# Design and Fabrication of 3D Electrostatic Energy Harvester

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**Abstract.** *This paper discusses the design of an electrostatic generator, power supply component of the self-powered microsystem, which is able to provide enough energy to power smart sensor chains or if necessary also other electronic monitoring devices. One of the requirements for this analyzer is the mobility, so designing the power supply expects use of an alternative way of getting electricity to power the device, rather than rely on periodic supply of external energy in the form of charging batteries, etc. In this case the most suitable method to use is so-called energy harvesting – a way how to gather energy. This uses the principle of non-electric conversion of energy into electrical energy in the form of converters. The present study describes the topology design of such structures of electrostatic generator. Structure is designed and modeled as a three-dimensional silicon based MEMS. Innovative approach involving the achievement of very low resonant frequency of the structure, while the minimum area of the chip, the ability to work in all 3 axes of the coordinate system and the ability to be tuned to reach desired parameters proves promising directions of possible further development of this issue. The work includes simulation of electro-mechanical and electrical properties of the structure, description of its behavior in different operating modes and phases of activity. Simulation results were compared with measured values of the produced prototype chip. These results can suggest possible modifications to the proposed structure for further optimization and application environment adaptation.*

## Keywords

MEMS, energy harvesting, electrostatic, generator.

## 1. Introduction

Due to great progress in the microelectronics there are applications with large demands on the individual components of the application chain. One example is an intelligent wireless sensor network [1] where each node needs to maximize the time that the sensor works and is independent of the energy supply from an external source. Using conventional batteries is not always convenient, because it requires human intervention for their replacement. For this reason it is a major problem to get electricity needed to operate these devices. One way to ensure power is to use other types of energy that are available in the vicinity of the powered device. Most of these devices use (depending on usage field) the heat, light or mechanical energy. In this way, gaining power can meet energy requirements throughout the life of the powered device. The process of obtaining energy from the environment, converting it into consumable electricity is generally known as energy harvesting. Devices using the principles of gathering energy are usually referred to as energy generators.

### 1.1 Sources of Energy Harvesting

The classification of energy harvesting can be organized on the basis of the form of energy they use to scavenge the power. For example piezoelectric harvesting devices scavenge mechanical energy and convert it into usable electrical energy. The various sources for energy harvesting are wind turbines, photovoltaic cells, thermoelectric generators and mechanical vibration devices such as piezoelectric devices, electromagnetic devices. Tab. 1 shows some of the harvesting energy sources with their power generation capability. The general properties to be considered to characterize a portable energy supplier are described by Fry, et al. [2].

| Energy Source | Power Density |
|---|---|
| Acoustic Pressure | 0,003 $\mu Wcm^{-3}$ (75 dB)<br>0,96 $\mu Wcm^{-3}$ (100 dB) |
| Temperature | 10 $\mu Wcm^{-3}$ |
| HF EM field | 1 $\mu Wcm^{-2}$ |
| Light | 10 $mWcm^{-2}$ (direct sun light)<br>100 $\mu Wcm^{-2}$ (office conditions) |
| Vibrations | 4 $\mu Wcm^{-3}$ (human power)<br>800 $\mu Wcm^{-3}$ (machines)<br>200 $\mu Wcm^{-2}$ (piezo) |
| Airflow | 1 $\mu Wcm^{-2}$ |

**Tab.1**. Power density of different energy sources.

Typical forms of ambient energy can be considered as solar radiation, mechanical (vibrational) energy, thermal energy or RF or microwave radiation. Sources working on the principle of collecting electrical energy can be used to extend run-time or can be used as an additional source in conjunction with a conventional power source (battery) or they can completely replace these primary power units [3].

The device, powered by such energy generator can then be used in inaccessible places or areas dangerous to humans and report status information remotely.

## 1.2 Energy Harvester Structures

In recent years, many published papers show several concepts of small energy harvesters, because this is becoming a key topic for today's mobile applications.

Micromachined silicon MEMS version of the cantilevermass geometry has been developed under a project funded by the European Union Framework 6 programmes entitled vibration energy scavenging (VIBES). The device, shown in Fig. 1, consists of a 1.5 mm × 0.75 mm area inertial mass deep reactive ion etched (DRIE) from an SOI wafer with a 400 μm thick handle wafer, 2 μm thick buried oxide and a 5 μm thick top silicon layer. The supporting cantilever is fabricated from the top silicon layer only and is 750 μm long. The structure has been simulated with 1 μm thick layers of aluminium nitride (AlN) and PZT piezoelectric materials. Modelling results predicted 100 nW for the AlN device and 600 nW for the PZT device at resonant frequencies of approximately 900 Hz [4].

