A MICRO CAPACITIVE VIBRATION ENERGY HARVESTER FOR LOW POWER ELECTRONICS

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Abstract: This paper presents the design and the experimental characterization of a micro capacitive device for harvesting of vibration energy. The mechanical design of the device was optimized to increase the capacitance variation. Increasing of capacitance variation improves the generated electrical voltage. An in-plane and area overlapping capacitive energy harvester was fabricated on a chip size of 6mm by 7mm based on SOI MEMS technology. The capacitance variation was maximized to a value of 70pF. Experimentally, the device generates an output voltage of 5.7Vp-p at acceleration amplitude of 1g with 25V as biasing DC voltage.

Keywords: Energy harvesting, capacitive converters, vibration energy, MEMS

INTRODUCTION

Smart environments are the future evolutionary development in buildings, industrial surroundings, at home and in automation systems [1]. Smart environments rely on sensory data which comes from multiple autonomous systems in distributed locations in the environment. Autonomous systems powered by ambient energy are not dependent on limited power sources and require no regular replacement of batteries. Typical autonomous systems are composed of one or more sensors, a microcontroller, an RF transmitter, a power management circuit, an energy storage and an energy harvester (Fig. 1).

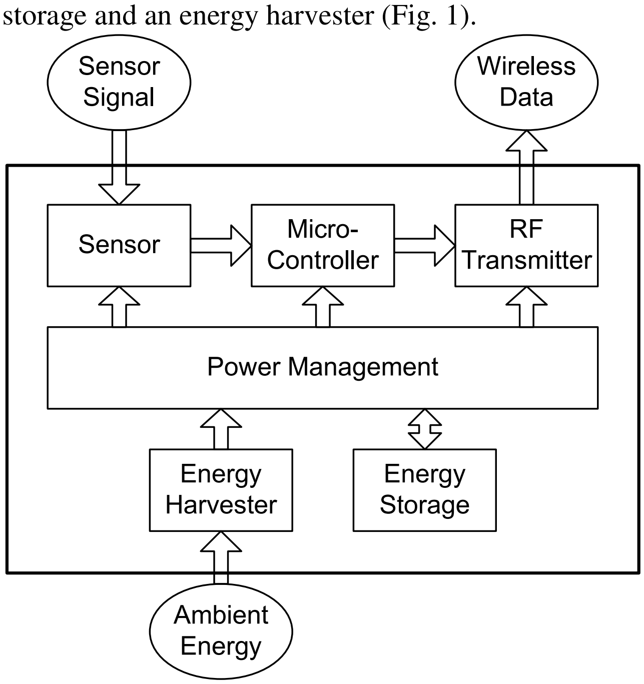

Fig. 1: Components of an autonomous system which is powered by energy harvesting.

The energy harvester converts ambient energy into electrical energy to power the electronics associated with the autonomous system. Ambient energy can be solar, electromagnetic, thermal or kinetic (e.g. vibration) energy [2]. This paper concentrates on the energy harvesting from vibration sources. Such vibrations can be found in the industrial and automotive fields with small amplitudes of acceleration and within a frequency range between 100 – 3000 Hz [3]. Converting vibration energy into electrical energy may be based on the inductive, piezoelectric or capacitive concept [4-6]. The capacitive concept has the potential to become the most preferable one in the future due to its miniaturization and compatibility with CMOS/MEMS fabrication technologies.

This paper presents the capacitive concept for converting the vibration energy into electrical energy, state of the art prototypes, the design of a micro capacitive vibration energy harvester with the emphasis on the improvement of capacitance variation, the fabrication and the experimental characterization of the device.

Energy Transduction

The capacitive harvester is composed of a seismic mass mechanically suspended by beams. This configuration can be modeled by a mass-spring-damper system (Fig. 2). This system is sensitive to vibration which results in deflection of the seismic mass.

The seismic mass is flanked by an electrode which forms the movable part of a variable capacitor.

A counter electrode is fixed on a substrate and it is called stationary electrode.

The deflection of the seismic mass results in a variation of the capacitance. The capacitance variation can be achieved by means of area overlapping or gap closing. In case of area overlapping, the mass deflection is in parallel to the capacitor's electrode such that only the overlapping area between the electrode and the counter electrode is changing. In the alternative case; i.e. the gap closing, the deflection of the seismic mass is normal to the capacitor's electrode such that only the gap between electrode and counter electrode is changing.

