A 3-DOF SOI MEMS ultrasonic energy harvester for implanted devices

A G Fowler1, S O R Moheimani1 and S Behrens2
1 School of Electrical Engineering and Computer Science, University of Newcastle, Callaghan, NSW 2308, Australia
2 CSIRO Energy Technology, PO Box 330, Newcastle, NSW 2300, Australia
E-mail: Reza.Moheimani@newcastle.edu.au

Abstract. This paper reports the design and testing of a microelectromechanical systems (MEMS) energy harvester that is designed to harvest electrical energy from an external source of ultrasonic waves. This mechanism is potentially suited to applications including the powering of implanted devices for biomedical applications. The harvester employs a novel 3-degree of freedom design, with electrical energy being generated from displacements of a proof mass via electrostatic transducers. A silicon-on-insulator MEMS process was used to fabricate the device, with experimental characterization showing that the harvester can generate 24.7 nW, 19.8 nW, and 14.5 nW of electrical power respectively through its x-, y-, and z-axis vibrational modes.

1. Introduction
Energy harvesting for microscale applications remains a major focus of microelectromechanical systems (MEMS) energy harvester that is designed to harvest electrical energy from an external source of ultrasonic waves. This mechanism is potentially suited to applications including the powering of implanted devices for biomedical applications. The harvester employs a novel 3-degree of freedom design, with electrical energy being generated from displacements of a proof mass via electrostatic transducers. A silicon-on-insulator MEMS process was used to fabricate the device, with experimental characterization showing that the harvester can generate 24.7 nW, 19.8 nW, and 14.5 nW of electrical power respectively through its x-, y-, and z-axis vibrational modes.

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1. Introduction
Energy harvesting for microscale applications remains a major focus of microelectromechanical systems (MEMS)-based research. Applications such as wearable electronics, wireless network nodes, and structural monitoring systems stand to gain a significant benefit by having their running time increased through the integration of MEMS-based energy harvesters [1–3]. In the majority of cases, such harvesting devices are designed to use environmental vibration sources to produce electrical power [4–6].

Implanted electronic systems in biomedical applications such as patient monitoring and drug delivery continue to use batteries as a primary power source, meaning that a surgical procedure is often required for battery replacement [7]. As a result, there is a continued interest in the development of methods to safely and reliably transfer electrical energy to electronic devices within the body. The use of ultrasonic waves as part of a MEMS-based energy harvesting system is a potential solution to this problem, with ultrasound having been demonstrated as being a viable means of transferring energy to a remote receiver [8, 9].

A MEMS-based 2-degree of freedom (DOF) ultrasonic energy harvester was reported in [10–12]. The device featured mechanical resonance modes in the in-plane x and y directions, and was used to harvest electrical energy from an external source of ultrasonic waves via electrostatic comb-finger transducers.

2. Design of a Novel 3-DOF Energy Harvester
This paper presents a MEMS energy harvester that is designed to utilize ultrasonic waves from an external transmitter as a source of mechanical excitation. In contrast to the 2-DOF system
Figure 1: a) Schematic diagram of 3-DOF ultrasonic energy harvester. b) Underside of harvester, with suspended substrate elements shown.

Figure 2: Simulated resonance modes. a) X axis. b) Y axis. c) Z axis.

reported in [12], the harvester uses a novel 3-DOF design that features mechanical resonance modes in the in-plane (x and y) and out-of-plane (z) directions. This configuration allows the system to harvest electrical energy in any orientation with respect to the external ultrasonic transmitter. Electrostatic comb-finger transducers are used to generate electrical energy from the mechanical vibrations of the harvester’s proof mass.

2.1. In-Plane Harvesting Mechanism
The MEMS harvester utilizes a parallel kinematic design for its in-plane harvesting mechanism, which is an extension of the 2-DOF structure presented in [12]. A schematic diagram of the device is shown in Fig. 1a. The harvester contains a proof mass in the center of the device, which is anchored to the substrate via a number of beam flexures. In addition to decoupling the motions of the mass in the x and y directions, the flexures are designed to create in-plane mechanical resonance modes at the desired frequency.

The in-plane oscillations of the proof mass are converted into electrical energy through the use of in-plane, overlap-varying comb finger electrodes placed around the edges of the device. Due to the decoupled motion of the mass, displacements in the x and y directions are harvested via independent electrodes.
2.2. Out-of-Plane Harvesting Mechanism
The MEMS harvester is also designed to feature an out-of-plane harvesting mechanism that enables the system to harvest energy from ultrasonic waves in the out-of-plane (z) direction. This mechanism is created by selectively etching the central structure to create a smaller 'sub-mass’, which remains connected to the remainder of the proof mass by a set of secondary beam flexures. This creates a nested structure, with the secondary flexures being designed to allow this sub-mass to possess a mechanical resonance mode in the out-of-plane direction. The entire mass structure continues to move in unison as a single unit for in-plane displacements.

