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Modelling of Silicon based Electrostatic Energy Harvester for Cardiac Implants

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ABSTRACT

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 for pacemakers uses angled electrodes unlike the traditional harvesters. 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: Biomechanics, energy harvesting, electrostatic, electrode, pacemaker.

1. INTRODUCTION

Patients are being provided with improved healthcare facilities such as cardiac implants due to the developments in wearable and implantable medical devices (IMDs). This results from the advances in electronics especially the ultra-low power design and MEMS which enabled the design of highly integrated system-on-chips (SoCs). A number of batteries have been proposed for IMDs after the introduction of first pacemaker in 1972 [1, 2-6]. However, lithium based batteries such as Li/I_2 have been proven to be safer and reliable from the last four decades and are commonly used for such implants due to small size and high density [4,7]. However these batteries suffer from a disadvantage of a limited life span and thus their replacement are required of for surgery. This issue calls for permanent and efficient alternative energy sources to power the IMDs and ensure their proper functioning. Energy harvesting is one such bio-compatible approach that can help in achieving the goal of designing self-powered and battery-less IMDs.

Energy harvesting can be simply viewed as the phenomenon of scavenging energy from various sources in the surrounding environment. There are four principle energy sources available in the surrounding namely vibrational [8-10], thermal energy [11-13], radiant energy [14,15] and biochemical [16-18]. Of these, the radiant energy particularly the sun is the most powerful energy source. However, for cardiac implants, radiant as well as thermal energy harvesting may

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not be feasible, whereas bio-fuel cells have low densities. Within the human body, vibrations can be converted into electricity and hence a few microwatts of energy can be scavenged from the human heart [19].

Vibrational based energy harvesting is a two steps process viz. mechanical-to-mechanical conversion (vibrations converted into relative motion by spring-mass system) and mechanical-to-electrical conversion. There are further three types of mechanical-to-electrical converters available which is electrostatic, electromagnetic and piezoelectric. A comparative analysis of these three converters is given in [20,22]. It is observed that electrostatic harvesters are more applicable for low frequency operations while being easy to fabricate and implement in micro-level. Hence, an electrostatic based energy harvester has been proposed in this paper for cardiac pacemakers. Similar research has been presented in [21], wherein a capacitance detection based biosensor has been proposed that 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.

The rest of the paper is organized as follows. In section 2,three standard topologies of electrostatic harvesters namely in-plane overlap, in-plane gap closing and out-of-plane gap closing, are presented along with their capacitance equations. The proposed structure for an electrostatic harvester and its mathematical modelling is presented in section 3 followed by results and discussion in section 4 and finally conclusion in section 5.

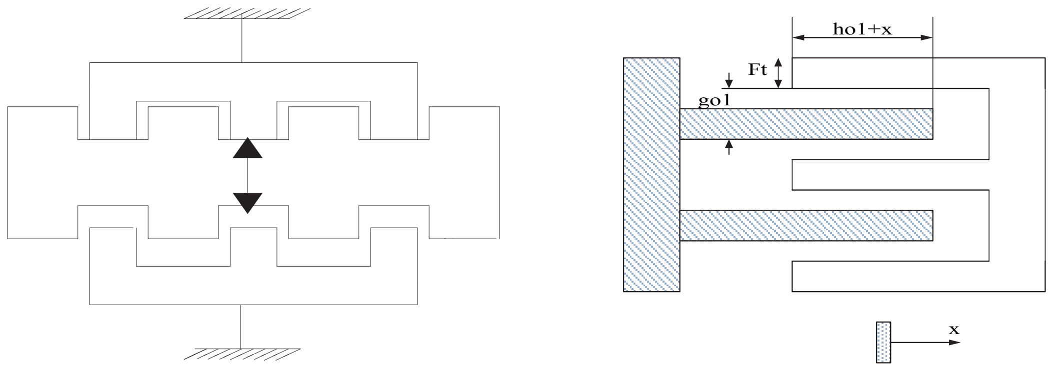
2. STANDARD TOPOLOGIES OF ELECTROSTATIC TRANSDUCTION

The electrostatic transduction mechanism [22] uses a variable capacitor structure whose capacitance is changed as a function of the mechanical displacement denoted by x. There are basically three generic topologies of electrostatic devices that differ in actuation direction. The following section discussed the standard topologies of the electrostatic transducers [22-25] and their capacitances.

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 Figure 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.

The 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, $C = 2C_1 = 2C_2$.



(a) (b)

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

The capacitance can be calculated using formula in Eq. (1), where the area of the electrodes is given by Eq. (2). Hence, capacitance variation can be obtained by the given relation in Eq. (3).

