CHARACTERIZATION OF A DC/DC CONVERTER USING AN IN-PLANE BULK SILICON CAPACITIVE TRANSDUCER FOR VIBRATION-TO-ELECTRICITY POWER CONVERSION

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Abstract: In this work, we have successfully implemented an electrostatic transducer in a charge-pump circuit for harvesting the energy from the mechanical vibrations. The transducer is an improved and mechanically reliable version of the resonant capacitive bulk-Si vibration energy harvester that we previously presented in [1]. Despite the low transducer volume of 27 mm^3, the targeted external vibration is a harmonic acceleration at 250 Hz of 0.25 g. We demonstrate a harvested power of 103 nW converted from the mechanical to the electrical domain. We have compared the measurements with an accurate mixed VHDL-AMS/Eldo model of the system. The modeling predicts currents and voltages evolution with an inaccuracy of less than 3%.

Key words: Vibration-to-electricity converters, Energy harvesting, Electrostatic transduction

1. INTRODUCTION

We previously presented a bulk silicon based vibration-to-electric energy converter based on an In-Plane Overlap Plates (IPOP) mechanism using an electrostatic transduction (cf. Fig. 1) [1]. The transducer is made up of a 380 µm thick silicon proof mass attached by anodic bonding to a handle glass wafer and having an in plane displacement. The device is 0.7 cm². Its main physical characteristics are given in table 1.

Table1: Characteristics of the energy harvester

Dimensions	11 x 6.5 x 0.86 mm^3
Horizontal resonance frequency	250 Hz
Vertical resonance frequency	3521 Hz
Quality factor	100
Proof mass	46.1 mg
Min. acceleration	0.1 g m/s²
Vertical pull in	12 V

The current work is about the characterization of the presented energy harvester. It includes a dynamic measurement of the capacitance variation and the evaluation of the power generation in a charge pump circuit including the harvester. In addition the experiment results are compared with an accurate mixed VHDL-AMS/Eldo model of the system simulated in AdvanceMS Environment.

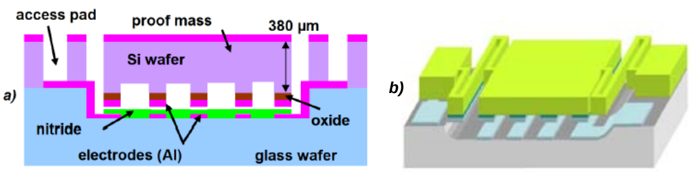

Fig. 1: Proposed energy harvester design: a) side view, b) 3d –view [1].

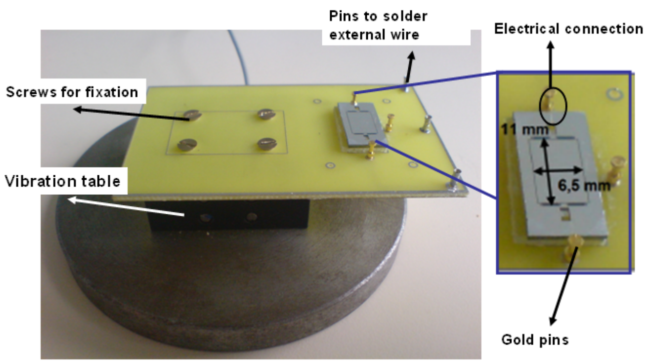

Fig. 2: Test bench with a zoom on the energy harvester

2. EXPERIMENTAL SETUPS

For the experiments, transducers are diced, mounted on a Printed Circuit Board (PCB) and are submitted to in-plane vibrations. The test bench is shown in Fig 2.

2.1 Dynamic capacitance measurement

Dynamic measurement of the transducer capacitance C_{var} is performed by measuring the phase shift in a RC_{var} circuit submitted to high-frequency sinusoidal voltage V_{HF}, while vibrations are applied to the transducer. The frequency f_{HF} is high compared to the frequency of the vibrations ω, so the phase shift between V_{HF} and the transducer voltage is expressed as $\Delta\varphi = \text{atan}(C_{\text{var}} R \omega_{HF})^{-1}$. Thus, knowing the phase shift, C_{var} can be found. The choice of ω_{HF} is determined by the needed accuracy: the ratio ω_{HF}/ω defines the number of measurement points per vibration period. Thus, the larger ω_{HF} is, the higher is the measurement accuracy of the extreme values of C_{var}, but the lower is the possible measurement time (defined by the storing capability of the used oscilloscope).

