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Modelling of silicon based electrostatic energy harvester for cardiac implants

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The concept of Energy Harvesting using the ability of heart to develop an acceptable amount of power for its natural operation (up to 10W) could address the power source requirements of leadless pacemakers. This paper presents a new structural geometry of Silicon based Electrostatic Energy Harvester which uses angled electrodes unlike the traditional harvesters for these pacemakers. It is observed that this topology provides a greater change of capacitance with respect to displacement compared to conventional topologies as it combines both In-Plane Gap and In-Plane Area Overlap capacitances. This harvester can thus be used as an alternate to the conventional battery sources used and act as a constant voltage source for various components of the pacemaker.

Keywords: Energy harvesting; Biomechanics; Electrostatic; Electrode; Pacemaker

1. INTRODUCTION

The output mechanical energy of the heart is in the order of ~1W. As the overall efficiency of the heart is about 20- 25%, this corresponds to an overall energy consumption of several Watts [1]. Therefore, it might be possible to scavenge tens of microwatts from the heartbeat by an energy harvester without affecting the natural functioning of the heart [2]. Hence, the goal of achieving self-powered electronic devices or battery less devices has gained attention and a lot of efforts have been initiated in this field. Energy harvesting is thus available as an option in powering of large number of devices and systems including the medical implants. Pacemaker is one such active implant device that needs continuous supply of power because the heart has to generate pulses all the time. Furthermore, knowing the fact that a significant amount of energy is produced in the human body, it motivates the development of an element or system that could extract a part of it. This generated energy is available at various locations in the body and can take different forms such as dissipated heat, inertia, muscle contraction, joint movement, heel strike, etc.

Vibrations are an effective source of energy present in the human body and we can use these vibrations for harvesting energy by converting the vibrations to electrical power. This idea of harvesting electrical energy from the body vibrations such as heartbeats, is gaining commendable interdisciplinary research interest. An analysis and comparison of three different types of vibration energy harvesting techniques: Electrostatic; Piezoelectric and, Electromagnetic Energy Harvesting for pacemakers has been presented in [3]. It can be concluded from the survey that Electrostatic based Transduction method of energy harvesting is most suitable for cardiac implants. The advantage of this technique is that it can be easily realizable as MEMS. Moreover, the output levels obtained satisfy the power requirements. One such research has been presented in [4] wherein a capacitance detection-based biosensor has been proposed which is Electrostatic in nature. The most essential feature of implants is that they should have small size that can be satisfied by using Electrostatic Transducer structure.

2. STANDARD TOPOLOGIES OF ELECTROSTATIC TRANSDUCTION

The electrostatic transduction mechanism uses a variable capacitor whose capacitance is changed as a function of the mechanical displacement denoted by x. In order to achieve maximum amount of harvested energy, the capacitance variation with respect to displacement needs to be as large as possible. There are various topologies for the MEMS electrostatic devices that differ in actuation direction. These standard topologies of the electrostatic transducers [5-7] and their capacitances are discussed below:

2.1 In-Plane Overlap

It is basically an inter-digitated comb structure with variable overlap of fingers and movement in plane as shown in Fig 1. This develops a capacitance variation by vibrating in plane of the device. For limiting the minimum dielectric gap in the inter-digitated fingers, the mechanical stops can be used.