The electromagnetic energy harvester has been developed by Beeby et al. A silicon-based generator comprises micromachined paddle, four NeFeB magnets and a wire-wound coil [5]. The device is shown in Fig. 2. Two of the magnets are located within etched recesses in the two Pyrex wafers, which are anodically bonded to each face of the silicon wafer. The coil is located on a silicon cantilevered paddle, which is designed to vibrate laterally in the plane of the wafer. The device has a resonant frequency of 9.5 kHz and has been shown to generate 21 nW of electrical power from 1.92 $ms^{-2}$ rms.

Fig. 3 shows an equivalent electric circuit of the inertia generator. The electronic circuit in the fuze consists of active components, i.e., microprocessors and operates after finishing charge process at the capacitor. To maximize the stored energy in a capacitor, the capacitor's capacitance should be designed as the optimized one.

Tashiro [7] describes a honeycomb structure as shown in Fig. 4 made up by folding a strip of a polyester film with aluminium evaporated on one surface. Two sheets of the film each 5 μm thick by 30 mm wide and 5 m long were mated together using a double-sided adhesive tape at 5 mm intervals. Then the sheets were folded and joined again using a doublesided tape. This produced a variable capacitor with 20 cells per layer and 50 layers resulting in 100 cells. The capacitor was suspended between acrylic boards using 12 springs and an inertial mass attached to one of the acrylic boards. The spring constant of the resonator was 1100 $Nm^{-1}$ with a total mass of 0.78 kg resulting in a resonant frequency of 6 Hz. After initially charging the capacitor to 45 V the generator was shaken at by a simulation of the movement produced by the left ventricular wall motion of a canine heart and produced a mean power of 36 μW (15 μA at 2.4 V) with peak powers as high as 500 μW. Accelerometer measurements showed this movement to be about 1 $ms^{-2}$ at 6 Hz.

