

Electrostatic energy scavengers for wireless autonomous transducer solutions

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Abstract— Autonomous devices such as wireless sensor nodes within sensor networks need a long life time; current battery solutions are not sufficient for these devices. A generator that extracts energy from the ambient would be a promising power supply for these sensor systems. This paper describes a MEMS-based energy scavenger that converts mechanical vibrations into electrical power by means of a variable capacitor.

Keywords— electret, electro-static, energy scavenging, MEMS, vibration, wafer bonding.

I. INTRODUCTION

The ongoing miniaturisation of electronic systems allows the widespread use of small, inexpensive, low power sensor and actuator devices, for example, in wireless sensor networks.

Parallel to the miniaturisation process, a need is generated for miniature power sources. Using batteries in these devices is impractical as their lifetime is limited [1] and replacing or recharging is often not feasible.

Energy scavenging is the process of converting currently unused ambient energy into usable electrical power. Examples of ambient energy sources are: light (using solar cells), mechanical vibrations [2] or heat [3], This paper focuses on a MEMS-based, electro-mechanical energy scavenger. *Energy scavengers* are considered a promising alternative to batteries, allowing autonomous operation of these sensor and actuator devices, increasing the theoretical lifetime of these devices to infinite.

This scavenger system consists of a seismic mass, suspended by springs. This movable mass couples an external movement onto a generator, which consists of a variable capacitor $C(z)$ that is polarised by a voltage V_{pol} . The movement of the seismic mass (Δz), resulting from an external vibration, is translated into a change of the capacitance (ΔC) and thus into a variation of the charge on the capacitor ($Q = C(z)V_{pol}$). The resulting current provides power to the load circuit. To polarise the capacitor, an *electret* [4] is used. The performance of the device can

be optimised by matching the resonance frequency of the mass-spring system to the frequency of the external vibration.

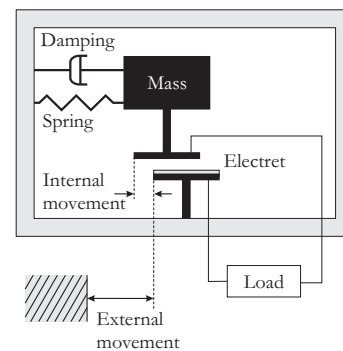


Fig. 1. Working principle of the electret-based scavenger

II. MODEL

To model such a scavenger system, a lumped model representation [5] is used where all the mechanical components are represented by their electrical equivalents. The model [4] is shown in Figure 2.

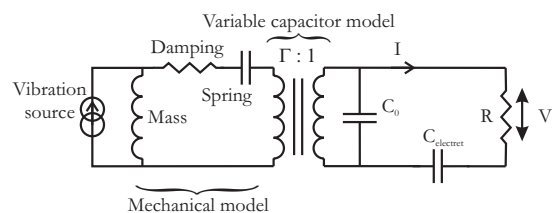


Fig. 2. Lumped element representation of the variable capacitor

The parameter Γ represents the transformation factor which is given by the product of the polarisation voltage V_{pol} and the space derivative of the capacitance, dC/dz . The output power as a function of the mechanical frequency is given by:

$$P(\omega) = \frac{\left(\frac{\omega}{\omega_1^*}\right)^4 \left(\frac{\omega}{\omega_2}\right)^2 \frac{\Gamma^2 Y^2}{C_0^2 2R}}{\left[\alpha - \left(\frac{\omega}{\omega_1^*}\right)^2\right]^2 + \left(\frac{\omega}{\omega_2}\right)^2 \left[1 - \left(\frac{\omega}{\omega_1^*}\right)^2\right]^2} \quad (1)$$

with:

$$\alpha = \frac{C_0 + (1 - \kappa^2)C_{\text{elec}}}{C_0 + C_{\text{elec}}} \quad (2)$$

and Y being the amplitude of the ambient vibration. Damping effects due to the viscosity of the air are neglected in this model.

The mechanical resonance frequency ω_1 ($= \sqrt{k/m}$, with k and m the spring constant of the springs and the mass of the seismic mass, respectively) has to be corrected for the influence of the electromechanical interaction. This results in:

$$\omega_1^* = \frac{\omega_1}{\sqrt{1 - \kappa^2}} \quad (3)$$

with $\kappa^2 = \frac{1}{1 + C_0 k / \Gamma^2}$, the coupling factor of the system, which represents the ratio between the converted energy and the energy stored in the system. C_0 is the capacitance at the rest position of the variable capacitor.