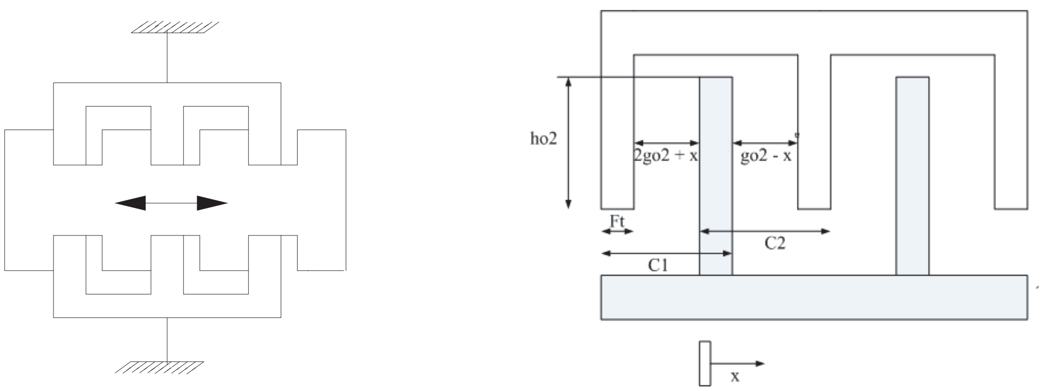
$$\text{Capactiance} = \mathcal{E}\ \frac{\text{Area of electrodes}}{\text{distance between electrodes}} \tag{1}$$

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

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

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 Figure 2.



(a) (b)

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

The 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 produced:

$$C = C_1 + C_2 \tag{4}$$

where,

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

and,

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

substituting these values gives the capacitance,

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

simplifying it further will give the final capacitance as,

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

2.3 Out-of-Plane Gap Closing

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

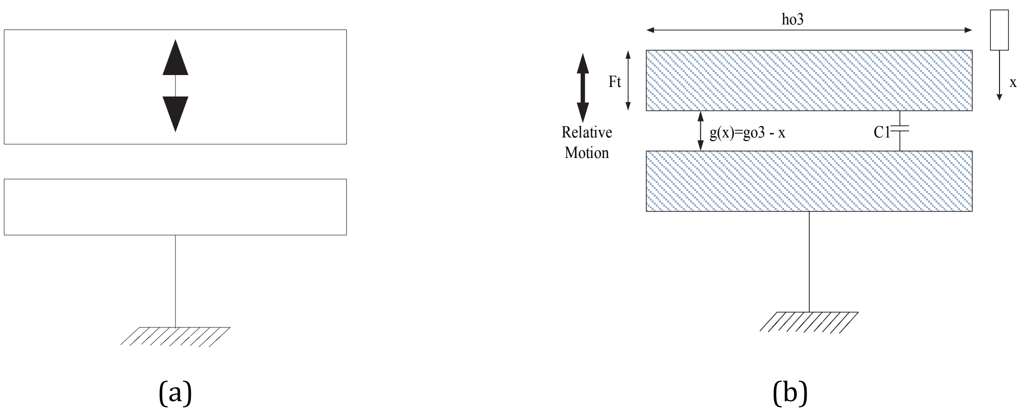


Figure 3. (a) Out-of-Plane Gap Closing Converter (b) Out-of-Plane Gap Closing structure

In this type of converter, the motion of the mobile part of the structure is out of plane. The mobile electrode moves above the fixed electrode 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

The previously discussed three standard cases can be categorized as either Area-Sensitive or Gap-Sensitive. The Area-Sensitive topology includes the In-Plane Overlap topology where 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 varying the area that overlap between the two electrodes of the capacitor structure while the gap between the electrodes remains constant. In the Gap-Sensitive topology, the capacitance variation is obtained by the change in the gap between the electrodes of the capacitor structure where the area of overlap of the two capacitor plates or electrodes remains the same. In order to maximize the obtainable capacitance variation, more advanced geometry that includes the sensitivity of both area and gap has to be designed.

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 Figure 4. By doing so, both the area and gap based capacitance variations can be obtained.

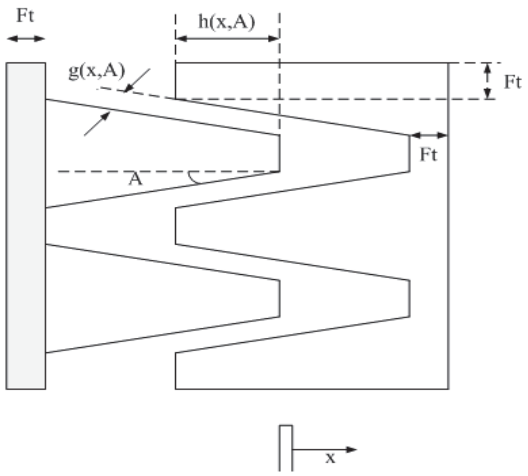


Figure 4. Architecture of the Proposed Comb Structure based Electrostatic Converter

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)* is the gap between the fingers as a function of angle A and displacement *x*, and *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 Figure 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, considers that the variation is due to the changes in the area of overlap of the two electrodes.

