WIDEBAND MEMS ELECTROSTATIC VIBRATION ENERGY HARVESTERS BASED ON GAP-CLOSING INTERDIGITED COMBS WITH A TRAPEZOIDAL CROSS SECTION

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ABSTRACT

This paper deals with a fully batch-processed MEMS electrostatic Vibration Energy Harvster (e-VEH) having a half-power frequency bandwidth of more than 30 % thanks to the combination of electrostatic and mechanical non-linearities. The electromechanical transducer is made of bulk-silicon gap-closing interdigited combs with a trapezoidal cross section. Up to 2.2 µW have been harvested at atmospheric pressure for an external acceleration of 1 *G* at 150 Hz.

INTRODUCTION

Vibration Energy Harvesters (VEH) catch mechanical energy trough a mass-spring system, and convert the largest possible fraction of this energy into electrical energy. To this end, electromagnetic, piezoelectric or electrostatic transduction can be used, and sometimes a combination of these. VEH with electrostatic transduction (e-VEH) present interesting features which can make the difference with the other transduction schemes: they are indeed suitable for fabrication in silicon-based MEMS technologies through fully batch fabrication process [1][2][3]. Moreover, the bulk crystalline silicon keeps repeatable elastic properties even under strong deformations [4]. Therefore, it can be used for fabrication of nonlinear springs for wideband VEH [5]. The main drawback of e-VEH is that contrary to electromagnetic and piezoelectric VEH, they need to be pre-charged in order to initiate the conversion process. So, to obtain a totally battery-free system, an electret or a piezoelectric layer needs to be added [6][7].

In a previous work, we have presented a MEMS e-VEH based on an In-Plane Overlap-Plate (IPOP) structure working at 250 Hz [1]. The device had generated around 1 nJ per mechanical oscillation in a continuous mode of operation [8], but only 2.4 pJ in a charge-pump conditioning circuit [9][1] because of its low capacitance variation. One of the main advantages of the IPOP geometry is the possibility to obtain a multiplication of the frequency of the transducer capacitance variation with regard to the mechanical vibration frequency factor, and a possibility to deposit an electret layer easily. On the other hand, it is hard to obtain a small gap between the two electrodes because of the electrostatic instabilities (pull-in and Paschen effects), which limits the maximum capacitance of the transducer and the applied voltage.

This paper deals with a new silicon-based e-VEH whose variable capacitance is made of gap-closing interdigited-combs, as proposed by Roundy in [10], but having trapezoidal cross sections. After describing the device and the experiment setup, we present various measurements of the harvested power from mechanical vibrations. These results demonstrate a large improvement of the power density and of the half-power bandwidth of the e-VEH with respect to previous work.

DESCRIPTION OF THE HARVESTERS

The MEMS device

The movable mass is attached to the rigid frame by 4 linear serpentine springs, and mechanical stoppers between the mass and the frame prevent from short circuits between fixed and movable fingers. The fabrication process is very simple. It is a full batch process which requires only two lithography masks. The movable part is etched by DRIE (Bosh process) in a 380 µm-thick doped Silicon wafer using an aluminum hardmask layer. The silicon etching has an intentional small undercut of about 0.8%, resulting in a trapezoidal cross section of the comb-fingers as shown in figure 1. Then a glass wafer, which is used only as a handle wafer, is etched by liquid HF below the mobile part in order to allow the displacement of the MEMS. Finally, both silicon and glass wafers are anodically bonded. After dicing, each e-VEH is glued onto a PCB, which is screwed to a vibrating shaker. Pictures of the device are shown in figure 2. The mobile mass is estimated to be equal to 6.6 10^{-5} kg and the total area/volume of the active parts (i.e. mass+springs+comb's fingers) is 1.1 cm^2/0.042 cm^3.

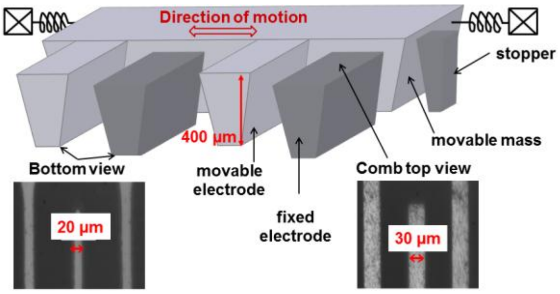

Figure 1: 3D- view of the comb's fingers. Insets: SEM pictures of top and bottom views of the fingers.