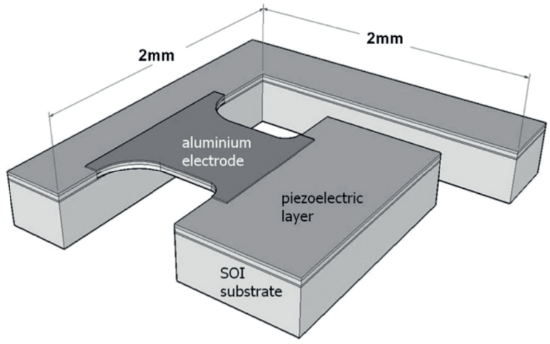


**Fig. 1.** Micromachined silicon cantilever mass piezoelectric generator [4].

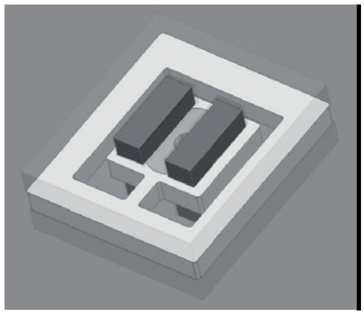

**Fig. 2.** A silicon electromagnetic generator ([5]).

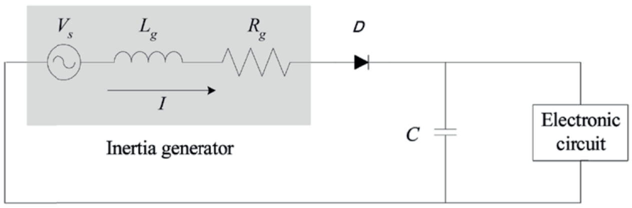


**Fig. 3.** A silicon electromagnetic generator [6].

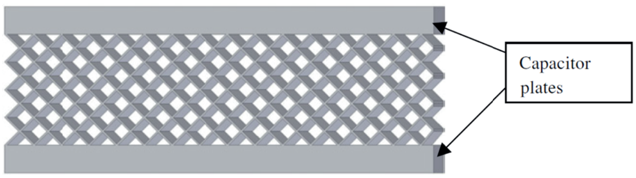


**Fig. 4.** Honeycomb-type variable capacitor [7].

## 1.3 Energy Harvester Propose

The main goal is to design the structure topology of the electrostatic generator in standard technologies available on the market. Structure based partly on basic beam structure is designed and modeled as three-dimensional silicon based MEMS. The main task is to optimize the dimensions of the structure due to the available production technology, optimize the geometry of the structure itself with regard to the environment in which the generator will be used and obtaining the excitation energy. Compared to already published proposals we expect to work in all 3 axes of Cartesian system. This makes the system more effective to environment waste energy and makes it possible to use all energy available. Another part of this work is a simulation of electro-mechanical and electrical properties of the structure, description of its behavior in different operating modes and phases of activity. After verifying the behavior of structures in the simulations the next task is the preparation of the production data in accordance with the design rules specified in the by the manufacturers delivered design kit. The fabricated prototype was characterized, tested on basic functions and these results will be later compared with simulated values.

## 2. Designing the Harvester

The designed power source is using a combination of electrostatic and piezoelectric generator (as required start-up power source) in the form of MEMS structures. Using CoventorWare we designed layout topology and 3D models. For a given structure solving network equations of deformation and mechanical stress were defined. Using the harmonic analysis we obtained response to changes in the structure of the excitation signal. Electrostatic generator uses the forces generated between the opposite charges on the plates of a charged capacitor. Separation of charge Q on the electrodes depends on the potential difference V between them according to equation $Q = CV_{VAR}$. The $C_{VAR}$ capacity is a function of geometry (topology) and electrode properties of materials that surround them. When moving a mass *m* in the range of *z(t)*, as shown in Fig. 5, the capacity changes between $C_{MAX}$ and $C_{MIN}$. From the mechanical movement extracted energy depends on how the variable capacity is connected to other electronic circuits. There are basically two basic techniques that were used to implement the electrostatic generator - switching or continuous mode.

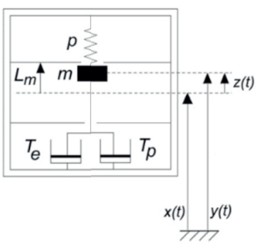


**Fig. 5.** Inertia generator principle.

### 2.1 Switching Mode – Constant Charge

In the case of using switching modes there is a switch between the generator and the rest of the circuit which allows time-dependent reconfiguration of the device (charging, discharging). When a pre-charged capacitor at its maximum capacity is disconnected from all external circuitry and the electrodes movement leads to a reduction of its capacity, but also to the generation of work, corresponding to overcome the electrostatic forces acting between the electrodes. This additional energy gained can then be used to power the circuit. The most common way to implement this system is shown in Fig. 6.

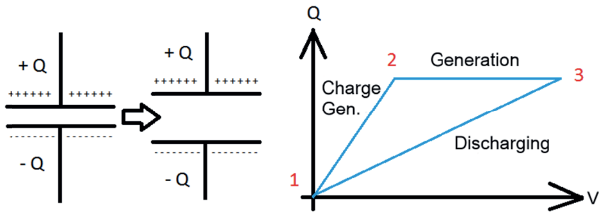


**Fig. 6.** Principle of operation of electrostatic generator in the constant charge mode and its QV characteristics.

Two parallel plate electrodes are arranged so that they could move away from each other. This kind of movement, in the case of constant charge on both plates of a capacitor, creates a constant force between these two electrodes. Fig. 6 shows the QV characteristic of the whole working cycle. First, the capacitor is connected to a power source and the electrodes are charged to the low voltage (jump from point 1 to point 2). Then the capacitor electrodes are disconnected from the source and moved away from each other while maintaining a constant charge on the electrodes (2-3). Finally, the charge is discharged within the third cycle (3-1). The capacity is then increased again and the generator is ready for a new cycle. The area bounded by trajectories connecting points 1 to 3 corresponds to the energy generated.

### 2.2 Switching Mode – Constant Voltage

If the capacitor is charged in advance and then, still connected to the constant voltage source, its capacity by moving panels to each other increases; it will increase the surface charge density and increase the electrostatic force between the charges on the capacitor plates. This is the constant voltage method. If the capacitor plates are operated in sliding mode, as shown in Fig. 7, the forces between the plates in the direction of relative movement remain constant.