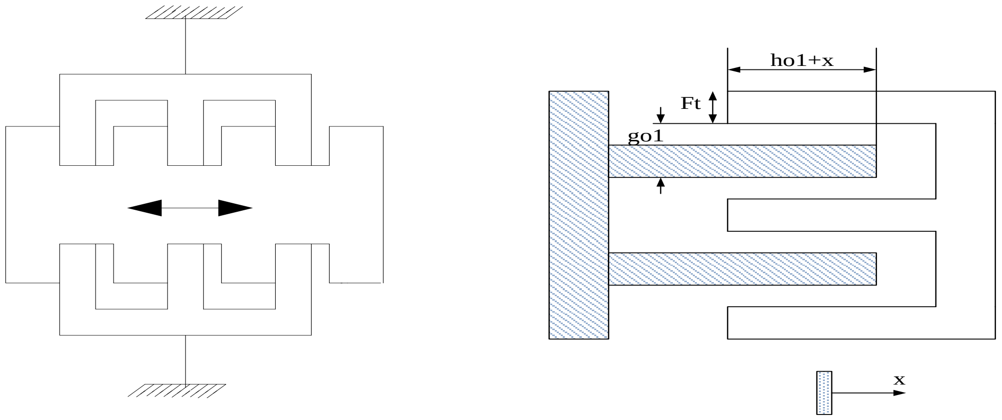

Figure 1 (a) In-Plane Overlap Converter (b) In-Plane Overlap Comb structure

Here $g_{o1}$is the initial gap between fingers, $h_{o1}$is the initial overlap of the fingers, F_t is the height of the electrode elements, x is the displacement, and Ɛ is the permittivity of the dielectric material between the electrodes of the capacitor. The capacitances C_1 and C_2 change with the movement of the mobile part of the structure. As can be seen, C_1 and C_2 appear to be in parallel hence are added up, i.e. $C = C_1 + C_2$ where, $C = 2C_1 = 2C_2$.

We know,

$$\text{Capactiance} = \varepsilon \, \frac{\text{Area of electrodes}}{\text{distance between electrodes}} \tag{1}$$

Here,

$$\text{Area of the electrode} = F_t \, [h_{o1} + x] \tag{2}$$

Hence, capacitance variation obtained can be given by the relation,

$$C = \frac{2\mathcal{E} F_t \, [h_{o1}+x]}{g_{o1}} \tag{3}$$

2.2 In-Plane Gap Closing

This represents an inter-digitated comb structure with variable gap between fingers and movement in plane as shown in Fig. 2.

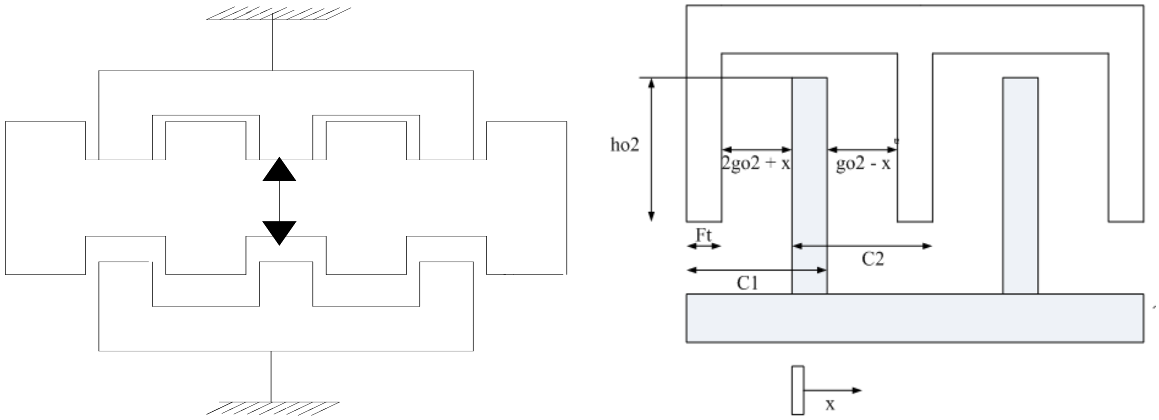

Figure 2 (a) In-Plane Gap Closing Converter (b) In-Plane Gap Closing Comb structure

Here g_{o2} is the initial gap between the fingers, h_{o2} is the initial overlap of the fingers and S_{o2} is the minimum gap at x_0. Since the two capacitances C_1 and C_2 appear to be in parallel combination, so applying the rule for total capacitance of two capacitances in parallel we get:

$$\mathrm{C} = \mathrm{C}_1 + \mathrm{C}_2 \tag{4}$$

where,

$$C_1 = \frac{\varepsilon \, F_t h_{o2}}{2g_{o2}+x} \text{ and } C_2 = \frac{\varepsilon \, F_t h_{o2}}{g_{o2}-x} \tag{5}$$

and,

$$g_{o2} = x_o + S_{o2} \tag{6}$$

Substituting these values, we get

$$C = ƐF_t h_{o2}\left[\frac{1}{2g_{o2} + x} + \frac{1}{g_{o2} - x}\right] \tag{7}$$

