A novel angular SiO$_2$ electret-based electrostatic energy harvester for cardiac and neural implants.

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Abstract

Energy harvesting as an alternate power source in miniaturized implantable medical devices, especially cardiac and neural implants has been investigated. An electret-based angular electrostatic energy harvester has been proposed along with a power management control circuit to harvest maximum possible energy. The proposed harvester incorporates the properties of both area-overlap and gap closing topologies to achieve larger capacitance variation with respect to displacement as is observed in the results. The maximum power that can be scavenged from the proposed harvester of size 2.5 × 3.5 mm^2 at maximum displacement is 9.6 µW.

Introduction

Currently the problem of powering and replacing the batteries in miniaturized medical implantable devices especially cardiac and neural implants calls for the development of an alternate power source. The output mechanical energy of the heart is in the order of ~1 W out of which only 20~25% is consumed [1,2]. Therefore it might be possible to scavenge power from the micro-vibrations of the heart upto few µWs without affecting the natural functioning of the heart [3]. Based on the analysis and comparison of three different micro-vibration energy conversion techniques *viz.* electrostatic, electromagnetic and piezoelectric harvesters presented in [1,4-8], it is observed that the capacitive electrostatic micro-generators create high electric field energy density and consequently high power along with being easily realizable in Micro-Electro-Mechanical Systems (MEMS) and small in size. These electrostatic generators can be classified into electret based or electret-free based on the conversion principle [9]. The electret-free converters need an external power source to apply the charge cycle on the structure and hence cannot address the need of battery-less implants, whereas the electret based converters use electrets and thus have the ability to directly convert mechanical power into electrical. Some of the most well-known and used electrets are presented in Table 1 [9]. For implants, size is a constraint, hence SiO$_2$ based electret has been selected due to minimum thickness and high surface charge density and its bio-compatibility.

Proposed Electrostatic Harvester Modeling

There are two basic topologies of electrostatic generators *viz.* area-overlap and gap-closing converters [6,9-13]. However they provide small capacitance variation. Hence, a new electret based electrostatic energy harvester with angular electrodes, shown in Figure 1a, has been proposed which obtains larger capacitance variation with respect to displacement of the generator mass. One such triangular electrode structure based electret-free harvester has been proposed [14]. Figure 1b shows the schematic view of the proposed electret based angular electrode structure wherein θ is the angle of the electrodes, L$_0$ the initial electrode fingers overlap length, L is the length of an electrode finger and WF its width. The capacitance between the inter-digitated electrodes is dependent on the height of the electrode fingers HF which is equal to the device layer thickness, gap g (x) between the electrodes and the overlap length l (x). The total capacitance of the proposed harvester consists of two components *viz.*, capacitance due to gap closing of electrode finger tips and capacitance due to gap and area overlap variation. The gap g (x) between the electrodes is a linear function of displacement x and is given as

$$g(x) = g_{min} + (x_{max} - x).\sin(\theta) \rightarrow (1)$$

The overlap length of the inter-digitated electrodes can be computed as

$$l(x) = \frac{x_{max} + x}{\cos(\theta)} + g(x).\sin(\theta) \rightarrow (2)$$

The capacitance due to gap closing of finger tips is given as

$$C_P(x) = \frac{2\varepsilon_0 w_F H_F}{d/\varepsilon + z + (x_{max} - x)} \rightarrow (3)$$

Where z is the minimum gap between the fingertip and base of the electret layer and ε is the permittivity of the electret.

Table 1. *Different available electrets and their properties.*

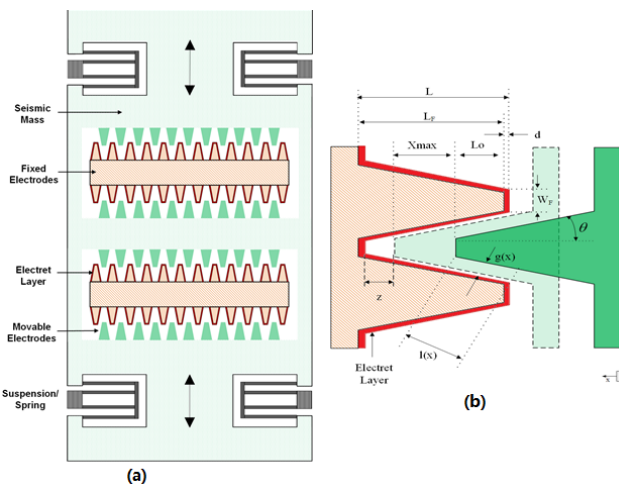| Electret material	Relative permittivity	Maximum thickness	Dielectric strength (V/μm)	Surface charge density (mC/m^2)
Teflon (PTFE/FEP/PFA)	2.1	~100 μm	100-140	0.1-0.25
SiO$_2$	4	<3 μm	500	05-11
Parylene (C/HT)	3	~10 μm	270	0.5-1
CYTOP	2	20 μm	110	01-2
Teflon AF	1.9	20 μm	200	0.1-0.25