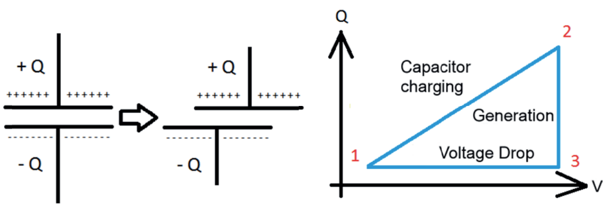


**Fig. 7.** Principle of operation of electrostatic generator in the constant voltage mode and its QV characteristics.

Fig. 7 shows the QV characteristic of the electrostatic generator working in constant voltage mode. The capacitor is pre-charged at its maximum capacity (1-2). Then, still connected to a power source, there is a reduction in capacity due to mechanical motion (receding from each electrode) and the charge returns back to the source (2-3).

This is the generation part of the cycle. Then the switch disconnects the capacitor from the power supply voltage, capacity is gradually increasing and stabilizing the charge at its initial value (3-1). Again, the area bounded by the curve in the QV characteristic is the amount of energy produced.

# 3. Harvesters Topology

There are three different types of electrostatic generator topologies, which differ in the way of mutual movement of fixed and movable electrode.

## 3.1 In-Plane Overlap Topology

The first type of generator shown schematically in Fig. 8 is called "In-Plane Overlap". This generator creates a capacitive difference in the plane of vibration device in the direction shown in Fig. 8.

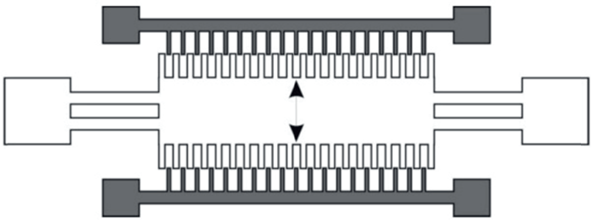

**Fig. 8.** In-Plane Overlap Topology [3].

This movement causes the overlapping area of comb electrodes changes, leading to a desired change in capacity. The maximum displacement is limited by the spatial gap in the direction of motion. To prevent damage to structures due to impact of both electrodes we propose mechanical stops to be used. Mechanical stops define the minimum gap forming the dielectric in the comb electrode structures, thereby determining the maximum capacity of the entire system. However, due to the topology of the two finger electrodes it is necessary to take such a risk of mechanical excitation, which causes torsion structures and possible short circuit between the electrodes.

## 3.2 In-Plane Gap Closing Topology

The second type known as "In-Plane Gap Closing", see Fig. 9, uses the same topology as the previous type, but the direction of the electrode is perpendicular to the direction used for type "In-Plane Overlap". Capacity change is directly proportional to the width of the gap between the electrodes.

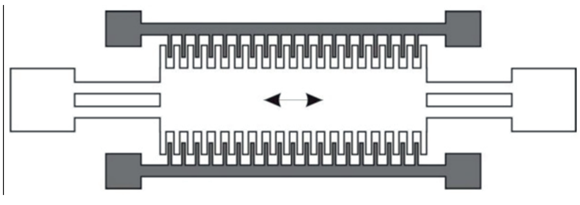

**Fig. 9.** In-Plane-Gap Closing Topology [3].

Like the previous type, this topology has the same limitations that require mechanical stops to prevent damage to the system. Roundy et al. [8] points out that this type of topology is more manageable and less prone to torsional motion and therefore it is most often used in practice.

## 3.3 Out-Of-Plane Topology

The last type of topology shown in Fig. 10 is referred to as "Out-of-Plane". Based again on the topology of the previous two solutions, but this time the direction of motion is perpendicular to the surface generator. Oscillating movement of the electrode surface provides the capacity change.

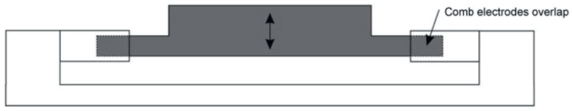


**Fig. 10.** Out-of-Plane Topology [3].

Topology "Out-of-Plane" is largely influenced by the damping caused by air flow in thin spaces between the fingers of the electrodes. In order to achieve satisfactory performance, this topology is suitable to operate in a vacuum. Then it is possible to achieve substantial growth in output. The possibility of encapsulation into the vacuum depends on the actual application. In addition, it is necessary to consider the mechanical stops to prevent the movable electrode from contacting the ground, which would lead to a short circuit.