Simplifying it further, we get the final capacitance as,

$$C = \frac{Ɛ\, F_t h_{o2}[3(x_o + S_{o2})]}{(x_o + S_{o2} - x)(2(x_o + S_{o2}) + x)} \tag{8}$$

2.3 Out-of-Plane Gap Closing

This topology shown in Fig. 3 represents a planar structure with variable air gaps between plates and perpendicular motion to the plane. The capacitance variation is obtained here by varying the gap between the fingers.

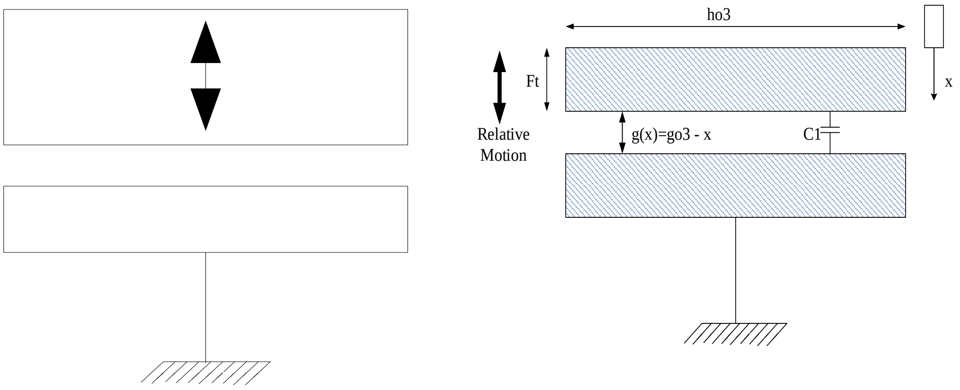

Figure 3 (a) Out-of-Plane Gap Closing Converter (b) Out-of-Plane Gap Closing structure

In this converter type, the motion of the mobile part of the structure is out of plane. The mobile electrode moves above the fixed electrode, this induces a variation of the gap between the electret and the mobile electrode. If g_{o3} is the initial gap between the two electrodes and h_{o3} is the initial overlap of the fingers, then

$$\text{Area of the electrode} = F_t\,[h_{o3}] \tag{9}$$

$$C = \frac{\mathcal{E}\, h_{o3} F_t}{(g_{o3} - x)} \tag{10}$$

3. PROPOSED TOPOLOGY AND IMPLEMENTATION

We can categorize the above discussed three standard cases either as Area-Sensitive or as Gap-Sensitive. Area-Sensitive topology includes the In-Plane Overlap topology whereas the Gap-

Sensitive topology includes the In-Plane Gap Closing and the Out-of-Plane Gap Closing topologies. In the Area-Sensitive topology, the capacitance variation is obtained by variation of area of overlap between the two electrodes of the capacitor structure whereas the gap between the electrodes remains constant throughout. In the Gap-Sensitive topology, the capacitance variation is obtained by the change in the gap between the electrodes of the capacitor structure whereas the area of overlap of the two capacitor plates or electrodes remains the same. In order to maximize the obtainable capacitance variation, we can think of a more advanced geometry that includes the sensitivity of both area and gap.

A new geometry for the fingers (electrode elements) of the harvester structure which is made of Silicon (Si), in which an angular component *'A'* in the electrode geometry introduced, has been proposed in this paper as shown in the Fig 4. By doing so we are able to obtain both the area and gap-based capacitance variations.