The variable capacitor is electrically polarized by integrating an electret on the stationary electrode [3, 7]. The electret is a quasi permanent charged dielectric material. This paper does not focus on the electret but on the mechanical design of the device.

The transduction of energy is based on the variation of an initially charged capacitor. The variation of the capacitor induces electrical charges on the movable electrode and therefore an electrical current is generated through the load.

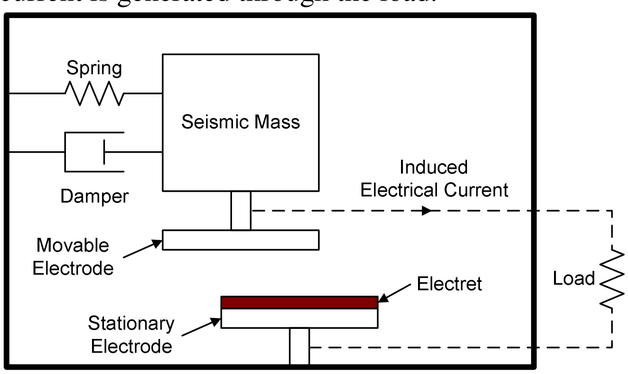

Fig. 2: Schematic view of capacitive harvester model.

State of the Art

The main characteristics of recent prototypes of capacitive vibration energy harvesters are presented in Table 1. The table presents for each referenced prototype the electrical output power per chip area (P_{out}), the biasing DC voltage (V_{bias}), the excitation acceleration amplitude (A_{ex}), the excitation frequency (F_{ex}) and the chip area (Area). The excitation acceleration amplitude is measured in units of gravitational acceleration (g) which is equal to 9.81 m/s^2.

The most important criterion of a harvester is the electrical output power value. However, the presented prototypes have different operation conditions which make such evaluation difficult. In general, the best harvester design should consider a large mass and a large maximum displacement of the seismic mass [5]. The design should also consider that the larger the capacitance variation is, the larger the magnitude of converted energy [3].

Table 1: State of the art of capacitive vibration energy harvesters.

Ref.	P_{out} µW/cm^2	V_{bias} volts	A_{ex} g	F_{ex} Hz	Area mm^2
This Work	11.9	25	1	1740	6x7
[6]	10.2	100	3	1000	7x7
[7]	4.1	600	3	50	18.5x16.5
[8]	1.2	9	3.3	1870	10x10
[9]	0.83	20	2.1	1500	5x6
[3]	0.064	15	1	2600	7x7

HARVESTER DESIGN & FABRICATION

In this work, the design is based on the mechanical optimization of the proposed prototype in [9] by means of maximizing the capacitance variation as well as increasing the mass to the possible largest magnitude within a certain layout area [3, 5] which is 4170µm by 5400µm in this case. The device is composed of a mechanical resonator with in-plane motion and a comb capacitive structure based on the area overlapping concept (Fig. 3). The capacitive structure optimization led to a one variable capacitor design as more layout area could be utilized compared to the design in [9].

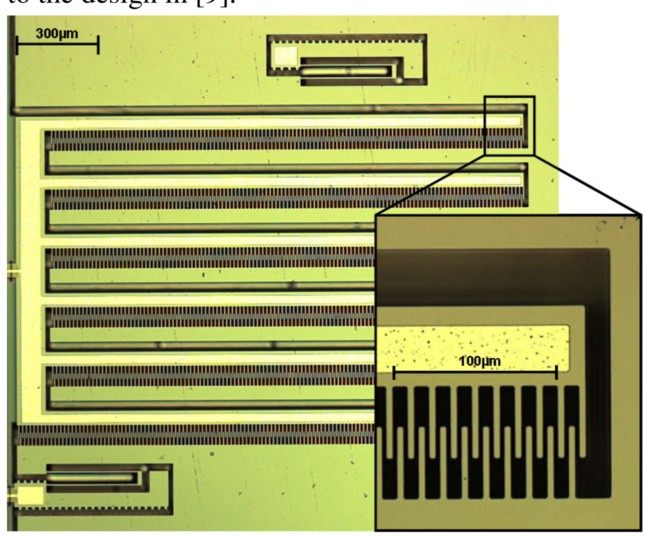

Fig. 3: Photograph of the fabricated micro capacitive energy harvester.