# 4. Energy Conversion Cycle

For each of the above described topologies there can be defined the relative position of electrodes at which it reaches the maximum or minimum capacity. However, what distinguishes these three topologies apart is the way to reach this maximum value. In-Plane Overlap type uses overlap change between the finger electrodes, the second type (In-Plane Closing Gap) changes the gap between the electrodes and Out-of-plane type changes the gap between the whole electrode plates. Greater popularity of the generating methods has the constant charge method, because it requires only one source of energy (eg battery). For this reason, further theoretical analysis will focus solely on this method. In describing the electrostatic generator, we assume the existence of a system moving in the shape of electrodes forming a capacitor structure. The energy conversion cycle begins with the vibration of the structure. At this time the capacitor reaches its maximum value $C_{MAX}$ and the capacity is connected to an external power supply that charges the capacitor plate to voltage $V_{START}$. This voltage can now be measured directly between the electrodes. The whole process is a path from point A to point B in Fig. 11.

After charging the capacitor to $V_{START}$ the plates start to move away from each other. The electrodes are electrically separated from each other and the physical distance between them begins to grow. This is a step that is itself an act of conversion of mechanical energy into electricity (in Fig. 10, B to C). During this phase, the charge on the plates remains constant; however, capacity decreases to a minimum $C_{MIN}$, and the potential difference between capacitor plates increases to a maximum $V_{MAX}$. Finally, when the variable capacitor again reaches its minimum value $C_{MIN}$, the charge on the capacitor is seduced back into the power source (battery). This is represented by the path from C to A, where the conversion cycle closes. A $C_{PAR}$ capacitor is parallel connected capacitor to the structure of the MEMS capacitor, which limits the maximum size of the voltage on the electrodes so as to avoid exceeding the dielectric strength and damage to the capacitive structures or switches. Sometimes this is a capacitor built in the form of parasitic capacity structure. With the addition of this capacitor into the equations of generated voltage and the energy obtained is transformed into shapes.

$$V_{MAX} = \frac{C_{MAX} + C_{PAR}}{C_{MIN} + C_{PAR}} V_{START}, \tag{1}$$

$$E_{CONV} = \frac{1}{2} V_{START}{}^{2} \frac{C_{MAX} + C_{PAR}}{C_{MIN} + C_{PAR}} (C_{MAX} - C_{MIN}), \tag{1}$$

$$E_{CONV} = \frac{1}{2} V_{START} V_{MAX} (C_{MAX} - C_{MIN}) \tag{3}$$

where $E_{CONV}$ represents the amount of energy obtained by conversion of mechanical energy into electricity in a single conversion cycle.

## 5. Topology Design and Models

The CoventorWare was used to create topology layout of the comb capacitor structure, the 3D model, simulation net, and to provide the electromechanical simulations. CoventorWare is an integrated suite of design and simulation software that has the accuracy, capacity, and speed to address real-world MEMS designs. The suite is filled with MEMS-specific features for accurately and efficiently simulating all types of MEMS, including inertial sensors (accelerometers and gyros), microphones, pressure sensors, resonators, and actuators. The included field solvers provide comprehensive coverage of MEMS-specific multi-physics, such as electrostatics, electro-mechanics, piezoelectric, piezoresistive, and damping effects. The goal is to verify that the characteristics of the real products agree with simulated results.

The whole topology can be divided into three main parts (see Fig. 12);

- Movable bomb electrode (building also the central mass) – green (part A) on picture;
- Fixed electrodes – red (part B) on picture;
- Spring suspension – blue (part C) on picture.

While the first two parts are paid attention only from the perspective of common areas in order to maximize

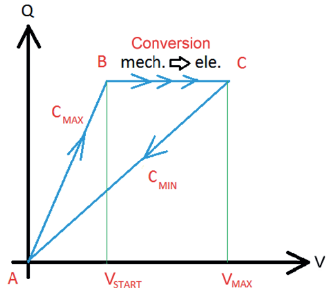


**Fig. 11.** Conversion cycle of generator based on constant charge method principle.

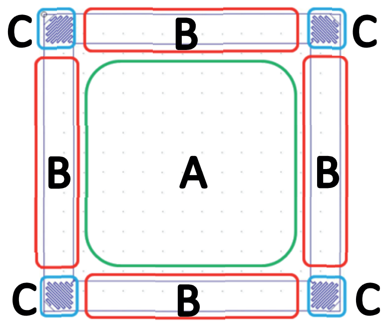


**Fig. 12.** Basic comb structure topology.

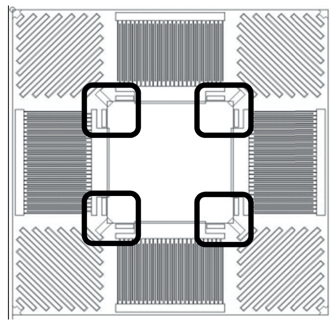

**Fig. 13.** Topology No. 4.

surface capacitance density, the third part is somewhat neglected while spring suspensions properties are crucial for many parameters of the resulting generator. The overall objective in the design topology of spring suspensions is their rigidity, minimum area, the distance between modal frequencies and amplitude (proportional to the magnitude of change).