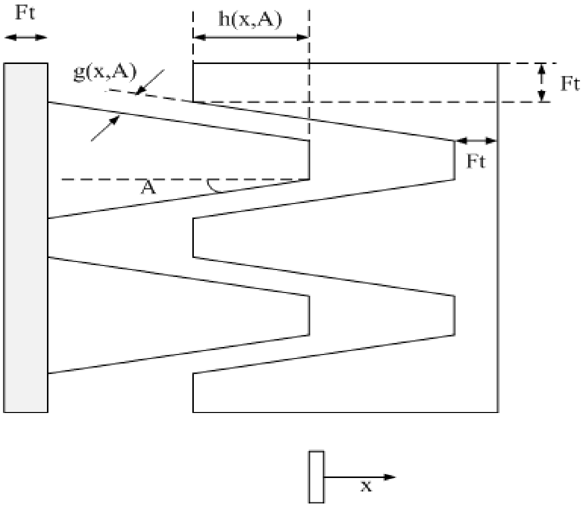

Figure. 4: Architecture of the Proposed Comb Structure based Electrostatic Converter

Various design parameters considered in the proposed topology are *x* which is the displacement of the mobile part of the inter-digitated comb structure; *g(x,A)*the gap between the fingers as a function of angle A and displacement *x*; *h(x,A)* is the overlap between the fingers as a function of angle A and displacement *x*.

3.1 Capacitances Calculations

Various dimensions of the proposed structure are shown in Fig. 5. The vibration source causes a displacement of the mobile part of the comb structure that is denoted by *x*. Now this displacement *x* causes the variation of capacitance by varying the area of overlap of the two electrodes as well as the gap between them.

First of all, considering the variations due to the changes in the area of overlap of the two electrodes:

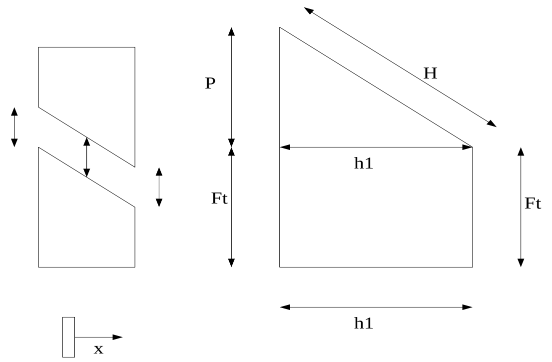

Figure. 5: Variations due to the changes in the area of overlap of the two electrodes

$$\text{Area of the overlapping parts of the electrodes} = \mathrm{F_t} * \mathrm{H} = \left(\frac{\mathrm{h_1}}{\cos \mathrm{A}}\right) * \mathrm{F_t} \tag{11}$$

where, h_1 is the initial overlap length of the mobile and the fixed part of the structure. Therefore, Capacitance is given by the expression:

$$C_1 = \frac{2\mathcal{E}(h_1 + x/cosA)F_t}{(g_o - x)} \tag{12}$$

We have to consider the variations caused in the capacitance due to the changes in the gaps between some of the other parts of the two electrodes. The variations of capacitance obtained here are denoted by C_2 and can be represented as in Fig. 6.

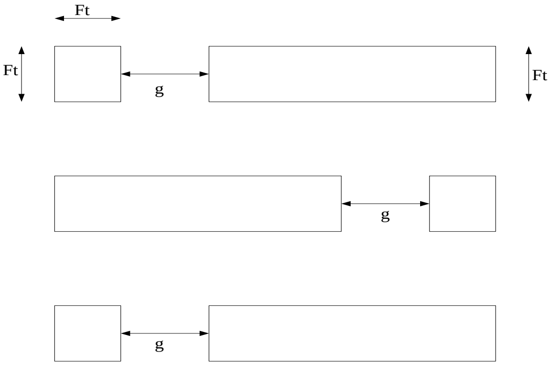

Figure. 6: Variations due to the changes in the horizontal gap between the two electrodes.

