Multilayer out-of-plane overlap electrostatic energy harvesting structure actuated by blood pressure for powering intra-cardiac implants

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Abstract. We present an innovative multilayer out-of-plane electrostatic energy harvesting device conceived in view of scavenging energy from regular blood pressure in the heart. This concept involves the use of a deformable packaging for the implant in order to transmit the blood pressure to the electrostatic transducer. As shown in previous work, this is possible by using thin metal micro-bellows structure, providing long term hermeticity and high flexibility. The design of the electrostatic device has overcome several challenges such as the very low frequency of the mechanical excitation (1 to 2 Hz) and the small available room in the medical implant. Analytical and numerical models have been used to maximize the capacitance variation, and hence to optimize the energy conversion. We have theoretically shown that a 25-layer transducer with 6-mm diameter and 1-mm thickness could harvest at least 20 mJ per heart beat in the left ventricle under a maximum voltage of 75 V. These results show that the proposed concept is promising and could power the next generation of leadless pacemakers.

1. Introduction
Devices harvesting energy from the body [1] are drawing increasing attention as industrials such as Sorin Group are investigating their integration into in vogue miniaturized leadless pacemakers that can be placed directly in the heart. Therefore, this paper focuses on an energy harvester which size is compatible with an intravenous introduction, i.e. which diameter is below 6 or 7 mm in order to fit in a catheter (figure 1). As the major part of the energy consumed by the heart is used to expel blood to the organs, we are proposing to exploit the regular blood pressure variations during the cardiac cycle to generate energy. Compared to the inertial approach, which has previously been considered to harvest mechanical energy in the heart [2], the regular blood pressure variation presents the advantage of being a very stable and predictable power source. Moreover, contrary to inertial devices which require very good matching of their resonance frequency with the frequency of the mechanical excitation, the non-resonant principle of operation of our device guarantees that the amount of energy harvested by heartbeat cycle is unaffected by heartbeat frequency changes. The targeted overall volume for the implant is 1 cm³, and its average power consumption is 10 µW. Given the size constraints, the power

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needs and the very low frequency of the mechanical energy source, the design of the mechanical-to-
electrical energy converter appears to be a real challenge. For the cylindrical shape volume of the
considered implant, the design of a device with three dimensional features is more advantageous. As
implanted devices should be compatible with MRI, miniature electromagnetic generators are discarded
for this application. Our previous works showed that piezoelectric materials are promising candidates
[4]. However, long term reliability of this technology must be assessed in depth before industrial
development of piezoelectric energy harvesters for medical implants can be considered.

Electrostatic energy conversion is also a promising way for implanted application. This technology has
a high integration potential and can be easily miniaturized. Contrary to piezoelectric energy
conversion which involves high mechanical stress of the active materials, electrostatic generators may
be designed in order to get low mechanical stress and thus lower risks of mechanical failure. In this
paper we present the study of a completely 3D electrostatic device. It takes the advantage of the
advanced 2D patterning techniques while stepping in the third dimension by bringing into play an
innovative and virtually unlimited stacking approach. Hence, a much higher output power can be
expected compared to 2D devices.

2. Electrostatic structure design

2.1. Converted energy

An electrostatic energy harvester is a variable capacitor whose capacitance is changed by relative
mechanical displacement of its electrodes. To maximize the energy transduction, the capacity variation
needs to be as large as possible. The two most common modes of operation are the voltage
constrained and the charge constrained cases [5]. In the voltage constrained case, a voltage $V_{\text{max}}$ is
applied across the capacitor when its maximum capacity $C_{\text{max}}$ is reached. Then, the capacitor is
discharged when its minimum value $C_{\text{min}}$ is reached. The energy $W_{\text{Vab}}$ extracted from the electrostatic
system is given by equation (1). In the charge constrained case, a voltage $V_0$ is applied across the
capacitor when its maximum capacity $C_{\text{max}}$ is reached. The capacitor is then left in open-circuit and the
movement induces the transition to $C_{\text{min}}$ while the voltage increases to the maximum value $V_{\text{max}}$. Then,
the capacitor is discharged. The energy $W_{\text{Charg}}$ extracted in this case is given by equation (2).

