NOVEL DESIGN AND FABRICATION OF A MEMS ELECTROSTATIC VIBRATION SCAVENGER

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Abstract

Vibration based energy scavengers are considered to be ideal power sources for low power autonomous devices in industrial environments, where vibrations are abundantly available. In this contribution a model for electrostatic generators is given and an optimised design and fabrication method are presented. The generator consists of an in-plane variable capacitor polarised by means of a SiO2/Si3N4 electret. In order to improve the transformation characteristics of the generator the capacitor is composed out of multiple shallow capacitors in parallel, which increases the coupling factor compared to non-facetted capacitors.

1 INTRODUCTION

Miniature generators gain interest as potential alternative to batteries in autonomous devices, their use leads to a potential decrease in volume and increase in lifetime. For devices with a relatively high power consumption the advantage is made by using fuel based power systems, as fuel has a much higher energy density than batteries [1], while low power applications benefit from generators that harvest energy from the environment [2]. These so-called energy scavengers tap into energy sources like temperature or mechanical vibrations. This paper presents the optimisation, design and fabrication of an electrostatic energy scavenger based on vibrations. A schematic view of an electrostatic scavenger is given in Figure 1. The device is build up around a seismic mass (m) that is suspended by springs, and damped by unwanted effects, such as air friction and hysteretic losses. The use of a seismic mass is needed to couple the external vibration to a movement on the micromachined generator: a vibration consists of a travelling wave across a solid material and it is often not possible to find a non-moving reference within the reach of the mechanical clamps of the generator. By using the inertia of the seismic mass the required relative movement is created. It is even possible to enhance the vibration amplitude when the vibration frequency equals the resonance frequency of the mass-spring system.

The movement z of the mass is then transferred to the generator, which is based on electromagnetic, piezo-electric or electrostatic conversion. Modelling and comparison of these three generator types favours the electrostatic generator in situations where the generator has to be small and the vibration frequency is high, as required in industrial environments [3].

The electrostatic generator consists of a variable capacitor C(z) that is polarised by a voltage Vpol. The movement z of the mass m is then translated into a change of the capacitance and thus into a change of the charge Q on the capacitor according to \( Q=C(z)V_{pol} \). This results in a current through the load circuit. To avoid circuitry that polarises the capacitor an electret is used, which consists of charges trapped in a dielectric material. Often a polymer such as Teflon is used for making electrets [4], however SiO2/Si3N4 layers are more suited for use in micromachined devices.

The need for miniaturisation of autonomous devices constrains the designer to a small seismic mass, but this causes a less effective coupling of the vibration towards the generator. To compensate for this loss in efficiency one needs to improve the characteristics of the generator. The optimisation of the generator is based on lumped element multi-domain modelling.

2 MODEL

In order to accurately model the flow of energy from the mechanical side to the electrical side a model is required that combines both domains into one system. Such a methodology is given by equivalent electrical schemes [5], where the mechanical parameters force F and speed \( \dot{z} \) are converted to the electrical parameters voltage V and current I. Using this analogy masses are modelled by inductances and springs are modelled by capacitors. Damping, if proportional to velocity, is modelled by a resistor, however other types of damping can be treated by equivalent velocity dampers. Analysis of capacitive
transducers and the equivalent model for electrets are derived in detail in [6], and lead to the equivalent circuit of Figure 2.

The power generated in the resistor by a sinusoidal vibration signal is given by:

$$ P = \frac{1}{2} R_{\text{load}} I^2 $$

where $I$ represents the amplitude of the current through the load. The behaviour of this power as a function of frequency is treated extensively in [6], where it is shown that the power reaches a maximum at two distinct resonance frequencies. In this analysis however the maximum travel length of the mass is not taken into account. In real-life generators the motion of the mass is limited by the dimensions of the system. In this case the maximum power is achieved by tuning the damping induced by the generator until the displacement of the mass equals the maximum allowed displacement [3,7].

The maximum power generated by an electrostatic generator is then given by:

$$ P(\omega) = \frac{1}{2} R_{\text{load}} \left( 1 + \left( \frac{\omega R_{\text{load}} C_0}{\omega R_{\text{load}} C_0 + 1} \right)^2 \right) \left( \frac{\omega z_{\text{max}}}{\omega z_{\text{max}}} \right)^2 $$

In this equation $z_{\text{max}}$ represents the maximum amplitude of the internal displacement for an input vibration with pulsation $\omega$. The capacitance at rest is given by $C_0$, while the transformation factor $\Gamma$ is given by the product of the polarization voltage $V_{\text{pol}}$ with the space derivative of the capacitance, $dC/dz$.

In most of the cases the expression in the denominator can be neglected, as the cut off frequency formed by $R_{\text{load}}C_0$ is of the order of 2 kHz, which is at the high end of the frequency range of industrial vibrations. This value is derived by assuming that the value of $C_0$ is limited by the size of the device to about $C_0=0.1\text{nF}$, and that a load impedance larger than $1\text{M} \Omega$ will be inconvenient for the design of power conditioning electronics.

Within these approximations the power is optimised taking into account the following design rules:

- maximize the capacitance change per unit displacement ($dC/dz$)
- maximize the polarisation voltage $V_{\text{pol}}$
- maximize the travel length of the mass $z_{\text{max}}$

If $\Gamma$ is known, the value of $R$ is determined by the condition $\omega = \omega_{\text{max}}$, and in case $RF_r^2$ is too small the mass will touch the outer package of the device and the damping induced by the generator must increase in order to achieve the optimum power. It is clear that a larger $\Gamma$ allows a more practical choice of $R$, which is favourable for power conditioning electronics as well as for realising the condition $\omega < (R_{\text{load}}C_0)^\dagger$.