Here, we have

$$g = g_o - x \tag{13}$$

$$\text{Area of the overlapping parts of the electrodes} = \mathrm{F_t} * \mathrm{F_t} \tag{14}$$

And,

$$C_2 = \frac{3\mathcal{E}(F_t{}^2)}{(g_o - x)} \tag{15}$$

Next, considering only the changes in the gap between slanting faces of the electrodes as shown in Fig. 7

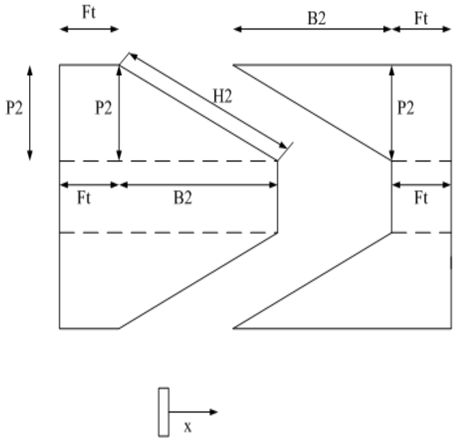

Figure. 7: Variations due to the changes in the slanting gap between the two electrodes

$$\text{Area of the overlapping parts of the electrodes} = \mathrm{F_t} * \mathrm{H_2} = \left(\frac{\mathrm{B_2}}{\cos \mathrm{A}}\right) * \mathrm{F_t} \tag{16}$$

$$C_3 = \frac{2\mathcal{E}B_2(F_t)}{cos\,A\,(g_o - x)} \tag{17}$$

4. RESULTS AND DISCUSSION

An energy source for leadless cardiac pacemaker should preferably be a perpetual power supply rather than a traditional battery with limited longevity. In order to achieve the conversion of these mechanical forces into electrical energy, the Electrostatic based transduction has been selected in the proposed design. An electrostatic transducer is basically a capacitor which capacitance is changed by mechanical forces, and from which energy is extracted by appropriate charge-discharge cycles. This method of transduction of energy has wide range of tuning capabilities and a large part of the incoming mechanical energy can be converted into electrical energy. The requirements for this are an efficient design of the transducer and power management circuit. Several topologies of electrostatic based energy harvesters that can be used to satisfy this need have been discussed, modeled and compared with the proposed topology using the SIMULINK package of MATLAB. The simulation parameters are given in Table 1.

Table 1 Design parameters of the proposed energy harvester.

Parameters	**Value**
Permittivity ($\mathcal{E}$)	11.7x8.854x10^{-12} F/m
Angle (A)	0.203 rad
Height of electrode (F_t)	50 µm
Initial Gap between electrodes (g_o)	25 µm

Initial Overlap of Fingers (h_1)	20 µm

The graph in Fig. 8 shows that the capacitance variation of the proposed topology with respect to displacement is greater as compared to standard topologies and hence a greater extent of energy can be harvested for cardiac implant.

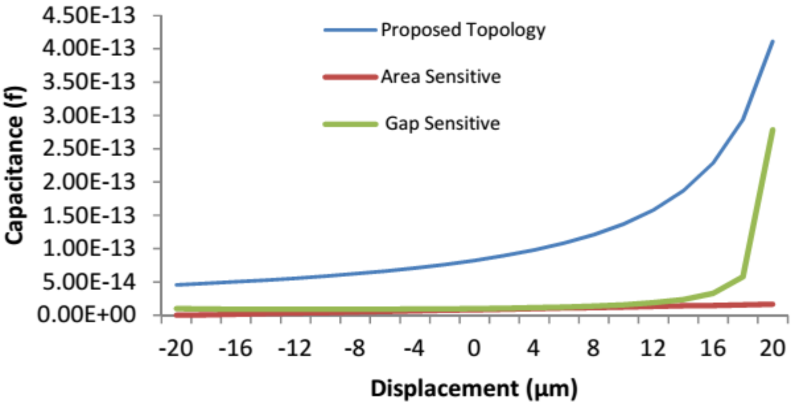

Figure 8 Variation of Capacitance obtained with respect to Displacement of various topologies

5. CONCLUSIONS

A new design for the electrode elements of an Electrostatic Energy Harvester is presented. This design is an improvement to the standard topologies of the Electrostatic Energy Harvester. This configuration provides relatively very large capacitance variation with respect to the displacement of the electrode elements of the harvester and is particularly suitable for leadless pacemaker geometric requirements as the dimensions of the electrode elements are in accordance with the leadless cardiac implant requirements.

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