The cut-off frequency ω_2 is determined by the filter formed by the load resistance R and the capacitances C_0 and C_{elec} . It is given by:

$$\omega_2 = \frac{C_0 + C_{\text{elec}}}{RC_0 C_{\text{elec}}} \quad (4)$$

To illustrate the behaviour of such a scavenger system the calculated output power of the device is shown in Figure 3. Typical values for the device parameters that have been used are shown in Table I.

TABLE I

TYPICAL VALUES FOR DEVICE PARAMETERS AS USED IN THE SIMULATION

C_0	3pC	C_{elec}	18pC
R	1 M Ω	ω_1	900 Hz
Y	10 μm	ω_1^*	1022 Hz
k	120 N/m	κ	47 %

The graph clearly shows that to maximise the output power the resonance frequency of the scavenger device must be matched to the ambient vibration frequency. Further maximising of the power can be done by:

- maximising the capacitance change per unit displacement dC/dz ;

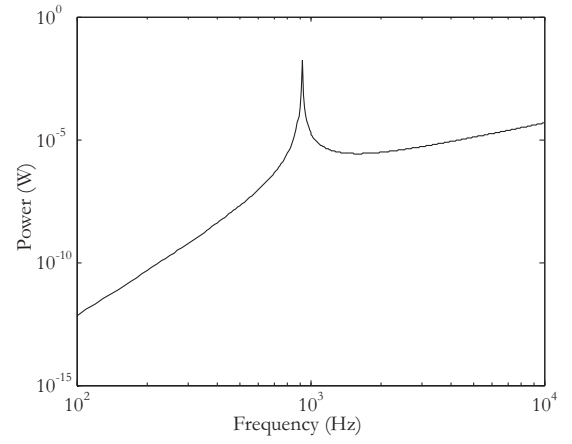


Fig. 3. Illustration of the power output showing the clear maximum in the output, underlining the significance of matching the resonance frequency of the scavenger to the ambient vibration.

- maximising the polarisation voltage;
- maximising the travel length of the seismic mass.

III. DESIGN

MEMS-based variable capacitors for sensor applications are often comb-drive structures. The scavenger that is discussed in this paper uses a different orientation of the capacitor electrodes: the electrodes are fabricated on two planes with a vertical spacing between them; one electrode is fixed while the other is attached to the movable seismic mass (see Figure 4). As a result, the device consists of three wafers (see Figure 4): a glass wafer containing the fixed electrode; a silicon wafer containing the seismic mass; and a silicon wafer containing the electret. The maximum achievable polarisation voltage is limited by the *pull-in* voltage of the system: by placing the electret opposite of the fixed electrode, the electrostatic force between the fixed electrode and the seismic mass can be compensated by the force between the electret and the seismic mass. This will increase the pull-in voltage and thereby the polarisation voltage.

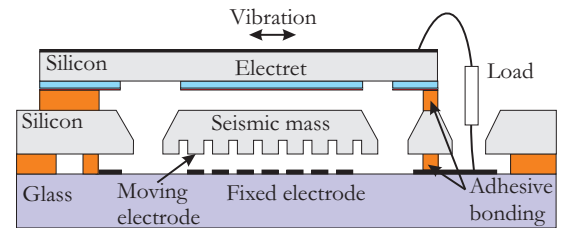


Fig. 4. Illustration of the three-wafer electro-static energy scavenger

The variable capacitor consists of N varying overlap parallel-plate capacitors connected in parallel with pitch p . The capacitance at zero displacement ($z = 0$) is given

by:

$$C_0 = N \frac{\epsilon_0 \epsilon_r w l}{d} \quad (5)$$

where w and l are the length and width of the individual capacitors and d is the vertical gap between the two electrodes of each capacitor. When p and w are scaled down while the size of the device is kept constant, N can be increased. This will result in an increase of dC/dz and thus in an increase of transformation factor Γ , while the total capacitance C_0 remains constant.

Figure 5 shows the simulated capacitance (solid line) as a function of the displacement. The triangles represent results that have been measured using a realised device (discussed further below).

