842.1
3	1686.7	1793.5	1869.2	1884.4
4	7230.4	7261.4	7137.4	7014.7
$\Delta f_{31} = f_3 - f_1$	476.9	556.3	603.1	568.6

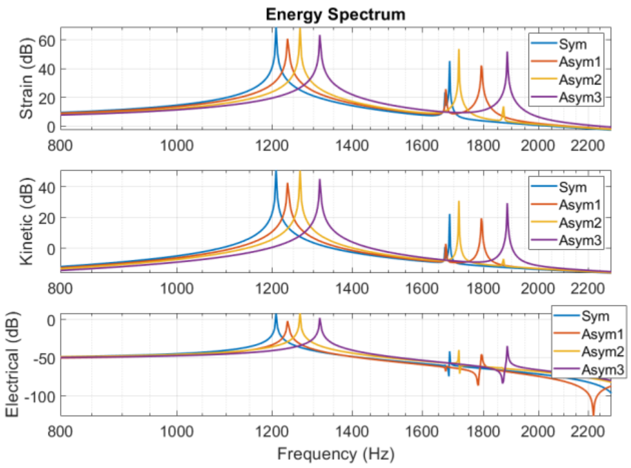

Fig. 4: Simulated harmonic energy spectrum for the proposed symmetric and asymmetric QOPS EH system, (a) Mechanical Strain Energy, (B) Electrical energy supplied to a 1MΩ resistor.

Asym3; see Table 1. For example, *Asym3* has experienced a higher increase in the spring stiffness of modes 2 and 3 compared with mode 1 as it can be seen in its resonance frequency shifts in mode 1 (Δf=13Hz), mode 2 (Δf=520Hz), and mode 3 (Δf=360Hz).

In addition, we have examined the frequency response of these structures by running direct harmonic analysis including piezoelectric and mechanical physics in Coventorware. The harmonic energy spectrum is simulated in 500 frequency points over 800Hz ~ 10 kHz bandwidth to highlight the critical frequencies only. The simulation results are shown in Fig 4. The strain energy and electrical output energy delivered to a 1MΩ resistor are illustrated separately for symmetric and asymmetric modes. It can be seen that the addition of asymmetries shifts up the resonant modes due to increased stiffness. In addition, this results in higher magnitude of non-dominant resonant modes, but these are still much smaller than the dominant mode. The experimental verification of the fabricated microdevices are reported in the following section.

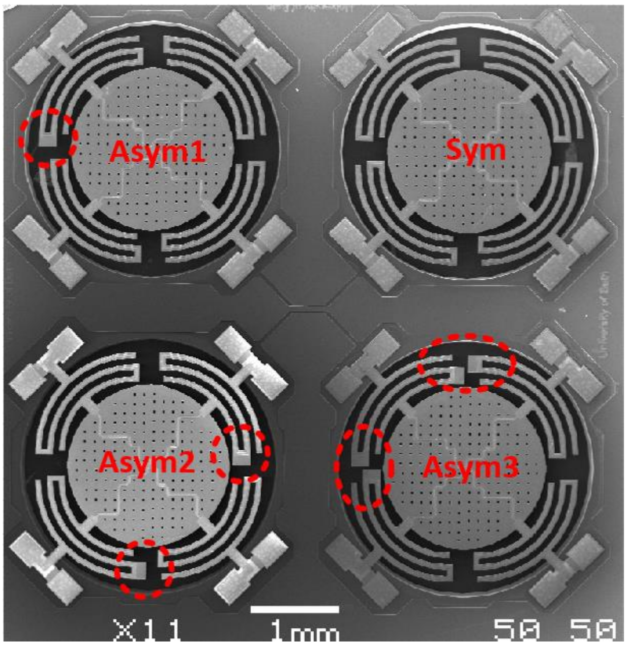

Fig. 5: SEM image of the chip manufactured in Pz-MUMP microfabrication process, with highlighted asymmetries in Asym1, Asym2 and Asym3.

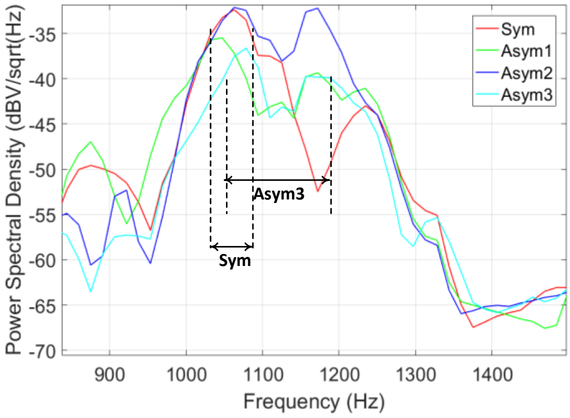

Fig. 6: Measured power spectrum of the symmetric and asymmetric configurations: adding asymmetric items increases the 3dB bandwidth.

MEASUREMENT RESULTS

The chip is implemented in Pz-MUMP microfabrication process technologies, and wire-bonded using non-vacuum chip-holders in our in-house cleanrooms for characterization purposes. An SEM image of symmetric and three asymmetric versions of the microdevice on the same chip is illustrated in Fig. 5. The chip-holder is mounted on a shaker, which is actuated by a sinusoidal sweep signal generator. The signal generator sweeps 0.5 kHz – 2 kHz frequency range in 40 s and the voltage output of the four QOPS EH resonators are measured individually by dynamic signal analyzer (SR760). The power spectrum of the measured voltages are shown in Fig 6, where it can be seen that the bandwidth increases by adding the asymmetries in the symmetric QOPS structure. In particular, the symmetric structure shows a sharper tip at the dominant resonant frequency whereas the asymmetric structures spread the output power over a wider spectrum. Critically *Asym3* is shown to have highest bandwidth compared with the symmetric structure. This is due to the increased stiffness of asymmetric springs in *Asym3*, which shifts the resonance frequency of modes 2 and 3 further away from the original symmetric frequency, as seen in Table 1. The results for Asym2 also agrees with the finite element analysis wherein the stiffness of springs has increased symmetrically for all modes, which has resulted in increased bandwidth but to a smaller degree than *Asym3*. Differences between the resonance frequencies attained in simulation and measurement might be due to the incomplete release etch at the back side of the circular disk mass, which adds to the weight of the microfabricated sample compared with the simulated 3D model.

CONCLUSION

The conversion efficieny of piezoelectric vibration energy harvesters is limited by sharp resonance behaviour especially in micro dimensions, which results in reduced ability to capture wideband meachnical vibrations. In this paper a arnge of nonlinear an dasymetric structures are investigated by both modelling and experimental charecterization to widen the bandwidth of these tansducers. The presented orthoplanar spring systems have potential for ease of integration in microfabrications processes. We investigated the effect of assymetric design in increasing the bandwidth. This approach provides a solution to realise broader band harvesting at the micro-scale using standard microfabrication processes.

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