MEMS DC/DC CONVERTER FOR 1D AND 2D
VIBRATION-TO-ELECTRICITY POWER CONVERSION

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ABSTRACT

This paper presents a working silicon-based MEMS electrostatic transducer for harvesting and converting the energy of vibrations into electrical energy. The transducer is fabricated in a batch silicon-on-glass process. Two designs, for 1D and 2D vibrations, are addressed. The 1D harvester demonstrates between 60 and 100 nW of mechanical-to-electrical power conversion at 250 Hz when implemented in a classical DC/DC converter circuit.

We also propose a new simple approach for the calculation of the maximum power that can be generated from a spring-mass system excited with a sinusoidal force, based on an electrical impedance network analogy. This paper ends with a comparison between several working electrostatic harvesters based on a novel figure of merit.

KEYWORDS

Energy harvesting, electrostatic transduction

INTRODUCTION

The process of electrical power generation from mechanical vibrations can be described in two stages involving a mechanical resonator and an electromechanical transducer. At first, a proof mass is coupled with the environmental vibrations through an elastic link: the mass and the spring constitute the resonator, present in all vibration energy harvesters. Thanks to this elastic coupling with the vibrating frame, the mass moves and the resonator accumulates a mechanical energy. The second stage consists in the conversion of this mechanical energy into electric energy. For this purpose, an electromechanical transducer should apply a damping force on the mass, *i.e.* should perform a negative work on the mechanical system. A conditioning circuit manages the electrical energy flow so to accumulate the maximum of energy in the reservoir which supplies the load. In addition, the conditioning circuit creates the electrical context necessary for the wanted operation of the electromechanical transducer.

The damping force is typically created by magnetic field, straining piezoelectric material or electric field. Electrostatic harvesters, as those considered in this paper, have a rather lower power density and need an initial pre-charge to start unless they use an electret layer. However such systems are still very attractive since they can be fabricated in a silicon micromachined process compatible with CMOS and are suitable for miniaturization

In this paper we present two designs of electrostatic energy harvesters from mechanical vibrations having 1D and 2D orientations, fabricated in a Silicon-on-Glass technology and having an In-Plane Overlap Plate (IPOP) configuration [1] (cf. fig. 1).
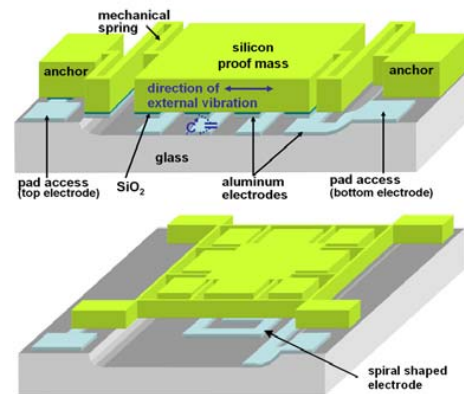

Figure 1: 3D views of the 1D (a) and 2D (b) electrostatic vibration-to-electricity energy harvester.
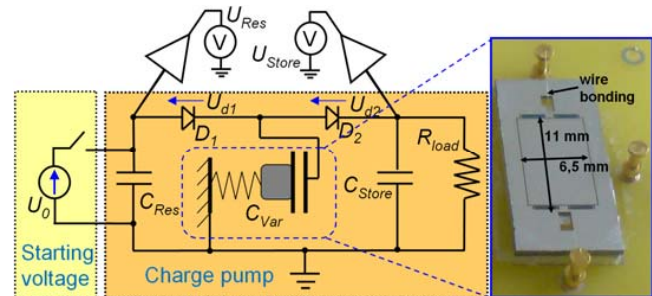

Figure 2: The 1D-transducer and its conditioning circuit.

1D ENERGY HARVESTER

The transducer designed to harvest energy from 1D-vibrations has been initially proposed in [1]. The proof mass is micromachined from a (100)-oriented 380 μm-thick single crystal silicon wafer, anodically bonded to a glass substrate. The electrodes of the variable capacitance C_{var}, which are made of aluminum, are on the top-side glass and back-side silicon wafers respectively (cf. fig. 1). In order to perform the measurements, the resonators were mounted on a PCB and wire-bonded to the charge-pump shown in fig. 2.