Once ω_{HF} chosen, R is chosen so to maximize the sensitivity $\partial\Delta\varphi / \partial C_{\text{var}}$. Thus, a simple analysis shows that R has to be chosen in a way to, with the average expected C_{var} value, $(RC_{var\_average})^{-1} = \omega_{HF}$. To note, the precision is degraded when C_{var} shifts from C_{var_average}. If the max-to-min ratio of C_{var} variation is large, it can be necessary to make several measurements with different R corresponding to different $C_{var\_average}$ values. In our case, $C_{max}/C_{min} \approx 2$, and the sensitivity degradation is negligible.

The phase difference between V_{RF} and the voltage across C_{var} can be evaluated as $\Delta\varphi = \omega_{HF}\Delta T / (2\pi)$ where ΔT is the time delay between both signals. Hence by measuring the value of the capacitance at all the points where a phase difference is calculated, a capacitance variation curve is obtained (cf. Fig. 3). The capacitance varies between 144 pF and 73 pF. During one mechanical cycle the proof mass passes twice through the mean position. Hence the frequency of C_{var} variation is twice to the mechanical frequency, i.e. 500 Hz.

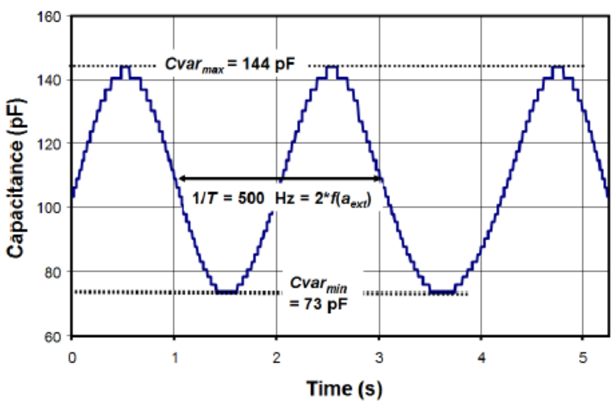

Fig. 3: Measurement of one of the transducer's capacitance variation with applied external acceleration equal to 0.1 g.

2.2 Converted energy evaluation

The energy harvester is implemented as a charge pump to study the continuous power generation. The measurement set-up scheme is shown in fig. 4 [3]. The charge pump circuit is mainly composed of three capacitors: C_{res} (~1 µF), C_{store} (~3.3 nF) and C_{var}. Without the resistor R_{load}, V_{store} increases and V_{res} decreases slightly, since $C_{res} >> C_{store}$, until the charge pump reaches a saturation, a regime at which no energy is generated. Thus, to observe a continuous energy generation, a load resistor is connected to C_{store}. The role of this resistor is to consume the charges accumulated on C_{store}, and in this way, to keep the charge pump away from the saturation and to allow a continuous energy harvesting.

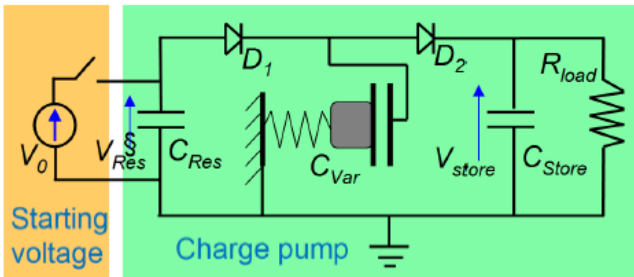

Fig. 4: The charge pump circuit

The measurements are achieved in the following way. First, C_{res} is pre-charged with a DC voltage. Then the voltage source V_o is switched off and the system becomes electrically autonomous. From the evolution of the voltage across C_{res} and C_{store}, it is possible to calculate the electrical power evolution associated with each electrical element. In our circuit, C_{res} and C_{store} discharge and so inject the energy into the circuit, and the diodes and R_{load} dissipate the energy. In a purely electrical circuit we should have $E_{Rload} + E_{diodes} = E_{Cres} + E_{Cstore}$, where E_{Rload}, E_{diodes}, E_{Cres} and E_{Cstore} are the energy dissipated by the load resistance and the diodes, and energy stored in C_{res} and C_{store} respectively. However, since the transducer provides energy, the measured dissipated energy is expected to be higher than the energy provided by the capacitor. Thus, the energy balancing equation for the given system is:

$$E_{mec} = E_{Rload} + E_{diodes} - E_{Cres} - E_{Cstore} \quad (1)$$

where E_{mec} is the energy generated by the mechanical vibrations. Net energy dissipated as heat by the diodes and the load resistance comes from the energy stored in C_{res} and C_{store} and the energy produced by the mechanical vibrations. Between time instants t_1 and t_2, these energies can be defined as:

$$E_{Rload} = \frac{1}{R_{load}} \int_{t1}^{t2} \frac{V^2_{store}(t)}{2} dt \quad (2)$$