Fig. 13 shows the 4$^{th}$ designed topology version, which already contains a complete set of both types of electrodes, modified spring suspensions and mechanical stops (highlighted), limiting the amplitude of mechanical displacement in order to avoid possible mechanical damage to the structure and short-circuit between the electrodes.

Fig. 14 shows the 8$^{th}$ version, in which spring suspensions are formed by wrapping the periodic structure of the girder type. Thanks to this we achieved such a suspension structure, which is mechanically equivalent to the suspension beam of great length, but on a much smaller effective area. Because of technological reason we changed the position of two contact pads on solid electrodes. Due to the asymmetrical handle of spring suspensions (see Fig. 14) to the moving electrode we obtained very little difference between the 1st and the 2nd modal frequency of the structure. In the case of fine oscillations a smooth transition from one type of conversion mechanism to another occurs which leads to increased efficiency and yield of the conversion cycle. Fig. 13 shows the final 9th topology, which was sent to production foundry and was modeled for simulations.

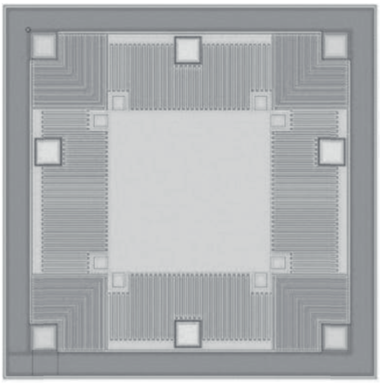

**Fig. 14.** Final 9th topology.

# 6. 3D Model

A 3D model has been created for electromechanical simulations in CoventorWare. Figs. 15-17 show details of the generated 3D model.

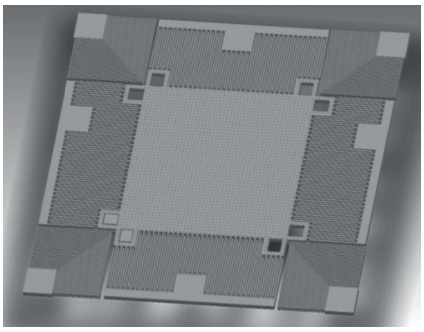

**Fig. 15.** 3D Model of topology No. 9 (only 2 stops visible).

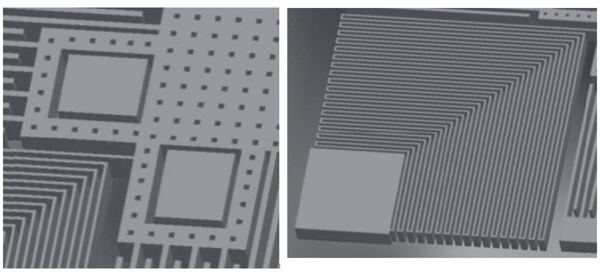

**Fig. 16.** Topology No. 9 (mechanical stops, spring suspensions).

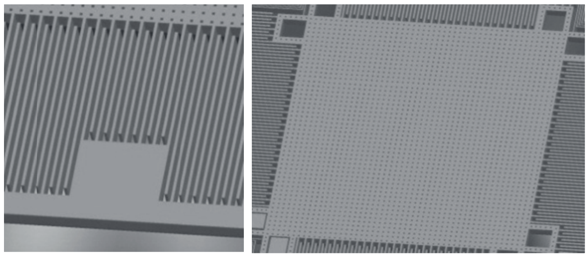

**Fig. 17.** Topology No. 9 (comb electrodes, central mass).

# 7. Simulations

## 7.1 Modal Analysis

Modal analysis can be obtained from the natural resonance frequency of the mechanical system in equilibrium. On these frequencies the mechanically undamped (lossless) system reacts to external motion excitation with unlimited deflection. The following figures show the mechanical simulations performed on the structure in CoventorWare. Figs. 18 and 19 show the degree and direction of the deflection structure. For the function generator only the first 4 natural frequencies are important, because in them there is the greatest change in the position of movable electrode. Other natural frequencies are already showing the effect of several orders of magnitude smaller. The scale of deflection is due to small shifts multiplied by the real and solid electrodes are not shown.