We applied in-plane vibrations at the proof-mass mechanical resonance frequency of 250 Hz, with a maximum acceleration of 0.25 g to displace the mass by +/- 50 µm. A dynamic measurement of the capacitance variation C_{var} is achieved by measuring the phase shift in a RC_{var} circuit. If a weak voltage is applied on C_{var}, it exhibits a variation from 73 to 144 pF. However, when the voltage increases, the vertical electrostatic force between top and bottom electrodes pulls the proof mass down to the substrate, reducing the ratio C_{max}/C_{min}, mainly because of increase of the fringe field responsible for C_{min} value. Thus, at 8 V_{DC}, the measured ratio C_{max}/C_{min} is 1.3. (cf. fig. 3). This corresponds to a gap reduction of almost 40 %, which is much bigger than the theoretical maximum gap reduction threshold of 33 % for pull-in instability in the case of an ideal electrostatic actuator. This behaviour is ascribed to a nonlinear spring stiffness, which increases at large displacement of the attached proof-mass.
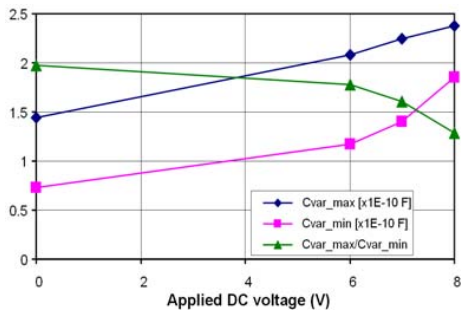

Figure 3: Measurement of Cvar$_{max}$, Cvar$_{min}$ and Cvar$_{max}$/Cvar$_{min}$ ratio with applied increasing applied DC voltage
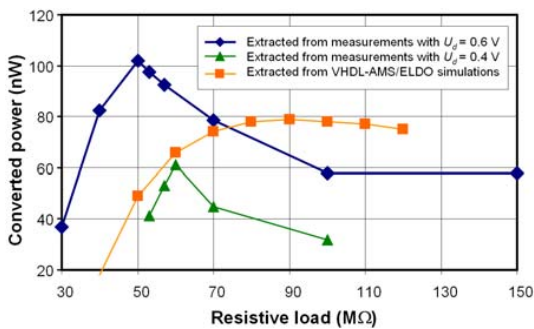

Figure 4: Harvested power versus the resistive load

Measurement of Converted Power

To demonstrate electromechanical energy generation, C_{res} and C_{store} are initially pre-charged with the DC voltage U_o = 6 V, corresponding to approximately half the pull-in voltage. Then the voltage source is switched off at t_0 and the system becomes electrically autonomous. Then the electrical network has three energy sources: the discharging capacitors C_{res} and C_{store}, and the capacitive transducer which transforms mechanical energy into electrical energy. Furthermore, energy dissipates in the resistive load and in the diodes. The balance equation for the corresponding electrical power is expressed as:

$$P_h + P_{Cres} + P_{Cstore} = P_{Rload} + P_{diodes} , \qquad (1)$$

where P_h is the power generated by the mechanical vibrations, P_{Rload} and P_{diodes} are the power dissipated by the load and the diodes, and P_{Cres} and P_{Cstore} are the power flows provided by the C_{res} and C_{store} discharges. The power terms are calculated over an interval of time of 6 sec after t_0. Details can be found in [2].

These experiments are also modelled using the VHDL-AMS model presented in [3], implemented with the same C_{max}/C_{min} ratio of 1.45 and with a realistic exponential diode model. For the capacitor voltage evolution, the modelling and the experiment agreed better than 3% [2].

We performed experiments with various non-zero loads from 30 to 150 MΩ. The plot in fig. 4 shows the value of P_h, calculated from measured and simulated voltage evolutions. When the power dissipated in the diodes is calculated with V_d = 0.4V/0.6 V assumed constant, we obtain a maximal electrical power generation of 61/103 nW on a 60/50 MΩ load resistor. The power extracted from the modeling experiments highlights a maximal power of 79 nW for an optimal load of 90 MΩ. This discrepancy results from the difficulty to account correctly for the diode losses in the calculation of the experimental power.
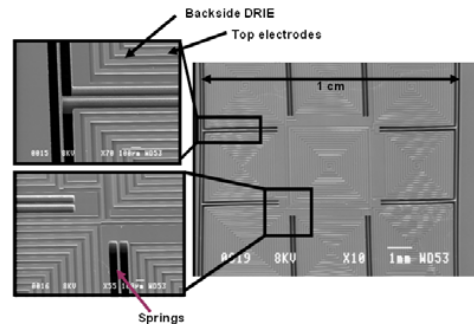

