A Silicon MEMS DC/DC Converter for Autonomous Vibration-to-Electrical-Energy Scavenger

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***Abstract*—This letter deals with an innovative design for a silicon MEMS dc/dc converter, to be used in autonomous mechanical-energy scavengers, based on electrostatic transduction. The device is made of bulk silicon and is fabricated using a batch process. It is 27 mm^3 in volume and resonates at 250 Hz. We demonstrate a net vibration-to-electricity power conversion of between 60 and 100 nW in autonomous mode, i.e., without injecting and introducing new charges from an external power supply. We have compared the measurements with the results of a mixed VHDL-AMS/ELDO modeling experiment, and the agreement between these two experiments is better than 3%.**

***Index Terms*—DC/DC power conversion, energy conversion, microelectromechanical devices.**

I. Introduction

A MECHANICAL-ENERGY harvester is composed of a mechanical resonator, an electromechanical transducer, and a conditioning circuit achieving the energy transfer from the transducer toward the electrical load [1]. In this letter, we deal with a capacitive (electrostatic) transducer. Other common types of harvesters use electromagnetic [2] or piezoelectric [3], [4] transduction. While electromagnetic transducers have the best power density, they require bulky parts. Efficient piezoelectric devices, on the other hand, need deposition of thin-film materials, which are not always compatible with a CMOS process. Electrostatic harvesters [5]–[14], as considered in this letter, have a lower power density and need an initial precharge to start, unless they use an electret layer. However, such systems are still very attractive since they can easily be fabricated in a silicon-micromachined process that is compatible with CMOS, and they are hence suitable for miniaturization.

The idea of electrostatic-energy harvesting could be summarized in three steps: putting an electrical charge Q on a variable capacitor when the capacitance C is high, reducing this capacitance thanks to the motion due to mechanical vibrations, and then discharging the capacitor [5]. Following the formula of electrostatic energy of the condenser $W = Q^2/(2C)$, the discharge energy is higher than the energy spent to charge the capacitor.

Manuscript received November 23, 2008; revised February 6, 2009. First published April 14, 2009; current version published April 28, 2009. This work was supported in part by the French National Research Agency (ANR) under Contract JC05-54551 and in part by the French competitiveness cluster Advan City. The review of this letter was arranged by Editor J. K. O. Sin.

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Digital Object Identifier 10.1109/LED.2009.2015780

In the existing literature, even though one can find macroscopic devices that use discrete-element technology [6]–[10] or exploit an electret layer to initialize the system [11]–[13], it is hard to find implementations of working electrostatic vibration harvester made of silicon with integrated features. A silicon-based transducer has been presented in [14], but the authors did not report on the converted output power. A promising conditioning circuits for electrostatic electret-free transducers has been proposed in [6]. It consists in a charge pump acting as a single-stage MEMS dc/dc converter that accumulates the energized charges [15], and an inductive flyback circuit that returns the charge pump to a preceding state away from saturation, while transferring the energy from the charge pump to a tank capacitor.

In this letter, we present an electromechanical dc/dc converter based on a new fully silicon-integrated MEMS resonator/transducer block that is included in a charge pump. The system is optimized to be powered by mechanical vibrations at 250 Hz. It effectively converts mechanical energy to electrical energy, which can be used to feed wireless low-power electronic devices, by increasing the lifetime of a battery in a vibrating environment or by being part of a full autonomous system for energy harvesting, like the one described in [6].

II. Transducer Description

The proof mass is micromachined from a (100)-oriented 380-μm-thick single-crystal silicon wafer, which is anodically bonded onto a glass substrate, and is designed to have an in-plane translational degree of freedom. The electrodes of the variable capacitance C_{var}, which are made of aluminum, are on top-side glass and back-side silicon wafers, respectively (Fig. 1). The fabrication process is explained in further detail in [16].

In order to perform the measurements, the resonators were mounted onto a PCB and wire bonded to the conditioning electronic circuit. We applied in-plane mechanical vibrations of 250 Hz with a maximum acceleration of 0.25 g. The proof mass is displaced by ± 50 μm. A dynamic measurement of the capacitance variation C_{var} is achieved by measuring the phase shift in an RC_{var} circuit. The measurement showed that 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 the top and bottom electrodes pulls the proof mass down to the substrate, reducing the ratio $C_{\max}/C_{\min}$, mainly because of the increase of the fringe field that is responsible for the $C_{\min}$ value. Thus, at 8 V_{DC}, the measured ratio $C_{\max}/C_{\min}$ is 1.3.