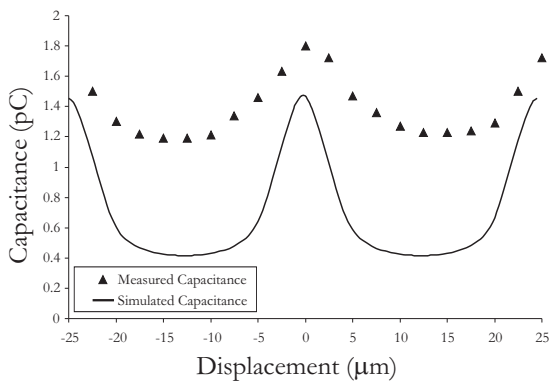


Fig. 5. Capacitance versus displacement for the scavenger device mentioned in the text. Solid line: simulated values; triangles: measured values.

IV. FABRICATION

The fixed electrode of the capacitor is fabricated on a Pyrex wafer to reduce parasitic capacitances as well as to tune the thermal expansion coefficients of the wafer. First, aluminium is sputtered on the wafer and subsequently patterned to create the fixed bottom electrode. Then photosensitive BCB (Benzo-Cyclo-Butene) is spun and patterned. Both the thickness of the aluminium layer and the BCB layer determine the distance d . The moveable electrode of the capacitor is bulk micromachined together with the mass and the suspension springs in a 100 mm silicon (100)-wafer. First, the capacitor, the mass and the springs are patterned and then etched into the silicon by deep reactive ion etching (DRIE) to a depth of 100 μm. Next, a 500 nm thick SiO₂ layer is grown using thermal oxidation and a 150 nm thick Si₃N₄ layer is grown using low pressure chemical vapour deposition (LPCVD). This layer stack is then patterned and etched to create openings for the subsequent anisotropic etching of the silicon. The two wafers are then combined using aligned wafer-to-wafer

bonding where the BCB layer acts as an adhesive. This two-wafer stack is then anisotropically etched in KOH through the entire wafer thickness to bulk-micromachine the seismic mass. This is followed by an isotropic dry etching step (RIE) of the SiO₂-Si₃N₄ layer stack to release the structures. The third wafer containing the electret is fabricated by depositing a 500 nm thick SiO₂ layer and 150 nm thick Si₃N₄ layer on the frontside of a Si wafer. These two layers are then patterned and etched using an RIE process to match the shape of the seismic mass. On the backside of the wafer a 250 nm thick Al layer is applied by evaporation. Then photosensitive BCB is spun and patterned. Next, the electret is charged by means of a corona setup and subsequently annealed in a nitrogen atmosphere at 140 °C for 30 minutes. The lifetime of these electrets is estimated to be 400 years [6]. Finally the electrets are bonded to the waferstack.

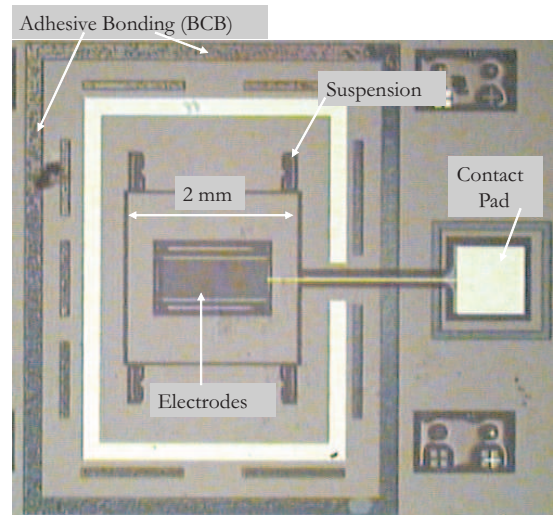


Fig. 6. Photograph of the realised electro-static energy scavenger before release of the seismic masses (bottom view, through the glass wafer).

Prior to the bonding of the electret wafer, the capacitance of the variable capacitance as a function of the displacement is measured. Results of these measurements are shown in Figure 5. The difference between the measured values and the simulation is attributed to parasitic capacitances.

V. CONCLUSIONS

In this paper an electrostatic energy scavenger is presented. A suitable process flow is described and fabrication is demonstrated. The design allows a higher coupling factor between the electrical domain and the mechanical domain, thus making a more efficient electrostatic energy converter.

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