Figure 5: SEM of the Si-wafer backside just before glass bonding

2D ENERGY HARVESTER

In most of cases, the available energy is equally distributed over the three degrees of freedom. Thus, in average, a 2D transducer is twice more efficient than its one-degree of freedom counterparts. The presented design is being inspired from 2-D gyroscope [4]. The net surface area of the device is 1 cm² and resonance frequency is measured at 246 Hz. The patterned electrodes are of a spiral rectangular shape. This is being done to achieve the same capacitance variation in either direction in the plane. The modeled values of max/min capacitances and pull-in voltage are 370 pF / 205 pF and 10 V respectively. Fig. 5 shows a SEM picture of the back side of the proof mass

with the zoomed view of the mechanical springs and the electrodes.

The ideal (maximal) value of the power generated by an electrostatic energy harvester using constant-charge triangular QV cycle [7] is given by:

$$P_{h\max} = U_0{}^2 C_{\max}\left(\frac{C_{\max}}{C_{\min}} - 1\right) f_{elec}\Big/2 ,\qquad (2)$$

where U_o is initial charge voltage which maximum is given by the pull-in voltage times C_{min}/C_{max}, and f_{elec} is the frequency of the transducer capacitance variations. In our transducers, f_{elec} is twice the mechanical resonance frequency. Eq. (2) with $U_0 = 6$ V gives 2.6 µW for the theoretical maximal harvested power at the resonance.
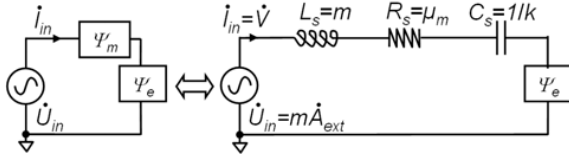

Figure 6: Equivalent electrical network of a spring-mass vibration energy harvester

MAXIMAL POWER GENERATION MODEL

Close-form expressions of the maximum power that can be generated from a spring-mass system excited with a sinusoidal force have already been presented in previous papers [5][6]. We present here a different approach using the electrical impedance network analogy. In the mechanical domain, the harvester can be represented by the equivalent electrical network in fig. 6, where m, k, A_{ext} and μ_m are mass, spring stiffness, acceleration of external vibrations and mechanical damping. In the following, ψ_e denotes the mechanical impedance of the transducer and ψ_m the mechanical impedance the resonator which is calculated by m, k and μ_m. In energy harvesting literature, the electromechanical transducer is often represented by an ideal damper, which has only a real impedance. But, this representation can only be applied to few particular cases (*e.g.* electromagnetic transduction). In general, the impedance is complex, and should be optimized to estimate the maximal power.

From the electromechanical analogy, the power absorbed by a dipole is the real part of the complex power, defined as the half square of module of the current times the impedance of the load. In the mechanical domain, the current is equivalent to the velocity and the mechanical impedance is defined as minus the ratio between the complex amplitudes of force ($\dot{F}$) and velocity ($\dot{V}$) (dotted letters represents complex quantities). The power harvested from mechanical-to-electrical domains is:

$$P_h = \frac{1}{2}\left|\dot{V}\right|^2 \mathrm{Re}(\psi_e),\qquad (3)$$

To maximized P_h, both $\dot{V}$ and $\mathrm{Re}(\psi_e)$ have to be maximized, but there is implicit relation between these two quantities. Let us express this relation. Analyzing the network in fig. 2, we have:

$$\psi_m + \psi_e = \frac{m\,\dot{A}_{ext}}{\dot{V}},\qquad (4)$$

Equating the absolute values of both parts and considering $\mathrm{Re}(\psi_e) + \mathrm{Re}(\psi_m)$ positive :

$$\mathrm{Re}(\psi_e) = \sqrt{\left(\frac{mA_{ext}}{V}\right)^2 - [\mathrm{Im}(\psi_m + \psi_e)]^2} - \mathrm{Re}(\psi_m),\qquad (5)$$