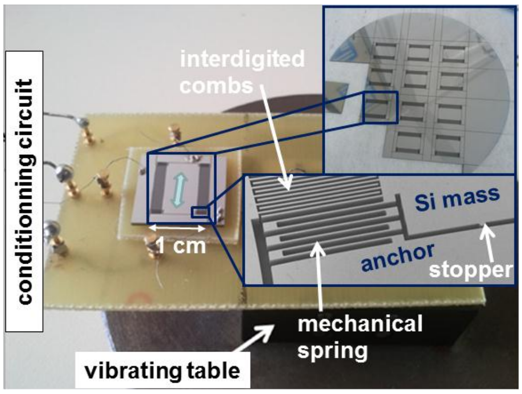

Figure 2: Pictures of the MEMS e-VEHs

Two designs, named *Type-1 and Type-2* e-VEH in the following, have been tested. They are almost identical except for the stopper position. *Type-1* stoppers are designed to hit the rigid frame when the gap between fixed and movable fingers is 1 µm, while for *Type-2*, the contact occurs when the gap is 3 µm.

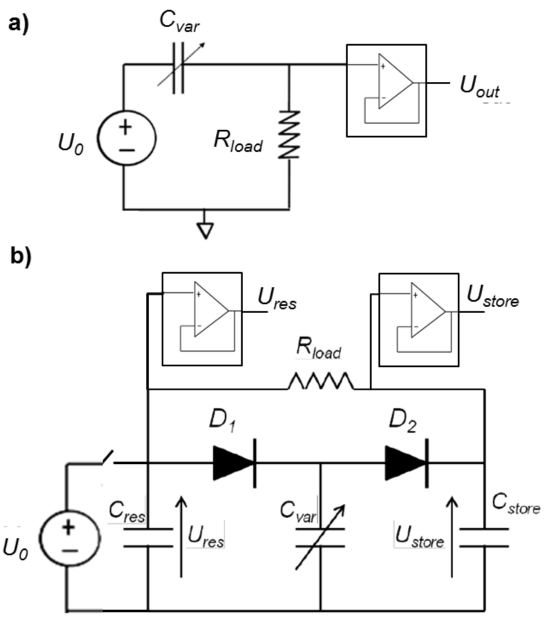

Figure 3: a) Basic continuous mode Conditioning Circuit(CC). b) Improved charge-pump CC.

The conditioning circuits

The role of the conditioning circuit (CC) is to implement a cyclic charge-discharge of the capacitive transducer C_{var}, as required for the electromechanical conversion. For this paper, the e-VEHs have been evaluated using two CCs. The first CC is shown in figure 3.a. It consists in a constant voltage source permanently connected to one terminal of C_{var} while the other terminal is connected to a resistive load. Thanks to the DC polarization of the $R_{load}C_{var}$ circuit, the capacitance variation induces an AC charge flow through the load, which dissipates the energy extracted from the mechanical domain. A high input impedance and low offset operational amplifier is used for the voltage probing.

The second CC is based on a charge pump circuit (figure 3.b). It is composed of three capacitors including a reservoir capacitor C_{res} (~1-10 µF) which provides an initial energy to the system, the electromechanical transducer C_{var} (0.1-1 nF) and a storage capacitor C_{store} (~1-10 nF) which accumulate the converted energy. The diodes D_1 and D_2 act as "passive" electrical switches which manage the charge flow automatically. The role of the charge pump is to transfer the charges from C_{res} toward C_{store}. Since $C_{store} << C_{res}$, this transfer requires an external energy which is provided by the mechanical vibrations through the variations of the C_{var}. Since such a charge pump saturates starting from some voltage level on Cstore capacitor, a flyback circuit returning the charges from C_{store} to C_{res} is necessary. This flyback circuit has to be designed so to maximize the power conversion. An inductive flyback, similar to a Buck DC-DC converter, has been proposed by Yen in [11]. This architecture can make the system fully autonomous and a control electronic with adaptive features can be implemented, as described in [12]. However in this paper we only use a resistance connected between $C_{res.}$ and C_{store}. So the autonomy of the system is limited by the current leakages in the capacitors.