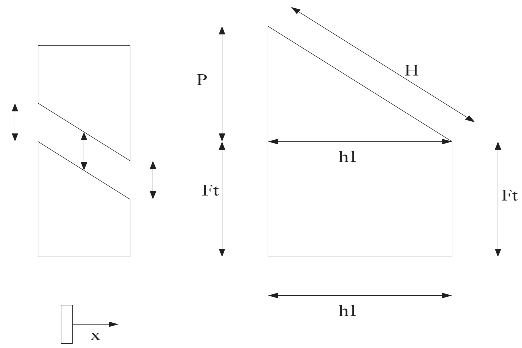


Figure 5. Variations due to the changes in the area of overlap of the two electrodes

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

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 in Eq. (12),

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

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

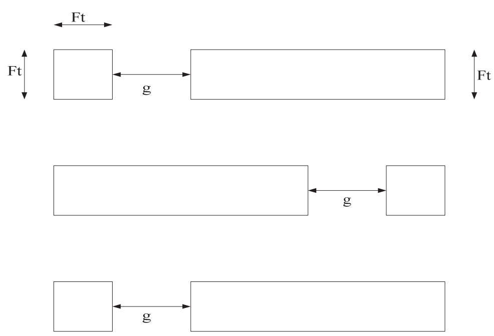


Figure 6. Variations due to the changes in the horizontal gap between the two electrodes

Here we have,

$$g = g_o - x \quad (13)$$

$$\text{Area of the overlapping parts of the electrodes} = F_t * F_t \quad (14)$$

and,

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

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

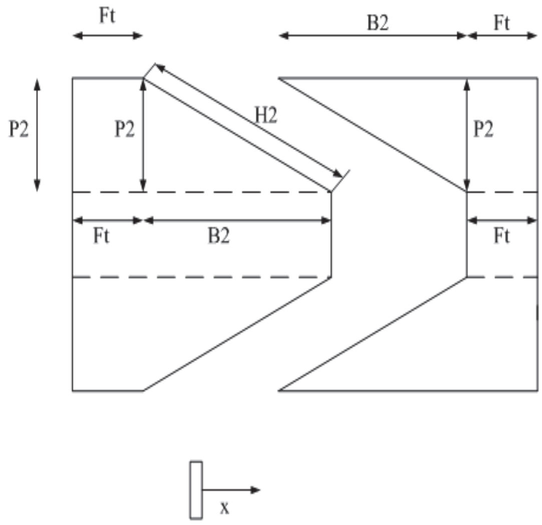


Figure 7. Variations due to the changes in the slanting gap between the two electrodes

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

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

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 for 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 (Ɛ)	11.7x8.854x10^{-12} F/m
Angle (A)	0.203 rad
Height of electrode ($\mathrm{F_t}$)	50 µm
Initial Gap between electrodes ($\mathrm{g_o}$)	25 µm
Initial Overlap of Fingers ($\mathrm{h_1}$)	20 µm

The graph in Figure 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.

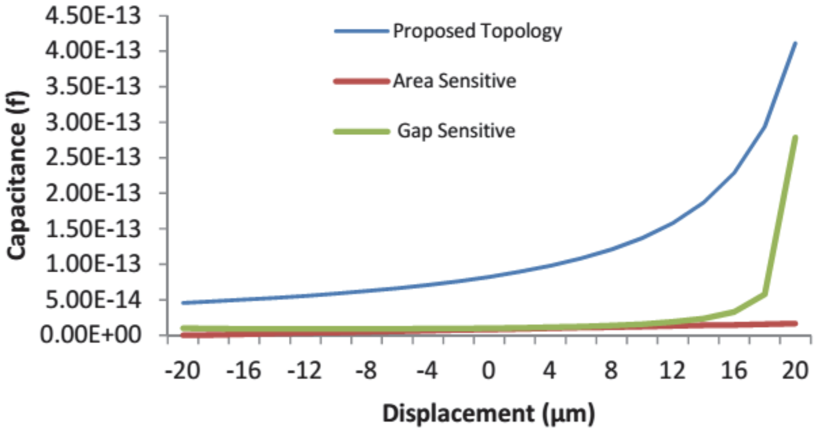


Figure 8. Variation of Capacitance obtained with respect to Displacement of various topologies

5. CONCLUSION

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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