Design improvements for an electret-based MEMS vibrational electrostatic energy harvester

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Abstract. This paper presents several improvements to the design of an electret-based MEMS vibrational electrostatic energy harvester that have led to a two orders of magnitude increase in power compared to a previously presented device. The device in this paper has a footprint of approximately 1 cm² and generated 175 µW. The following two improvements to the design are discussed: the electrical connection principle of the harvester and the electrode geometrical configuration. The measured performance of the device is compared with simulations. When excited by sinusoidal vibration, a device employing the two design improvements but with a higher resonance frequency and higher electret potential generated 495 µW AC power, which is the highest reported value for electret-based MEMS vibrational electrostatic energy harvesters with a similar footprint. This makes this device a promising candidate for the targeted application of wireless tire pressure monitoring systems (TPMS).

1. Introduction

Tire pressure monitoring systems (TPMS) is a very promising application area for vibration energy harvesters. Presently, TPMS is already mandatory in the United States for all new cars and upcoming legislation in Europe and parts of Asia makes that these regions will follow soon. This will open up a multi-million units per year market with a demand for low-power miniaturized sensor systems. The currently used, valve-mounted systems need a large-sized battery which needs to be replaced every 3-7 years [1]. Integrating battery-operated TPMS in the inner liner of the tire means that only smaller, low-capacity batteries could be used, thereby increasing the replacement frequency and therefore the costs. An energy harvester can replace the batteries to avoid the high replacement costs and also provide the autonomy for the TPMS during the life time of the tire or car.

Mechanical vibrations are abundant in the (internal) environment of the tire and therefore, vibrational energy harvesters are prime candidates to convert the energy present in these vibrations into useful electrical power for the TPMS. There are three main methods to convert mechanical energy into electrical energy: based on electromagnetic [2]; piezo-electric [3] and electrostatic [4] transduction. We have already shown the feasibility of using a piezo-electric harvester as a power source for TPMS in [5] where several 10’s of microwatts were generated from harvesting the mechanical shocks in the tire that occur during driving. This paper will show the potential of a device using the electrostatic conversion method as a power source for TPMS. The electrostatic energy harvester has the advantage over the piezo-electric harvester that the mechanical parts of the device can be independently designed and optimized from the electrical parts whereas in a piezo-electric device, the design and optimization of these parts are interconnected.
Being able to measure the pressure in a tire using a harvester-powered sensor system is the stepping stone towards a truly intelligent tire, one which is not only able to measure its pressure but also can sense the forces which act upon it and detect changes in the contact area with the road surface, thereby providing input for the various control systems (e.g. ABS and ESP) in the automobile thus improving the overall safety and comfort when driving.

2. Device description
The device, previously published in [6], is schematically shown in figure 1. It consists of a mass-spring system acting as one of the plates of a variable capacitor, itself polarized by an electret. The harvester is essentially a 3-terminal transducer (figure 2). It is fabricated from a stack of three wafers with two metal electrodes on the glass bottom wafer and one connection to the bulk silicon of the middle wafer which contains the electret; the device is capped by a glass top wafer. Glass wafers were chosen to reduce the effect of parasitic capacitances in the device. For the electret, we use a stack of SiO$_2$-Si$_3$N$_4$ for its compatibility with CMOS/MEMS processing [7,8]. This stack is deposited on a corrugated Si wafer. Both the corrugation for the electret and the suspension springs in wafer W2 are fabricated by deep reactive ion etching (DRIE). The corrugations are 100 µm deep; the suspension springs are etched through the entire Si wafer. A more detailed description of the device fabrication is given in [6].

![Figure 1](#) Figure 1. Left: schematic operation of the harvester; middle: drawing of the device showing glass wafer W1 containing electrodes (1) and (2); Si wafer W2 containing backside electrode (3), proof mass (4), springs (5) and corrugated electret; and glass capping wafer W3. The three wafers are bonded together using polymer bond frames (6); right: photograph of a fabricated device (top view).