Figure 1. *(a) Schematic view of the layout of the proposed electret based electrostatic energy harvester depicting electret layer over fixed electrodes, springs and movement of direction (b) Zoomed view of an angled electrode structure.*

The capacitance for the single inter-digitated electrode element due to area overlap and gap variations is given as

$$C_g(x) = \frac{2\varepsilon_0 l(x) H_F}{d/\varepsilon + g(x)} \rightarrow (4)$$

Substituting $g(x)$ and $l(x)$ from Equations 1 and 2 into 4, we get the expression of the capacitance variation with respect to the displacement as

$$C_g(x) = \frac{2\varepsilon_0 H_F\left[x_{max} + x + g_{min}\sin(\theta) + (x_{max} - x).\sin^2(\theta)\right]}{\frac{d}{\varepsilon}\cos(\theta) + g_{min}.\cos(\theta) + (x_{max} - x)\sin(\theta)\cos(\theta)}$$

$$\rightarrow (5)$$

The total capacitance of the proposed electret based energy harvester is given as

$$C_T(x) = 2N(\theta).\left[C_P(x) + C_g(x)\right] = 2N(\theta).C_{SE}(x) \rightarrow (6)$$

Here $C_{SE}(x)$ is the total capacitance of single electrode structure shown in Figure 2 and $N(\theta)$, a function of angle θ, is

the number of electrode fingers in the proposed harvester, given as

$$N(\theta) = \frac{L_T}{2\left[w_F + \left(L_f + d\right).\tan(\theta)\right]} \rightarrow (7)$$

The maximum capacitance of single electrode element can be computed for maximum displacement and is given as

$$C_{SE}^{max}(x) = 2\varepsilon_0 H_F\left[\frac{2x_{max} + g_{min}\sin(\theta)}{\frac{d}{\varepsilon}\cos(\theta) + g_{min}.\cos(\theta)} + \frac{w_F}{d/\varepsilon + z}\right] \rightarrow (8)$$

And the total maximum possible capacitance of the proposed electret based harvester can then be computed as

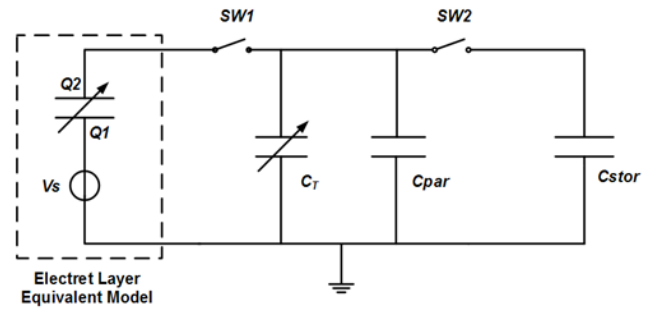$$C_T^{max}(\theta) = 2N^{max}(\theta).C_{SE}^{max}(\theta) \rightarrow (9)$$

Figure 2. *Schematic circuit of a basic switching converter for the harvester.*

The output of the energy harvester is fed to the converter shown in Figure 2, where V_s is the surface potential of the electret, SW1 and SW2 are the switches which are opened during most part of the conversion process. C_{par} is the parasitic capacitance and C_{stor} is the storage capacitor. The cycle begins with both switches open and the vibrating mass at maximum deflection. The capacitance of the variable capacitor CT is at maximum value (C_T^{max}). SW1 closes and the charge is transferred from the electret surface to the movable electrodes of the capacitor CT. Then SW1 opens and the deflection of the vibrating mass decreases. When the variable capacitance reaches its minimum (C_T^{min}) at x=-x$_{max}$, the voltage across the capacitor has to increase. Then SW2 closes and the charge

moves to the storage capacitor (C_{stor}) and the deflection then increases and the next conversion cycle starts again. When the amount of energy on the storage capacitor stays constant, maximum energy is scavenged from the harvester.