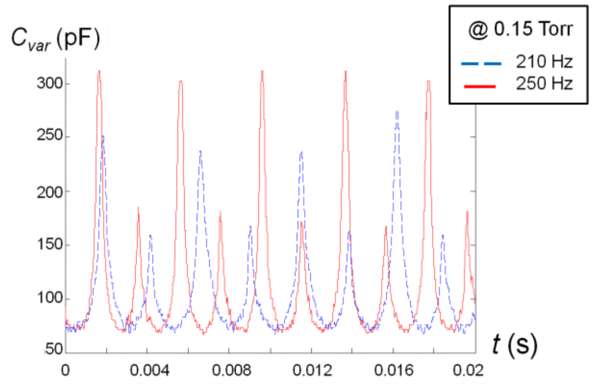

Figure 4: Transducer capacitance's variation of a Type I-device for a 10-µm displacement of the rigid frame at 210 Hz and 250 Hz at a pressure of 150 mTorr

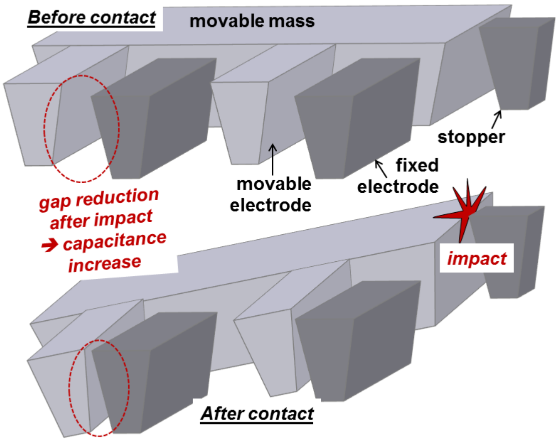

Figure 5: Illustration of the consequence of the spring deformation after stopper contact

EXPERIMENTAL RESULTS

The natural resonance frequency of both e-VEH designs is 162 Hz, if excited at low accelerations and with a low polarization voltage U_0. However non-linear behaviors occur when these parameters increase, as shown in the following section.

Characterization of *Type 1* e-VEH

Type-1 e-VEH has been tested in a vacuum chamber with a vibrating piezoelectric table having a constant displacement while sweeping the vibration frequencies. A measurement of the transducer capacitance C_{var} has been performed by measuring the phase shift in a RC_{var} circuit [1]. Measurement results (including a 30 pF parasitic capacitance from the setup) for a 10-µm excitation of the rigid frame of the harvester, are shown in figure 4. The alternative variation of the local maximum value of C_{var} observed on the figure is attributed to the inelastic collision between the mobile mass and the stoppers. It could also be explained by the non-linear behavior of the electrostatic force when the two electrodes become close enough, responsible of an asymmetry in the mass displacement. However, in this experiment, the electrostatic force is not large enough to generate such a behavior. Although in both cases the mobile mass hits the stoppers, the maximal capacitance is higher for the excitation at the highest vibration frequency (then at a higher acceleration). This is understood as an effect of the trapezoidal shape of the electrodes, which allows a further capacitance increase after an out-of-axis deformation of the springs, as illustrated in figure 5.

Fig. 6 shows the power versus frequency obtained with the continuous-mode CC (figure 3.a) at 1 Torr on a 1 MΩ load. The voltage U_0 = 5 V. The power increases naturally with the frequency until 180 Hz. The monotonicity alteration observed near the resonance frequency corresponds to the impact of the mobile mass with the frame, demonstrating a non-elastic shock. This can be deduced from the observed fluctuation of the output voltage envelop. Then, a highly non-linear behavior is observed: while the linear resonance of the tested device is 162 Hz, the maximum power is obtained at a frequency above 300 Hz. This indicates an increase of the effective spring stiffness. The oscillator hitting stoppers behave as a piecewise-defined nonlinear system [13], which explains the large increase of the bandwidth. As the frequency increase, we observe three dynamic behaviors of the mobile mass: firstly the mobile mass oscillates freely, then the mass hits the stoppers once per mechanical period and finally a short-circuit occurs due to too large acceleration amplitude or due to pull-in phenomenon.