The mechanical resonator has a seismic mass of 918µg which is suspended by 8 U-springs each with a stiffness constant value of 17 N/m. The calculated natural resonance frequency is 1936Hz. The deflection of the seismic mass is limited to a peak amplitude of 20µm by using mechanical stoppers.

The capacitor electrode has a length of 45µm, a width of 4µm and a height of 50µm. The gab between each electrode and counter electrode is 2.5µm. The initial overlapping between electrodes is 20µm. The calculated initial capacitance is 35pF and the maximum possible capacitance change is 70pF.

The device was fabricated on a chip size of 6mm by 7mm at HSG-IMIT institute based on silicon-on-insulator (SOI) technology [9]. The chip consists of a 50µm device layer bonded to a substrate and an encapsulation wafer using glass frit bonding (Fig. 4). This provides protection of the micro structure and allows operation in a well defined pressure [9]. Both the substrate and the encapsulation wafer contain a cavity of 50µm depth to allow free movement for the seismic mass.

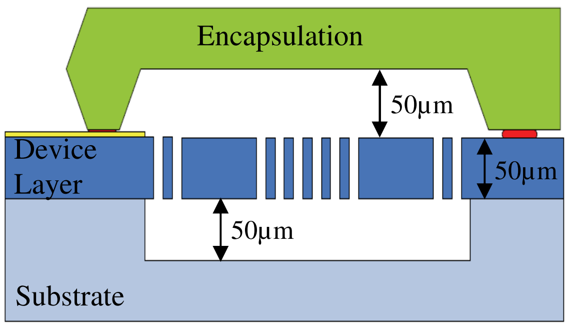

Fig. 4: Cross section view of the capacitive energy harvester chip.

EXPERIMENTAL RESULTS

The measurement setup consists of a mechanical shaker as a vibration energy source, a DC voltage source for electrical biasing of the variable capacitor and a resistive load (Fig. 5). The chip containing the micro capacitive energy harvester and a reference accelerometer are mounted on the mechanical shaker TIRAvib TV51110 (Fig. 6). The reference accelerometer, the control unit and the amplifier are used to control the mechanical shaker to a specific acceleration amplitude and frequency value (Fig. 5). The desired acceleration amplitude and the frequency value can be assigned by using control software which is associated with the mechanical shaker.

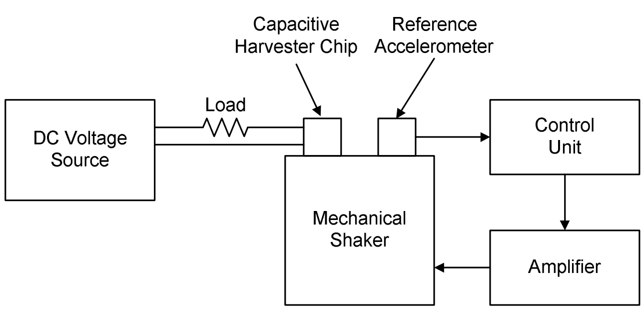

Fig. 5: Schematic of the measurement setup

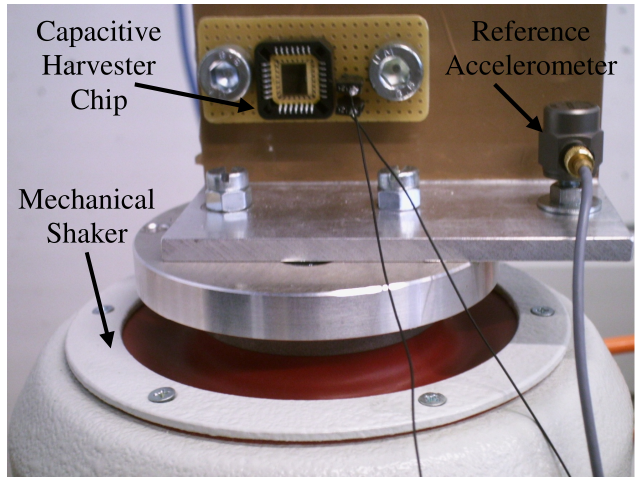

Fig. 6: Photograph of capacitive harvester chip and reference accelerometer mounted on the mechanical shaker.

The initial capacitance of the device is determined at the mechanical rest; i.e. no excitation acceleration is exerted on the device. A precision impedance analyzer (Agilent 4294A) is used to measure the capacitance which is found to be 38pF. This measured value is very close to the calculated value of 35pF.