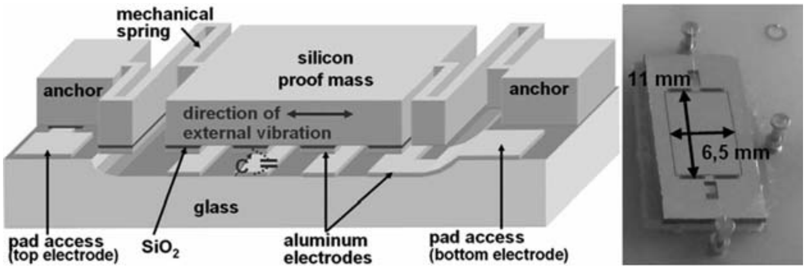

Fig. 1. Three-dimensional schematic view and photograph of the fabricated transducer.

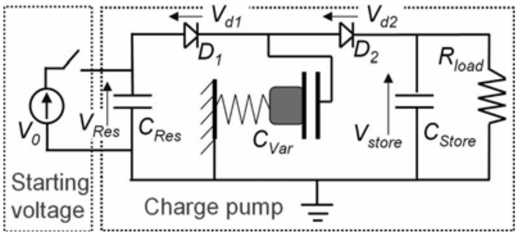

Fig. 2. Charge pump circuit.

During one mechanical cycle, the proof mass passes twice through the mean position, so the frequency of C_{var} variation is consequently twice the mechanical-vibration frequency.

III. Converted-Energy Measurement

A. Description of the Experiment

The charge pump circuit is shown in Fig. 2. To demonstrate electromechanical-energy generation, C_{res} and C_{store} are initially precharged with the dc voltage V_o. Then, the voltage source is switched off, and the system becomes electrically autonomous. The electrical network has three energy sources: the discharging capacitors C_{res} and C_{store} and the capacitive transducer that 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

$$P_{\mathrm{mec}} + P_{C_{\mathrm{res}}} + P_{C_{\mathrm{store}}} = P_{R_{\mathrm{load}}} + P_{\mathrm{diodes}} \tag{1}$$

where P_{mec} is the power generated by the mechanical vibrations, $P_{R_{\mathrm{load}}}$ and P_{diodes} are the power dissipated by the load and the diodes, and $P_{C_{\mathrm{res}}}$ and $P_{C_{\mathrm{store}}}$ are the power flows provided by the C_{res} and C_{store} discharges. $P_{C_{\mathrm{res}}}$, $P_{C_{\mathrm{store}}}$, and $P_{R_{\mathrm{load}}}$ can be considered as constant on a small time interval Δt and can be measured directly. P_{diodes} is estimated as

$$P_{\mathrm{diodes}} = V_{\mathrm{diodes}} \cdot \overline{I}_{\mathrm{diodes}} \tag{2}$$

where $\overline{I}_{\mathrm{diodes}}$ is the mean current flowing from C_{res} to R_{load} (it is the same for both diodes) and is calculated as

$$\overline{I}_{\mathrm{diodes}} = -\frac{\Delta Q_{\mathrm{res}}}{\Delta t} = \frac{C_{\mathrm{res}}\left[V_0 - V_{\mathrm{res}}(\Delta t)\right]}{\Delta t} \tag{3}$$

where ΔQ_{res} is the charge variation on C_{res} during Δt and $V_{\mathrm{res}}(\Delta t)$ is the voltage across C_{res} after the time interval Δt.

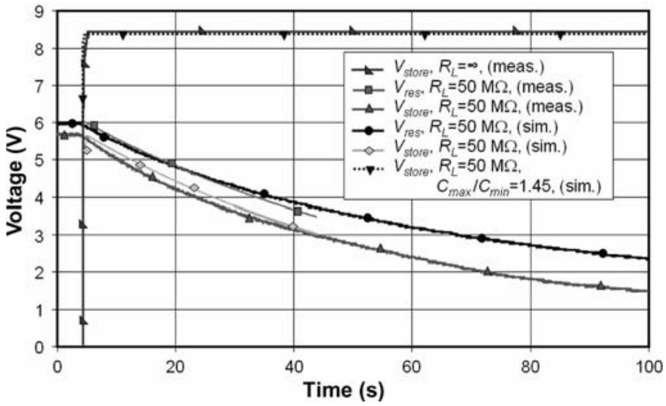

Fig. 3. Measurements and theoretical evolutions with time of V_{res} and V_{store}, with and without a resistive load.