### 3 DESIGN & FABRICATION

The design proposed in this paper is given in Figure 3. The device is constructed using three wafers, of which the bottom and the middle wafer form the variable capacitor and the third wafer comprises the electret.

**Capacitor design**

The capacitor in Figure 3 consists of $N$ varying overlap capacitors connected in parallel, placed at a constant pitch $p$. The capacitance at $z=0$ is given by:

$$ C_0 = N \frac{\varepsilon_0 \varepsilon_r w_l}{d} = \frac{W \varepsilon_0 \varepsilon_r w_l}{p d} $$

where $w$, $l$ and $d$ represent the width, the length and the gap of one capacitor, and $W=Np$ is the total width available for realizing $N$ capacitors. If the width $w$ and the pitch $p$ of one capacitor are scaled by the same factor, the number of capacitors $N$ to fit on the same surface will increase, but the maximum capacitance will remain at the same value. The change in capacitance per $\mu\text{m}$ will however increase, resulting in a better transformation factor $\Gamma$!

**Simulations of the capacitance as a function of displacement**

Simulations of the capacitance as a function of displacement are given in Figures 4a and 4b, for a capacitor with length $l$ equal to 1 mm and for $N=10$ electrodes in parallel. Note that the displacement is given as a percentage of the pitch. The first graph illustrates the importance of the ratio between the width $w$ and the pitch $p$, while the second graph indicates the advantage of realising a small gap $d$. These simulations also indicate the limitations of this technique: due to fringing fields the minimum capacitance that can be reached is not zero, thus reducing $dC/dz$. Note that an increase in $\Gamma$ without a significant increase of $C_0$ also increases the coupling factor $\kappa$ of the system:

$$ \kappa^2 = \sqrt{1 + \frac{C k}{\Gamma^2}} $$

which represents the ratio between the converted energy and the energy stored in the system. It is thus a measure for the efficiency of the system [5].

![Equivalent electrical circuit of Figure 1](image)

**Figure 2:** Equivalent electrical circuit of Figure 1

The power generated in the resistor by a sinusoidal vibration signal is given by:

![Cross-section of the device](image)

**Figure 3:** Cross-section of the device
Capacitor fabrication

The movable electrode of the capacitor is bulk micromachined together with the mass and the suspensions into a low resistivity 8” silicon wafer. The wafer is completely covered by a thermally grown SiO$_2$ layer of 500 nm and 150 nm LPCVD Si$_3$N$_4$. In a first step both the capacitor grating and the suspensions are patterned into the SiO$_2$/Si$_3$N$_4$ layer. Then this pattern is etched to 100 µm deep by DRIE. During this step the low resistivity of the wafer is needed to obtain a good profile at the top of the capacitors electrodes: local charging of the silicon during DRIE etch deforms the uniformity of the etching (Figure 5). This charging effect is avoided when the wafer is highly doped. After stripping the resist the wafer is again thermally oxidised. The backside SiO$_2$/Si$_3$N$_4$ layer of the wafer is then patterned in order to create openings for the subsequent anisotropic etching.

The fixed bottom electrode of the capacitor is fabricated on a Pyrex wafer in order to reduce parasitic capacitances. A mesa is etched into the glass with Buffered Oxide Etchant. After evaporation of aluminium the bottom electrode is patterned on top of the mesa. Finally a photosensitive BCB layer is spun on and patterned in the desired shape. The thickness of the BCB is controllable within a small range by changing the spin conditions. By tuning the BCB thickness it is possible to control the gap spacing of the capacitor down to 1 µm. Adhesive wafer-to-wafer bonding combines the two wafers.

The combination of the two wafers is then submerged into aqueous KOH (35%) to bulk-micromachine the mass. A final etch of the oxide stopping layer releases the structure. A bottom view of the device before the release step is shown in Figure 6. The inset in the figure shows a detailed view of the suspensions and of the grid-shaped electrodes of the capacitor. In this design the full wafer thickness is used to obtain a high mass to surface ratio. Because the thickness of the suspension does not depend on the thickness of the mass one can easily change the resonance frequency of the structure by etching deeper or less deep into the silicon. On top of this stack a third wafer is bonded featuring the electret, which is composed of a 500 nm SiO$_2$ and a 150 nm Si$_3$N$_4$ layer. This wafer has an aluminium back contact, and is patterned to tune the electret size to a desired value: by changing the electret surface also the electrostatic force between the movable mass and the electret changes. If this force equals the force between the fingers of the capacitor then the voltage to reach pull-in of the mass towards either side will increase significantly.

The electret is then charged by means of a corona setup. The surface voltage of the electret is controlled linearly by varying the charge time (Figure 7), and saturates at 300V. Stability is improved by annealing the electret at 140ºC for 30 minutes. In this way the lifetime of these electrets is estimated up to 400 years [8].
**5 CONCLUSIONS**

In this paper an alternative concept and design for a variable capacitor is treated. A process flow for this capacitor has been proposed and the fabrication technology has been validated. The design allows realizing a higher coupling factor between the mechanical and electrical domain, thus fulfilling the requirements needed to make an efficient electrostatic power generator.

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