where V and A_{ext} are modulus of complex values. If we choose ψ_e so that:

$$\mathrm{Im}(\psi_e) = -\mathrm{Im}(\psi_m),\qquad (6)$$

thus $\mathrm{Re}(\psi_e)$ is maximized and is linked with V as:

$$\mathrm{Re}(\psi_e) = \frac{mA_{ext}}{V} - \mu_m ,\qquad (7)$$

Injecting (7) into (3) we get:

$$P_h = \frac{1}{2}V^2\left(\frac{mA_{ext}}{V} - \mu_m\right) = \frac{1}{2}V(mA_{ext} - \mu_m V),\qquad (8)$$

This expression is maximum when $V = 0.5 mA_{ext}/\mu_m$, which gives the expression:

$$P_h = \frac{1}{8}(mA_{ext})^2\Big/\mu_m ,\qquad (9)$$

However, in practice, often the mass vibration is limited at X_{max} (by the position of the stoppers for instance). If $X_{max} < 0.5 mA_{ext}/\mu_m$, we are in a so-called "amplitude-constrained" case, and the maximal velocity is $V = \omega X_{max}$. To maximize the harvested power, the designer should choose this maximal velocity value to get as close as possible to the optimal V. From (8), we have the harvested power:

$$P_h = \frac{1}{2}X_{\max}{}^2\omega^2\left(\frac{mA_{ext}}{X_{\max}\omega} - \mu_m\right),\qquad (10)$$

If μ_m is negligible as it was supposed in [5], we come to the exactly same formula for *Velocity-Damped Resonant Generator* (VDRG) having a harmonic motion:

$$P_{h\max} = \frac{1}{2}X_{\max}\omega mA_{ext} = \frac{1}{2}X_{\max}\omega^3 mX_{ext} ,\qquad (11)$$

where X_{ext} is the displacement amplitude of the external vibrations, related with A_{ext} as $A_{ext}=X_{ext}\omega^2$.

CONCLUSION

We have shown experimentally the ability to scavenge mechanical vibrations energy in order to provide electrical power to a resistive load, with the use of an electrostatic silicon-based MEMS transducer fabricated in a CMOS-compatible technology. This work is the first fully working electrostatic energy harvester fabricated in a silicon batch process without using an electret. The converted power lies between 60 nW and 100 nW, with external vibrations at 250 Hz and an acceleration amplitude of 0.25 g.

To make an adequate comparison of our work with

other electrostatic harvesters, we propose a figure of merit (FOM) defined as a normalized converted power:

$$FOM = \frac{P_h}{U^2 fA},$$ (12)

where P_h is the power converted from the mechanical to the electrical domain, U is the maximal voltage applied on the capacitive transducer, f is the external vibration frequency and A is the device area. Indeed, it is well-recognized that the output power of capacitive harvesters is proportional to the square of the pre-charge voltage, to the frequency and to the maximal transducer capacitance value. The latter is more or less directly proportional to the device area. The table 2 presents the calculation of this FOM for several published works that have demonstrate effective power conversion; it can be seen that our 1D transducer has one of the best figure of merit.

ACKNOWLEDGMENTS

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Table 1: Comparison of electrostatic energy harvesters.

Author, [ref.]	Year	Operating frequency f, [Hz]	Device area A, [mm²]	Operation voltage, [V]	Converted power P_h, [μW]	Figure of merit (FOM) $P_h/(U^2 fA)$, [10⁸μW/(mm²HzV²)⁻¹]
G. Despesse *et al.,* [8]	2005	50	1800	120	1050	81
B. Yen *et al.,* [9]	2006	1560	4356	6	9.47[1]	3.9
T. Tsutsumino *et al.,* [10]	2006	20	200	950 (electret)	37.7	1.0
W. Ma *et al*., [11]	2007	4100	25.9	15 ("electret like")	0.065	0.27
Y. Suzuiki *et al.,* [12]	2008	37	900	450 (electret)	0.28	0.0034
This work	2009	250	66	8	0.061	5.7

[1] The authors provide only the power delivered to the load (1.8 μW), and they note that the efficiency is about 19 %. Thus, to roughly estimate the converted power, we divided 1.8 μW by. 0.19.