The natural resonance frequency is investigated by connecting the chip in series to 10MΩ resistor and biased by a DC voltage value of 1V. The low voltage value is used in order to minimize the possible effect of electrostatic force on the resonance frequency. The chip is then mechanically excited with low vibration amplitude of 0.1g in order to avoid the nonlinearities due to the mechanical stopper. The normalized output power is shown in Fig. 7. The natural resonance frequency is found to be at 1721Hz with a quality factor of 191.

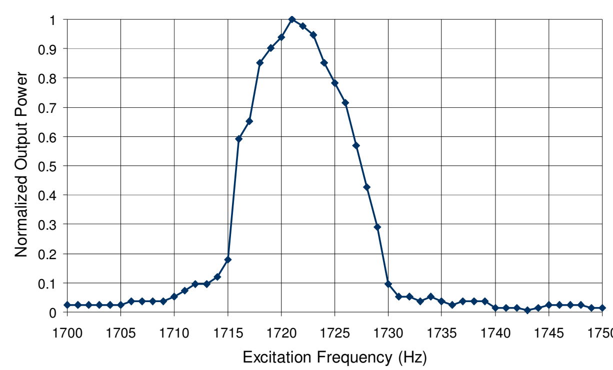

Fig. 7: Natural resonance frequency.

The effect of the mechanical stopper is investigated by exciting the chip with an acceleration amplitude of 1g at which impact with the mechanical stoppers occurs. The chip is connected in series to an 800kΩ resistor and biased by a DC voltage of 10V.

The maximum output power is found to be 718nW RMS. The frequency response shows a bandwidth of 230Hz (Fig. 8).

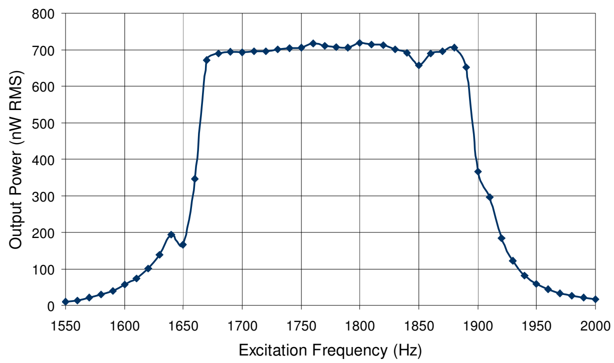

Fig. 8: Broad band frequency response.

The maximum possible output power is investigated by sweeping the biasing DC voltage. A maximum output power of 5µW RMS is generated at an 800kΩ load resistance when the device is mechanically excited with an acceleration amplitude of 1g, at a frequency of 1740Hz and biased by 25V (Fig. 9). The electrostatic force response of the device increases nonlinearly with the applied biasing DC voltage (Fig. 9).

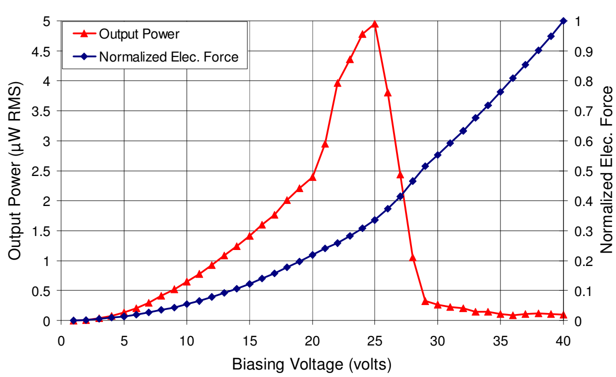

Fig. 9: Electrical output power and the normalized electrostatic force.

DISCUSSION

The generated output power starts to dramatically decrease after the maximum point (Fig. 9). The higher electrostatic force reduces the deflection amplitude of the seismic mass, thus the converted amount of mechanical energy and also the electrical output power decreases.

The device can be characterized by the value of output power per chip area in order to compare between different devices. In this work a value of 11.9µW RMS/cm^2 is achieved which is a new improvement among the presented devices in table 1.

CONCLUSION

A micro capacitive vibration energy harvester was designed, fabricated and experimentally characterized. The device generates an output voltage of 5.7Vp-p at an 800kΩ load. A broad band frequency response is observed when the nonlinear effect of mechanical stoppers is utilized.

ACKNOWLEDGEMENT

This work is supported by the German Research Foundation (Deutsche Forschungsgemeinschaft – DFG) under grant number GR 1322.

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