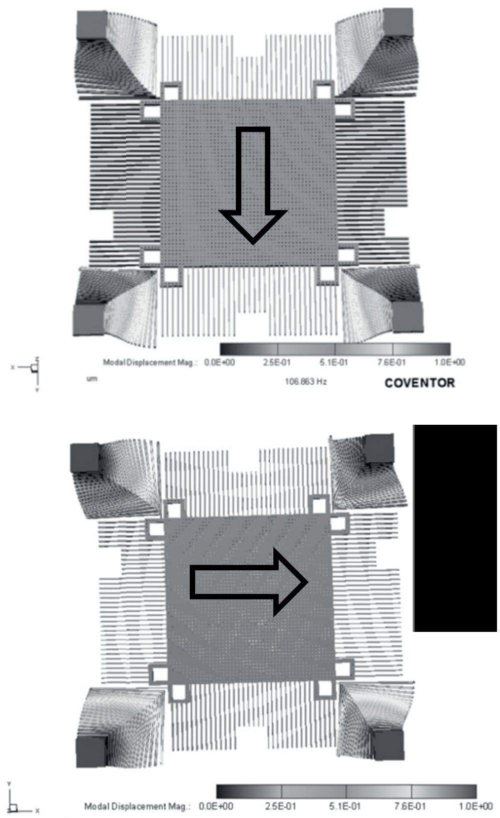


**Fig. 18.** 1st and 2nd modal frequency simulation.

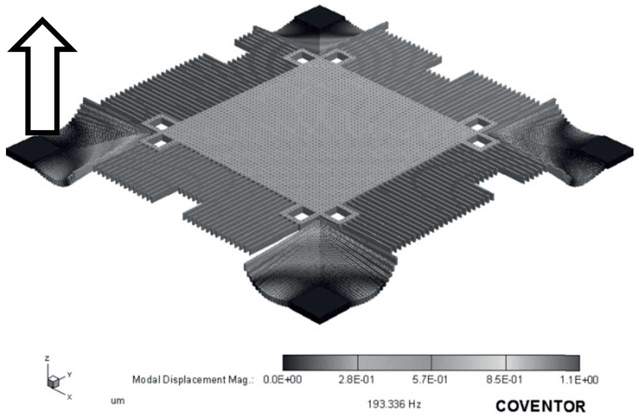


**Fig. 19.** 3rd modal frequency simulation.

Another important aspect is the mechanical stress (Fig. 20) inside the structure caused by mechanical vibrations. The most commonly used method of hanging capacitor structures in published papers is based on the topology of a simple bridge from one side firmly fixed to the frame chip and on the other side connected to the floating electrode. After exposure to mechanical vibration the movable electrode starts to swing. The maximum deflection of the assembly depends on the frequency of oscillation of the mechanical excitation, the total weight, mechanical properties of the material and topology. The weight is generally to reduce the natural frequencies and increase the deflection and internal stress.

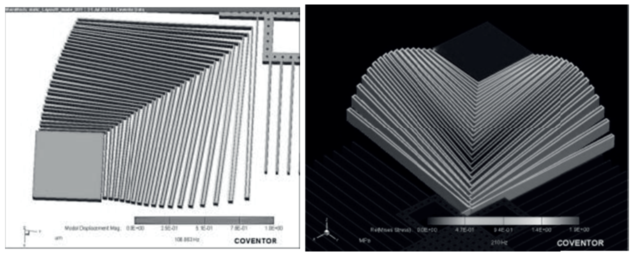


**Fig. 20.** Mechanical excitation (left) and internal stress on 3rd modal frequency

## 7.2 Harmonic Analysis

Using harmonic analysis, we can find the dynamic response of the system with harmonically variable load. Fig. 21 shows the statistical study of the mechanical response of structure to random excitation of periodic oscillations in all three axes. The vertical axis shows the excitation in X, Y and Z. The horizontal axis shows frequency in Hz. On frequencies around 100 Hz (1st and 2nd modal frequency) the structure shows a movement in both directions X and Y. Thus, there are local maxima of both curves X (blue) and Y (red). The 3rd modal frequency of 193 Hz has a major move in the Z axis, suggesting a local maximum of the green curve. The 4th modal frequency at which the structure exhibits rotational motion around the Z axis is seen in the local maxima of both curves X and Y. The 5th modal frequency at 305 Hz shows again movement mainly in the Z axis. The local minima at the 4th and 5th modal frequencies are equivalent to the standing wave due to movement around the axis or point of symmetry, which is located within the housing structure.