$$W_{\text{Vab}} = \frac{1}{2} (C_{\text{max}} - C_{\text{min}}) V_{\text{max}}^2$$  \hspace{1cm} (1)

$$W_{\text{Charg}} = \frac{1}{2} \frac{C_{\text{max}}}{C_{\text{min}}} (C_{\text{max}} - C_{\text{min}}) V_{\text{max}}^2$$  \hspace{1cm} (2)
Considering same values of maximum voltage, we can easily observe from (1) and (2) that the charge constrained case generates less energy in theory. However, the efficiency of the power management circuits related to both modes of operation should be taken into account to make a choice. As the mode of operation has no major influence on the design of the electromechanical transducer, we have arbitrarily chosen to consider the voltage constrained case in the following developments.

2.2. Flexible packaging
The packaging of the pressure harvesting device has to be flexible to engender a displacement upon variation of the pressure load, while transmitting the largest possible force to the transducer. The more flexible the packaging will be, the more mechanical energy will be transmitted to the electrostatic device. However, long term medical implant packaging is subjected to very stringent requirement in term of permeability. This is why the packaging of long-term implants is traditionally made of metals (for instance titanium). Flexible materials such as polymers are not hermetic enough for this application. Therefore, we have developed a thin metal packaging with micro-bellows structure in order to get very low stiffness. Experimental measurements carried out on 8-µm thick nickel bellows packaging with 7 corrugations showed that stiffness as low as 135 N/m are attainable using metal packaging [4].

2.3. Out-of-plane overlap electrostatic structure
In the goal of optimizing the available volume in the implant, we propose to have a transducer structure that fits the just the capsule and which the geometry is a disc with a 6-mm diameter and height as small as possible (up to one millimetre). Due to the design of the flexible packaging, the mechanical movement is generated along the symmetry axis of the capsule. Therefore, we have opted for an out-of-plane electrostatic structure. Also, aiming for the highest possible capacitance variation invites us to have a multilayer or a comb-like structure, which significantly increases the facing surfaces of the capacitor. In figure 2 is illustrated this structure for a single layer implementation (i) and for a multi-layer implementation (ii). The illustration of this principle adapted to the cylindrical geometry that we target is shown in figure 3 (i). The fixed part (in blue) is connected to the rigid base of the implant, and the moving part (in red) is connected to the flexible part of the implant. The gap between the fingers stays constant but their overlapping surface is dependent on the movement.

![Figure 2. Principle of the proposed out-of-plane overlap electrostatic structure: single layer structure (i) and multi-layer structure (ii).](image)

2.4. Capacitance variation
For a structure with a number \( n_l \) of layers as schematically depicted in figure 3 (ii), the total capacitance was first analytically calculated using the first order approximation of “infinite” parallel plate capacitors. As this assumption breaks down relatively fast due to electrostatic side effects, numerical simulation have been run on the electrostatic module of COMSOL software in the goal of determining the actual profile of the capacitance. As we consider that the fingers are very long compared to their width and height, the numerical model is bi-dimensional along a cross-section perpendicular to the fingers. Numerical simulations were used to determine the domain of validity and the accuracy of the analytical model, and also to carry out calculations when analytical assumptions are not accurate. An example of the linear capacitance \( C_l \) as a function of the displacement \( w \) of the mobile part is plotted in figure 4 in the case of a 6-layer electrostatic structure with \( w_f=2 \) µm \( h_f=20 \).
$\mu m$, $h_i=30 \, \mu m$ and $g=2 \, \mu m$. With these dimensions, the results given by the analytical model are close to those given by the numerical model, indicating that minor electrostatic side effects occur.

Figure 3. Multi-layer structure adapted for cylindrical geometries (i), and schematic cross-section view showing the dimensions parameters of the system (ii).