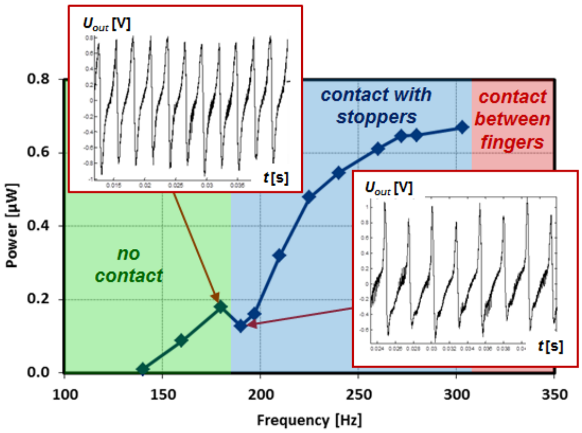

Figure 6: Harvested power measured with the circuit in figure 3.a for Type-2 e-VEH at 1 Torr, on a 1 MΩ load and U_0 = 5 V.

Figure 7 presents the harvested power measured with the circuit in figure 3.a for different values of U_0 at 0.15 Torr and for an external acceleration of 1 *G*. Up to 2.3 µW were obtained on a 1 MΩ load for U_0 = 10 V at a frequency of 260 Hz (i.e. 8.8 nJ/mechanical cycle). For higher voltage, pull-in occurs during the device operation.

We also have monitored the harvested power versus time in similar conditions but in autonomous mode using the charge-pump conditioning circuit of figure 3.b. The system is initially pre-charged at 10.6 V and, at $t = t_0$, the voltage source U_0 is disconnected from C_{res}. Measurements of voltages across C_{res} and C_{store} are shown in fig. 8. We can observe a decrease of the harvested power from 1.4 µW to 0.94 µW after 500 sec on an optimal resistive load of 15 MΩ. This decrease is attributed to capacitance leakages.

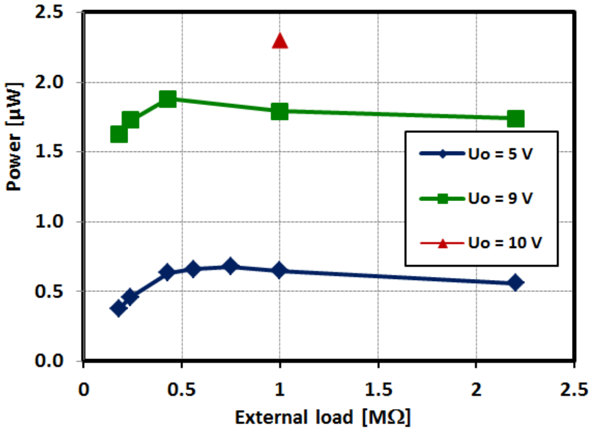

Figure 7: Maximum harvested power with the circuit in figure 3.a of Type-I eVEH at 150 mTorr for different values of U_0 and for 1 g of external acceleration

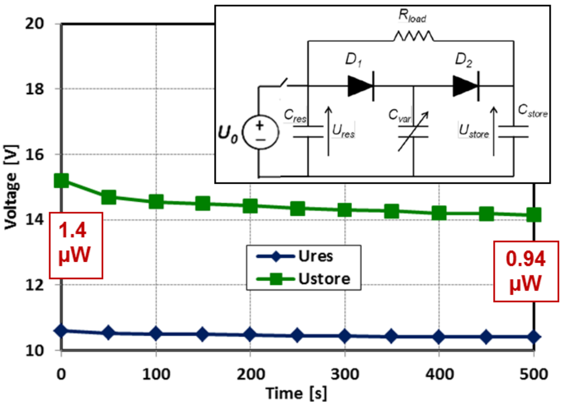

Figure 8: Measurements of the harvested power versus time on a 15 MΩ load of type-I eVEH at 150 mTorr with the circuit in fig. 3.b. U_0 is set to 10.6 V and is disconnected at t = 0 s