![Figure 2](#) Figure 2. Schematic overview of the device showing electrodes (1) and (2) on the glass bottom wafer W1 and electrode (3) on the backside of the corrugated Si electret wafer W2.

3. Design improvements
In the following sections the two improvements to the design of the previous device presented in [9], the electrical connection principle and the geometric configuration of the electrodes, will be discussed in detail. In addition to these two improvements, compared to the previous device, also the electret was changed to a corrugated electret fabricated by deep-etching of the Si substrate. This change of the electret is also discussed extensively in [6].

3.1. Electrical connection principle
Two connection schemes for the load circuit are investigated: the ‘slot-effect’ scheme [10], where the external load is connected between the two electrodes on wafer 1 (figure 3a and b); and the ‘cross-wafer’ scheme, where the load is connected between one of the bottom electrodes and the connection to the Si bulk of wafer 2 (figure 3c and d). In the slot-effect scheme, the remaining terminal of the device is the backside of the electret wafer; in the cross-wafer scheme, the remaining terminal is one of the electrodes on wafer 1 (which is then generally referred to as the ‘guard’ electrode). In both
schemes, this remaining terminal can be left floating (figure 3a and c) or be connected to ground (figure 3b and d).

Figure 3. Slot-effect and cross-wafer connection schemes. a: slot-effect, electret floating; b: slot-effect, electret grounded; c: cross-wafer, guard electrode floating; d: cross-wafer, guard electrode grounded.

Figure 4 shows the experimentally measured output power using the different connection schemes as a function of the applied frequency (sinusoidal vibration with an acceleration of 2 G at the device’s optimal load). Clearly, the slot-effect connection scheme (with floating electret backside connection), used in our present devices, is superior in output compared to the cross-wafer scheme as used in our previous devices. Additionally, grounding the guard electrode in the cross-wafer scheme does improve the performance of this scheme by approximately 40% but even then the slot-effect scheme delivers almost a factor of two more power.

Figure 4. Power output of slot-effect scheme (S-E) and cross-wafer (C-W) scheme. The device was excited at an acceleration of 2 G. The optimal load resistances were 5 MΩ for S-E and 4 MΩ for C-W. The power is computed by measuring the electrical current through the load resistor as shown in figure 3.

3.2. Electrode geometrical configuration

The design of the electrodes/electret geometrical arrangement has a significant influence on the device’s output power. The dimensions of the electrode (relative to the maximum peak-to-peak mass displacement $d_{\text{max}}$) need to be optimized to ensure maximum power output. Figure 5 schematically shows the different possibilities that were investigated. The lateral dimensions of the electrodes can be equal to $d_{\text{max}}$ (Type 1) or smaller than $d_{\text{max}}$ (Type 2). These two types have been simulated using a combination of analytical expressions and FEM calculations.

Figure 5. Schematic for two different electrode configurations: Left: Type 1, electrode width=$d_{\text{max}}$; right: Type 2, electrode width=0.5$d_{\text{max}}$. The displacement is represented by the dashed outline.

The modelled output power as function of the mass displacement and the voltage waveforms are shown in figure 6 using a resonance frequency of 1 kHz and $d_{\text{max}}=100$ µm. The waveform for the Type 1 device (middle graph) has a frequency of 1 kHz; in the waveform for Type 2 (right graph) higher frequency components are visible because of multiple crossings of the electrodes during one period. The optimal resistive load from the theoretical model was 8 MΩ for Type 1 and 5 MΩ for Type 2; experimentally, slightly lower values were obtained.
Figure 6. Modelled output of the electrostatic harvester for a resonance frequency of 1 kHz, \( d_{\text{max}} = 100 \, \mu \text{m} \) and optimal resistive load of 8 M\( \Omega \) for Type 1 and 5 M\( \Omega \) for Type 2. Left: power output versus mass displacement of the two device types for different electret potentials; middle, right: voltage waveforms of type 1 devices (middle) and type 2 devices (right).