Figure 4. Linear capacitance of a 6-layer structure versus the displacement calculated using the analytical model (in blue) and the numerical model (in yellow).

### 2.5. Parameters optimization considerations

For the constrained voltage case, the extracted energy is proportional to the sum of $(C_{\text{max}}-C_{\text{min}})$ calculated for the full displacement of the mobile part. Examples of dimensions and corresponding sum of capacitance variation for full displacement of the mobile electrodes are given in Table 1. Several considerations could be drawn from simulation results (not entirely presented in this paper for the sake of compactness). First, we observed that the finger width $w_f$ has only a small influence on the linear capacitance. As expected, the gap plays a big role and a closer investigation tends to prove that the capacitance increases roughly in a $h_f g^{-1}$ fashion. As also anticipated, the number of layers $n_l$ plays linear behaviour in the capacitance variation. The inter-layer height $h_i$ is not trivial to determine. Indeed, if the layers are very close, important side effects occur and therefore the total capacitance variation is small. On the other hand, if the interlayer space is large, side effects are negligible and the capacitance variation per pitch is large, but the total capacitance variation for a given displacement will be small. Hence, there is an optimal inter-layer size for a given displacement. Furthermore, the interlayer gap has a strong effect on the total height of the system. Consequently, the optimization strategy will be different if the device limitation comes from the maximum allowable height or the maximum of comb layers (due to fabrication considerations for instance).
Table 1. Dimensional parameters and corresponding sum of the capacitance variations for maximum displacement (10 layer structure).

| $h_f$ (µm) | $w_f$ (µm) | $g$ (µm) | $h_i$ (µm) | $\Sigma(C_{\text{max}} - C_{\text{min}})$ (pF/m) |
|-----------|-----------|----------|-----------|---------------------------------|
| 20        | 20        | 10       | 80        | 910                             |
| 10        | 5         | 2.5      | 10        | 650                             |
| 40        | 20        | 20       | 120       | 640                             |
| 60        | 6         | 30       | 120       | 440                             |
| 10        | 5         | 10       | 40        | 370                             |

As shown by (1), the energy converted is proportional to $V_{\text{max}}^2$. However, high voltage values may induce two undesirable effects: fingers electrostatic instability and electrical breakdown. Taking into account all the factors discussed in this subsection, we have calculated that more than 20 µJ per heart beat could be converted by our electrostatic energy harvester implanted in the left ventricle, working with a maximum voltage of 75 V. This electrostatic device is 6 mm in diameter and has 25 layers. Its other characteristic dimensions are $h_f=10$ µm, $w_f=30$ µm, $g=7.5$ µm and $h_i=30$ µm.

2.6. Fabrication considerations

Two fabrication processes were considered. The first one is based on wafer stacking, each silicon wafer being first micromachined using DRIE process. The second one consists in layer-by-layer electroplating of structural and sacrificial metals. The 3D structure is built by repeating 2D surface micromachining and polishing steps. Then, the sacrificial material is etched away, which releases the device. As the stacking of numerous wafers seems challenging, we have chosen to focus on fabrication method based on layer-by-layer electroplating. This process is currently under development at the Institut d’Electronique Fondamentale of the University of Paris-Sud.

3. Conclusion

We have presented an innovative multilayer out-of-plane gap overlap electrostatic transducer for harvesting the regular blood pressure variation. This device was thoroughly studied in considering its numerous geometrical degrees of freedom. The design for a maximum variation of capacitance, and hence for an optimal energy conversion, was performed in considering a layer-by-layer electroplating fabrication technology. Limitations such as electrostatic pull-in and voltage breakdown were taken into account. We showed that it would be possible to generate more than 20 µJ per heart beat using an electrostatic device with 6-mm diameter and 1-mm thickness. These results show that this concept is promising and applicable to industrial devices. With further development on manufacturing of the multilayer device and the associated electronics circuitry, this would provide enough power for the next generation of leadless pacemakers.

4. References

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