Characterization of *Type-2* eVEH

The *Type-2* e-VEH has been tested at atmospheric pressure with an electromagnetic shaker whose acceleration amplitude of the vibrations remains constant during the frequency sweeps. Figure 9 shows the harvested power with the continuous mode conditioning circuit in figure 3.a and for different values of U_o up to 30 V. The acceleration is set to 0.25 *G*, and we optically check that the mass does not touch the stoppers. The typical electrostatic spring softening phenomena, which decreases the useful frequency span, can be observed. For U_0 = 30 V, the maximum harvested power is 0.153 µW at 153 Hz, while the half-power bandwidth is 8.5 %.

In figure 10, the acceleration is increased to 1 *G* and the mobile mass starts hitting the stoppers. With the highest values of U_0, a small difference is observed between the *up* and *down* frequency sweeps. While the voltage U_0 increases (and so the attractive electrostatic force between the electrodes), a combined effect of the electrostatic spring softening and the mechanical spring stiffening leads to a large increase of the bandwidth. For $U_0 = 30$ V, the maximum harvested power is 2.2 µW at 150 Hz (i.e. 14 nJ/mechanical cycle), while the half-power bandwidth is now 32%. For U_0=10V, the power is 1.3 µW and the bandwidth is

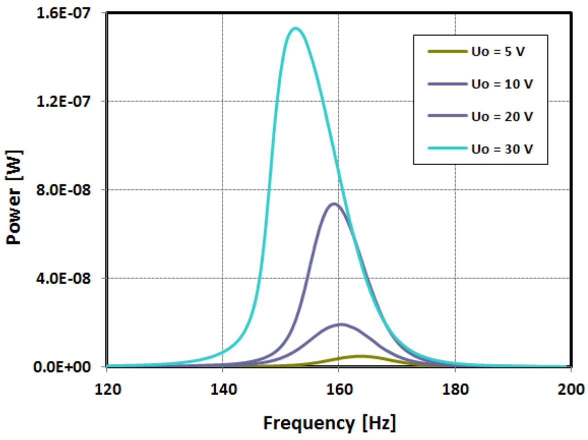

Figure 9: Harvested power measured with the circuit in figure 3.a for Type-2 e-VEH at 1 atm, on a 5.4 MΩ load and for 0.25 G_{rms} of external acceleration.

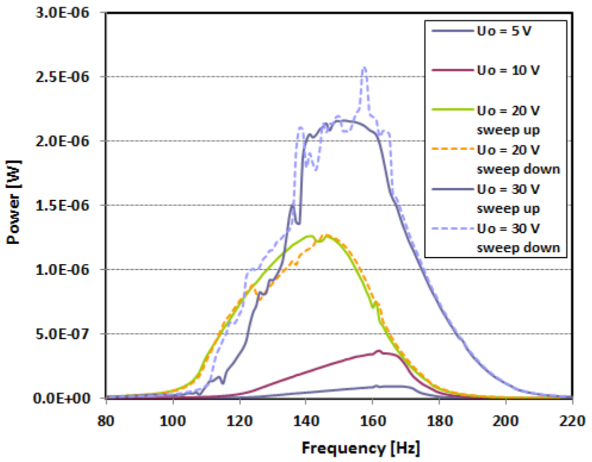

Figure 9: Harvested power measured with the circuit in figure 3.a for Type-2 e-VEH at 1 atm, on a 5.4 MΩ load and for 1 G_{rms} of external acceleration.

CONCLUSION

The MEMS e-VEH presented in this paper converts up to 2.2 µW from the mechanical to the electrical domain at atmospheric pressure and mechanical vibrations of 1 *G* at 150 Hz. Thanks to the trapezoidal shape of the capacitance electrode's cross section, the transducer capacitance continues to increase after the contact of the mobile electrode with stoppers, inducing non-linear behavior in the mechanical spring. The combined effect of electrostatic spring softening and mechanical spring stiffening generates a high half-power bandwidth of more than 30% of the central frequency.

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