Results and Discussion

The minimum gap between the electrodes g_{min} is the distance between the electrodes when displacement is maximum $x=x_{max}$. Based on the fabrication set-up and limitations [14], the minimum allowable feature size is 2.5 µm, hence the minimum gap g_{min} must be greater than or equal to 2.5 µm. When simulated in MATLAB, from Equation 1 it is observed that for $g_{min} \geq 2.5$ µm, the angle θ must be greater than 5.74º. For Length (LF) and Width (wF) of electrode finger as 45 µm and 4 µm respectively and the maximum possible displacement x_{max} of 20 µm, the maximum capacitance of a single electrode structure given in Equation 8 increases with increasing value of θ and the overlap length $l(x)$ approaches to infinity for $\theta=90º$, however due to the design area limitation, it is not possible. Hence, instead of considering $C_{SE}^{max}(x)$ as the criteria for selecting the value of θ, the variation of maximum total capacitance of the entire structure $C_T^{max}(x)$ at different values of θ is considered. Higher capacitance is achieved for lower values of θ, hence the minimum possible value of θ i.e. 5.74º is selected as the optimal value of the angle of the electrodes to achieve maximum capacitance variation. The capacitance varies inversely with increasing electret thickness d, hence the minimum possible size of 0.5 µm is selected as the electret thickness. For the same design specifications, it is evident from Figure 3 that the proposed harvester provides much better capacitance variation in comparison to the electret based area-overlap [9] and gap closing harvesters [9]. The converter is able is scavenge a maximum power of around 9.6 µW when the proposed active generator, of layout size 2.5 × 3.5 mm², is displaced to a maximum value of $x=x_{max}$, as shown in Figure 4. A dc-dc converter can further be applied to generate a constant voltage from the harvester.
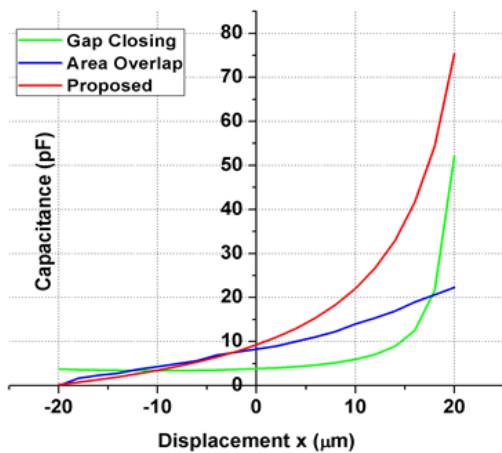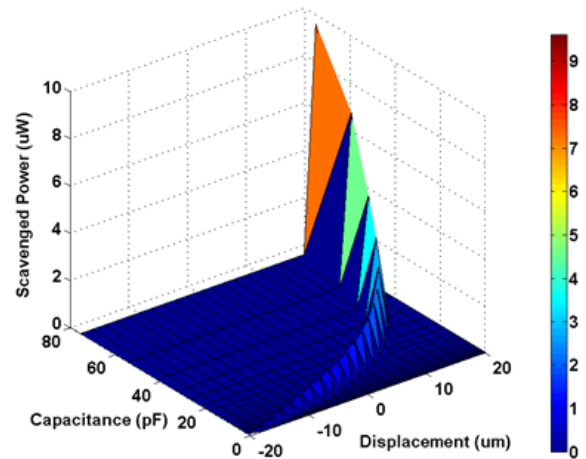

Figure 4. *Energy generated by the proposed harvester as a function of displacement and capacitance.*

Conclusion

SiO$_2$ electret-based angular electrode structure was designed for incorporation into an in-plane electrostatic energy harvester with an aim to provide an alternate energy source to miniaturized cardiac and neural implantable medical devices. Mathematical modeling and analysis showed that the angle θ of the electrodes and the electret layer thickness d are the important design parameters, constrained by the minimum fabrication feature size available to achieve maximum capacitance variations. The results showed that in comparison to standard area-overlap and gap-closing topologies, the proposed harvester provides larger capacitance variation with respect to displacement. The output of the harvester structure when fed to the switching converter is able to scavenge energy up to 9.6 µW at maximum displacement. Thus the proposed harvester, being small in size of only 2.5 × 3.5 mm² can be used as an energy source for cardiac and neural implants as they consume power in the range of ~10 µW.

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Figure 3. *Performance comparison of capacitance of proposed electret based harvester with other harvester topologies.*

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