In our experiment, the system is precharged with $V_0 = 6$ V, corresponding to approximately half of the out-of-plane pull-in voltage. Thus, at each period of C_{var} variation, the pump charge transfers the charge amount $(C_{\max} - C_{\min})V_0$ ~420 pC from C_{res} to C_{store}, which corresponds to a mean current of ~210 nA. The parasitic leakage currents need to be much smaller in order to perform accurate measurements. In our measurement setup, we used JPAD5-E3 diodes that account for only 5 pA of leak. The voltage measurement circuit results in a leakage current of 250 fA. Such low values of current imply that the direct voltages of the diodes are lower than the usual 0.6–0.7 V. Our modeling and indirect measurements indicate a V_d of 0.4 V for these levels of current.

B. Results

Fig. 3 shows the voltage evolutions of V_{res} and V_{store} with and without a resistive load of 50 MΩ. The measurement without the load identifies the saturation voltage of the charge pump $V_{\mathrm{store\_sat}}$ to be 8.4 V (Fig. 3, curve on top). From the theory, $V_{\mathrm{store\_sat}} = (V_0 - V_d)C_{\max}/C_{\min} - V_d$ that is nearly 8.45 V for $C_{\max}/C_{\min} = 1.45$ and $V_d = 0.1$ V. Such a low diode voltage is explained by the fact that there is nearly no charge transferred when the charge pump is saturated.

This experiment is also modeled using the VHDL-AMS model presented in [17], which is 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 modeling and the experiment agreed better than 3%.

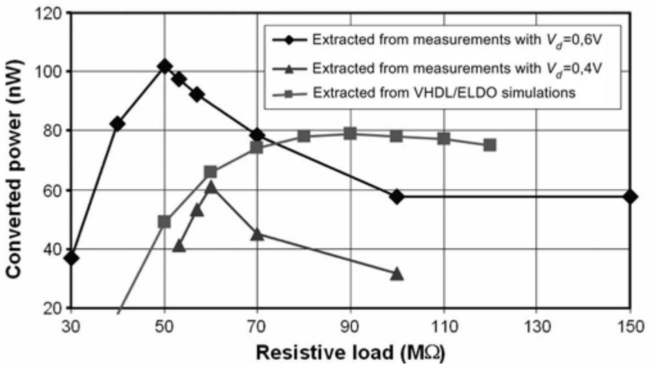

Fig. 4. Harvested power versus the resistive load.

To evaluate the part of the power that is harvested from the mechanical domain based on (1), we performed experiments with various nonzero loads from 30 to 150 MΩ. The qualitatively similar curves of those shown in Fig. 3 were obtained. The plot in Fig. 4 shows the value of P_{mec}, which is calculated from measured and simulated voltage evolutions. When the power dissipated in the diodes is calculated from (2) and (3), with $V_d = 0.4\ \mathrm{V}/0.6\ \mathrm{V}$ being 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.

IV. Conclusion

We have shown experimentally the ability to scavenge the energy from mechanical vibrations 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. To our knowledge, this is the first fully working electrostatic-energy harvester fabricated in such a batch process. After a precharge of the transducer at 6 V, the measurements have been performed in autonomous mode (no voltage source was connected to the system). The converted power lies between 60 nW (pessimistic estimation) and 100 nW, with external vibrations at 250 Hz and an acceleration amplitude of 0.25 g.

It is very difficult to compare the results of various vibration harvesters. Depending on the transduction mechanism, the input acceleration, the frequency of operation, and the mass and volume of the transducer, the harvested power can range from few nanowatts to several tens of microwatts. However, in order to have a useful generator, several microwatts are mandatory. For our device, the output power is mainly limited by the high value of the transducer parasitic capacitance and by the ability of our capacitive transducer to sustain a high voltage. With the technology we presented in this letter, much more electrical power would be available if the device was designed for higher vibration frequencies–which are a typical in the ambient environment [10], [18]. The increase of the harvested power when the frequency of vibration is high is due to the increased number of capacitance variation cycles per second, but also to the increase of the pull-in voltage resulting from the increase of the spring stiffness. Consequently, higher precharge voltages can be used. For instance, if we consider the spring beam's width to be W, the resonance frequency f_0 of the transducer scales as $W^{3/2}$ and its pull-in voltage scales as $W^{1/2}$. The harvested power, which is proportional to f_0 and V_0^2 [5], scales as $W^{5/2}$. Here, doubling W leads to a six-time increase of the harvested power. For our device, P_{mec} would be above 340 nW at 500 Hz or above 2 μW at 1 kHz.

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