$$E_{diodes} = \Delta Q_{res} V_d + \Delta Q_{store} V_d \quad (3)$$

$$E_{C_{res}} = \frac{C_{res}}{2} \left(V_{res_o}{}^2 - V_{resn}{}^2 \right) \quad (4)$$

$$E_{C_{store}} = \frac{C_{store}}{2} \left(V_{store_o}{}^2 - V_{storen}{}^2 \right) \quad (5)$$

where $\Delta Q_{res} = C_{res} \Delta V_{res}$, $\Delta Q_{store} = C_{store} \Delta V_{store}$, and V_d, ΔV_{res}, ΔV_{store}, V_{reso}, V_{resn}, V_{storeo} and V_{storen} are the threshold voltage of the diode, change in the voltage across C_{res} and C_{store}, the voltages across C_{res} and C_{store} at the initial and final time respectively.

The power generated by the mechanical vibrations in certain time frame Δt is then given as:

$$P_{mec} = \frac{E_{mec}}{\Delta t} \quad (6)$$

The diodes used in the charge pump should have low reverse leakage current to avoid the discharge of the initial charge stored in the harvester. Hence:

$$Q_{initial} = C_{\max} V_o >> Q_{leakage} = I_{reverse} T_{period} \quad (7)$$

where $Q_{initial}$, C_{max}, V_o, $I_{reverse}$, $Q_{leakage}$ and T_{period} are the initial charge stored on the transducer, the maximum capacitance of the transducer, the initial voltage applied, the reverse leakage current, the charge lost due to it, and the electrical time period of the cycle. In our case the system is pre-charged with 6 V, hence $Q_{initial}$ is 858 pC. Diodes with low leakage current of 5 pA are used. Hence, with the electrical frequency 500 Hz, $Q_{leakage}$ is 10 fC. Voltages measurements are done through an OpAmp voltage follower with high input impedance and low input bias current of 250 fA.

3. EXPERIMENTAL RESULTS

Firstly the charge pump is tested without the load resistance. C_{res} is initially charged with a DC voltage of 6 V. Due to the external vibrations, the voltage across C_{store} increases and gets saturated after some time as shown in Fig. 5. At saturation, theoretically V_{store} is calculated as [2]:

$$V_{store} \approx (V_o - V_d) \frac{C_{\max}}{C_{\min}} - V_d \quad (8)$$

The ratio C_{max}/C_{min} for the tested transducer is 1.9, hence corresponding V_{store} theoretical value at saturation is around 11 V. The value of V_d is assumed to be constant and equal to 0.6 V. However the measured value of V_{store} is around 8 V, which is smaller than expected. It is because of the non negligible vertical electrostatic force between top and bottom electrodes which pull the proof mass down to the substrate and thus reduces slightly the ratio C_{max}/C_{min}. The best fitting of measured and theoretical curve of V_{store} is found for the capacitance ratio 1.45. In the presence of the vertical electrostatic force, the acceleration required to reach the resonance is no more 0.1 *g* but *0.25 g*.

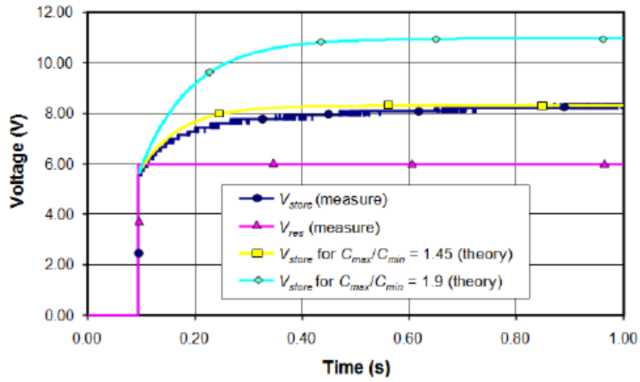

Fig. 5: Measurement and theoretical evolution with time of V_{res} and V_{store} with an infinite load after an initial pre-charge of $V_0 = 6$ V on V_{res}.

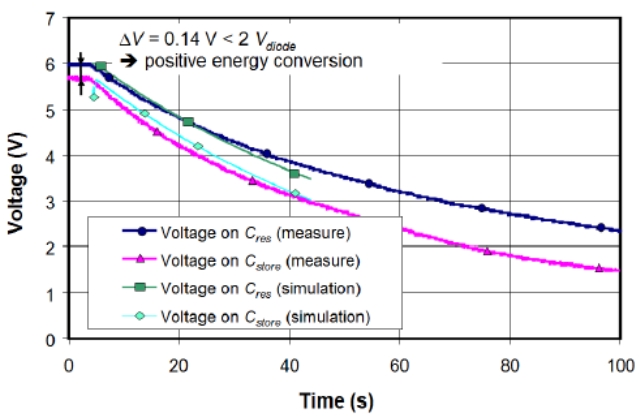

Fig. 6: Measurements and simulations of the charge-pump operation in autonomous mode on a 50 MΩ load resistance for a pre-charge of 6 V.