The out-of-plane vibrations of the sub-mass are harvested via a separate electrostatic transducer, which takes the form of additional comb finger electrodes attached to both the sub-mass and the surrounding structure. This creates a variable capacitor whose capacitance is dependent on the out-of-plane displacement of the sub-mass. The silicon-on-insulator (SOI) layer is etched in strategic locations to electrically isolate the sub-mass from the rest of the moving structure. Elements of the die’s substrate are retained in these areas to maintain a mechanical connection between the electrically-isolated components, as shown in Fig. 1b.

2.3. Modal Simulations
The harvester is designed to be mechanically excited by ultrasonic waves from an external transmitter. To maximize the amplitude of the resulting vibrations and thus the harvested electrical power, the device’s resonance mode frequencies should be matched to the frequency of the transmitter. A target frequency of 25 kHz was used in the design of the harvester, as this is a common frequency for off-the-shelf ultrasonic transmitters.

The harvester was designed using CoventorWare, and a simulation of the device’s mechanical resonance modes are shown in Fig. 2. Both the in-plane and out-of-plane modes are located close to 25 kHz.

3. MEMS Harvester Fabrication
The harvester was fabricated via MEMSCAP’s SOIMUMPs prototype process [13], with 25 µm-thick doped silicon comprising the main device layer. The 400 µm-thick silicon substrate is largely etched away except in certain areas as described in Section 2.2, where it remains connected to the SOI layer via a 2 µm-thick layer of buried oxide.

Scanning electron microscope (SEM) images of the fabricated MEMS harvester are shown in Fig. 3.
4. Experimental Characterization

4.1. Identification of Resonance Modes

The resonance frequencies of the fabricated device were measured using a Polytec MSA-050-3D Micro System Analyzer (MSA). The MSA uses three laser vibrometers to measure the vibrations of a test subject, with the vibrations being resolved into their x-, y-, and z-axis components. The harvester was mechanically excited by applying a small-amplitude chirp signal with a 60 V DC bias to the device’s capacitive electrodes, with the resulting frequency response being shown in Fig. 4a. This magnitude plot indicates three clear resonance frequencies at 24.30 kHz, 24.08 kHz, and 26.23 kHz, corresponding with the resonance modes of the x, y, and z axes respectively. These are close to the target frequency of 25 kHz, with the variations being attributed to tolerances in the fabrication process.

The operation of the harvester’s electrostatic transducers was verified by performing a second frequency response measurement using the device’s electrical output. Each of the harvester’s transducers were biased with a 60 V DC voltage, and were connected in parallel to the input of a signal analyzer. The harvester was mechanically excited by a 25 kHz Prowave 250SR160 ultrasonic transmitter, which has a center frequency that is close to the frequencies of the harvester’s resonant modes. The transmitter was driven by a 20 V rms wideband chirp signal and placed near the MEMS device at a 45° angle to the harvester’s three axes. The three expected resonance modes are clearly evident in the obtained frequency response (shown in Fig. 4b), with the frequency of each mode being consistent with those obtained using the MSA.

4.2. Measurement of Harvested Power

The device’s power harvesting ability was measured by using the converted electrical energy to charge a load capacitor. The electrostatic transducers were each connected to a full-wave diode rectifier and a 1 µF electrolytic capacitor, with the voltage on the capacitor being monitored by...
an oscilloscope connected via a low-noise voltage preamplifier.

Testing was performed by placing the ultrasonic transmitter approximately 5 cm away from the MEMS harvester while aligned along one of the device’s primary axes. The transmitter was driven by a 20 Vrms sine wave at the identified frequency of the corresponding resonance mode, while the electrostatic transducers were again biased with 60 V DC.

The evolution of the voltages on the load capacitor resulting from the harvesting of the ultrasonic waves is shown in Fig. 5. Based on the calculated change in energy stored by the capacitor over the initial 15 second period, the average power harvested by the device was determined to be 24.7 nW, 19.8 nW, and 14.5 nW for the x, y, and z axes respectively.

5. Conclusion
The design and characterization of a MEMS ultrasonic energy harvester has been presented, which features a novel 3-DOF design that allows it to harvest energy regardless of its position with respect to an external source of ultrasonic waves.

The harvester was fabricated using a SOI MEMS process, with experimental testing showing that its resonance modes are close to the targeted frequency of 25 kHz. Its energy harvesting performance was demonstrated by exciting the device using an ultrasonic transmitter, with a load capacitor being used to collect the harvested electrical power.

This ultrasonic energy harvesting mechanism is particularly suited to applications such as the powering of implanted electronic devices for biomedical applications. The additional considerations that must be met to create a practical implantation of such an implantable system are the subject of future work.

Acknowledgments
This research was supported by the Australian Research Council (ARC) and the Commonwealth Scientific and Industrial Research Organisation (CSIRO). Experimental work was performed at the Laboratory for Dynamics and Control of Nanosystems at the University of Newcastle, Australia.

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