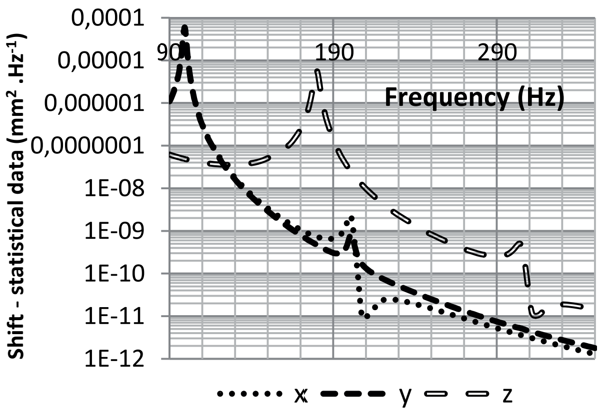


**Fig. 21.** Randon vibrations excitation in all three axis with a constant statistical distribution from 90 Hz to 350 Hz. Acceleration 3500 $(mm.s^{-2})^2.Hz^{-1}$.

# 8. Fabrication

The proposed generator was produced by SOI HARM 60 µm Tronics® technology. Figs. 22 and 23 show details of the laboratory sample.

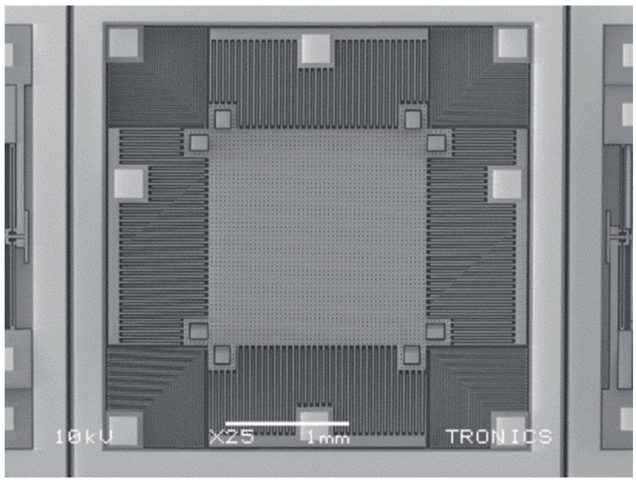


**Fig. 22.** Real sample of energy harvester.

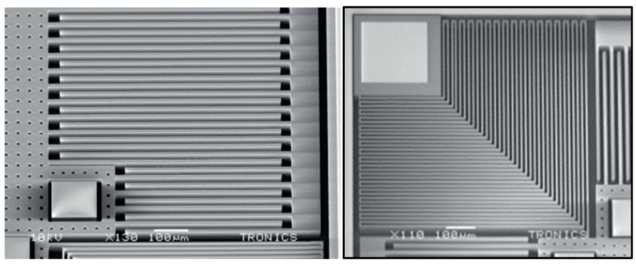


**Fig. 23.** Details of the real sample of energy harvester.

# 9. Characterization

A measurement chain for modal frequencies can be seen in Fig. 24. We use Capacitance Bridge with periodic signal excitation. The generator is placed on a vibration table KCF ES02 with KCF PA5100 signal generator.

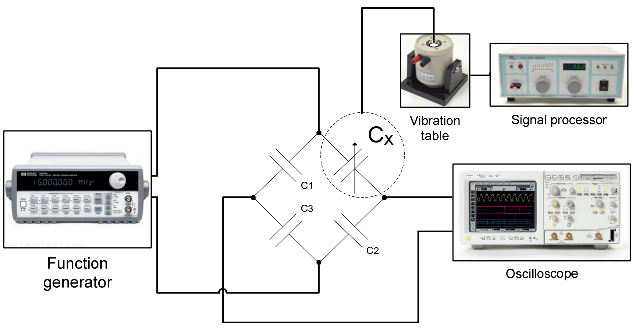


**Fig. 24.** Measurement chain for generator characterization,

# 10. Conclusions

The proposed generator is able to work in all 3 axes, has very low modal frequencies (about 108 Hz), in-build stops-structures against damage of the electrodes and very small dimensions. These properties make it possible to use this generator in embedded systems. It is proposed to be used in combination with piezoelectric source which acts as start-up source.

# Acknowledgements

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