A second experiment is made using a resistive load in parallel with C_{store}. The evolution of V_{res} and V_{store} with a 50 MΩ load resistor is shown in Fig. 6. As expected the voltages evolve exponentially while discharging on R_{load}. Using these curves and the energy balancing equation defined in (1) to (5), the net power generated by the mechanical domain is calculated. This demonstrates a positive electrical energy generation of 103 nW, coming necessarily from the mechanical domain. The power balance diagram of the system is shown in Fig. 7, using the 50 MΩ load resistance. The threshold voltage of diode for calculating the energy dissipated in diodes is taken as 0.6 V.

In addition the system has been modeled as a mixed Eldo/VHDL-AMS model and simulated in AdvanceMS environment. The VHDL-AMS model of the transducer is based on the device physical equations described in [4]. For the other electrical elements of the system, Eldo models are being used. In Fig. 6, the simulated results are also plotted along with the measured results. A very good match can be observed between simulated and measured results, less then 3% for the voltages evolution.

Fig. 8 shows the harvested power for various resistive loads and pre-charge of 6 V. The maximal power of 103 nW is generated on the 50 MΩ load. The power estimated by the Eldo/VHDL-AMS model simulated in AdvanceMS environment for the various resistances is also plotted. The modeling highlighted a maximal power of 75 nW for the optimal load of 90 MΩ. The discrepancy between the harvester power extracted from the simulated data and experimental results comes from the difficulty to account correctly for the diode losses in the power calculation from the physical experiment. For this, a fixed threshold diode representation was used, whereas the Eldo model used a more realistic exponential diode representation.

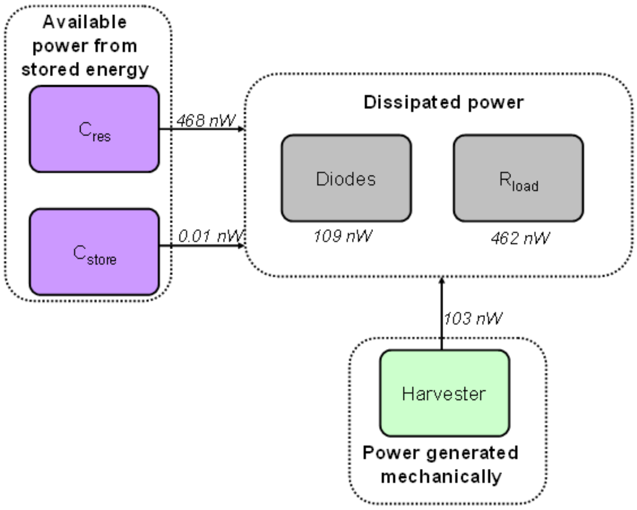

Fig. 7: Power balance diagram

4. CONCLUSION

In this work, we have successfully implemented a "CMOS-compatible" transducer in a charge pump circuit for harvesting the energy in mechanical vibrations. With a harvester of 27 mm^3, at the resonance frequency of 250 Hz and an acceleration of 0.25 *g*, a harvested power of 103 nW from mechanical domain is being demonstrated. The value of the optimum load resistance is 50 MΩ. The limit of the transducer is the pull-in effect which is about 12 V, corresponding to an initial pre-charge of 7 V. The system is also simulated using the VHDL-AMS model for the harvester and ELDO models for the passive elements in the AdvanceMS environment. The modeling predicts currents and voltages evolution in the system with an inaccuracy of less then 3% compared to the measurements.

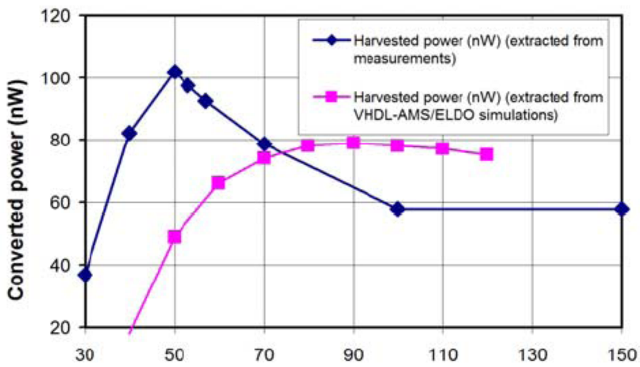

Fig. 8: Harvested power converted from the mechanical to the electrical domain in the charge-pump.

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