Figure 7 shows the measured output power for the two configurations (for optimal resistive load and slot-effect connection scheme). The output of the Type 1 device (squares) continues to rise with increasing displacement while the Type 2 output (triangles) starts to level off when the displacement equals the electrode dimension, as predicted by the model. The lower measured power output of Type 2 is partly attributed to a lower electret potential which is also shown in the modelled output (figure 6).

Figure 7. Measured output power of the two different electrode configurations. The resonance frequency and optimal load for the Type 1 device were 730 Hz and 5 M\( \Omega \), respectively. The resonance frequency and optimal load for the Type 2 device were 710 Hz and 3 M\( \Omega \), respectively.

For a Type 1 device from a next generation of devices employing the same discussed design improvements but with a higher resonance frequency and a higher value of the electret potential, a record output power of 495 \( \mu \text{W} \) was obtained using an input acceleration of 1187 Hz with 2.5 G amplitude and an optimal resistive load of 3.2 M\( \Omega \). The electret potential is estimated to be approximately 200 V, using the measurement method described in [11].

4. Discussion

In table 1 the generated power output of the device in this work is compared to the power output of devices listed in a recently published overview of state-of-the-art vibrational-type electret-based harvesters (data taken from [12], sorted by power output in \( \mu \text{W} \)). Note that the top-most harvester that generates 700 \( \mu \text{W} \) (Sakane [13]) is not an integrated device but a macroscopic structure where the electret and the counter electrode are mounted on a shaker and a 6-DOF positioner, respectively, while being placed in a SF\(_6\)-gas-filled box to prevent discharge between the electret and the counter electrode.

It is clear that the device presented in this paper performs very well, in particular when the footprint (active surface) is taken into account. For TPMS, the total device size, and therefore the active area, of the device should be small as not to interfere with the alignment and balance of the tire. The main challenge will be the reliability of the harvester and the sensor system when mounted in the tire. It needs to withstand very high accelerations and for automotive applications the highest acceleration specification is 2900 G [14].
Table 1. Comparison of this work with state-of-the-art electret-based vibrational energy harvesters (data taken from [12])

| Author      | Acceleration [G] | Frequency [Hz] | Active surface [cm²] | Electret potential [V] | Output power [µW] |
|-------------|------------------|----------------|----------------------|------------------------|------------------|
| Sakane      | 0.94             | 20             | 4                    | 640                    | 700              |
| **This work** | **2.5**         | **1187**       | **1**                | **200**                | **495**          |
| Boisseau    | 0.1              | 50             | 4.16                 | 1400                   | 50               |
| Naruse      | 0.4              | 2              | 9                    | 600                    | 40               |
| Tsutsumino  | 1.58             | 20             | 4                    | 1100                   | 38               |
| Lo          | 4.9              | 50             | 6                    | 1500                   | 18               |
| Edamoto     | 0.87             | 21             | 3                    | 600                    | 12               |
| Boland      | 7.1              | 60             | 0.12                 | 850                    | 6                |
| Kloub       | 0.96             | 1740           | 0.42                 | 25                     | 5                |
| Lo          | 14.2             | 60             | 4.84                 | 300                    | 2.26             |

5. Conclusions

An electret-based MEMS vibrational energy harvester has been modelled and characterized with sinusoidal excitation. The harvester generated a power output of 175 µW. Compared to a previously published device, a two orders of magnitude increase in power output was obtained. This increase in output power is the result of the combination of two improvements with respect to the previous device: a different electrical connection principle of the harvester and an optimized geometrical configuration of the electrodes. Another device from a next generation, employing the same improvements but with a higher resonance frequency and electret potential, produced an output power of 495 µW. This makes this device a promising candidate for the targeted application of wireless tire pressure monitoring systems (TPMS).

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