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2016 J. Phys.: Conf. Ser. 773 012048

(http://iopscience.iop.org/1742-6596/773/1/012048)

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Cuong Phu Le and Einar Halvorsen
University College of Southeast Norway, Norway
E-mail: `Einar.Halvorsen@hbv.no`

Abstract. This paper analyses the possibility of MEMS electrostatic influence machines using electromechanical switches like the historical predecessors did two centuries ago. We find that a generator design relying entirely on standard silicon-on-insulator(SOI) micromachining is conceivable and analyze its performance by simulations. The concept appears preferable over comparable diode circuits due to its higher maximum energy, faster charging and low precharging voltage. A full electromechanical lumped-model including parasitic capacitances of the switches is built to capture the dynamic of the generator. Simulation results show that the output voltage can be exponentially bootstrapped from a very low precharging voltage so that otherwise inadequately small voltage differences or charge imbalances can be made useful.

1. Introduction

A vibration energy harvester typically consists of a spring-mass system and an electromechanical transducer. The electrostatic transducer is particularly suitable for realization in microfabrication processes [1, 2, 3]. A capacitive structure with electrodes whose relative motion is driven by ambient mechanical oscillations constitutes the transducer. The electrostatic energy harvester can be operated in either continuous or switched mode [4].

In the continuous mode, the harvester is biased by external sources in the form of a provided voltage or charge, or by internal sources such as work function differences between electrode materials [5], precharged floating electrodes [6] or electrets [7]. While using an external bias delegates the problem of charge or energy retention to other parts of the system such as the power electronics, or is used solely for test purposes, an internal bias provides a more complete and self-sufficient integration that contains the solution to the problem on chip. As far as the MEMS device is concerned, the internal bias poses challenges regarding more sophisticated materials technology, additional demanding process steps and limitations on operating temperature.

In the switched mode, a control circuit is utilized to operate the harvester in a power conversion cycle that can be synchronous or asynchronous with respect to the vibration. Several circuit topologies [2, 8, 9] show the ability of making the harvester system self-sustaining. However, they employ switched inductor circuits that possibly face problems of system integration and power loss due to switching.

Recently, influence machines have inspired or been the subject of several works based on the Bennet or Nicholson [10] doubler principle which is shown in figure 1a. By a sequence of grounding or connecting capacitor plates when one plate C is moved so that it alternates between being aligned with the fixed plates A or B, a doubling of charge is achieved. For repeated cycles, the charge then grows exponentially. The control was originally realized by parts making or breaking contact as the plate moves. By similar means, an electrostatic harvesters should be

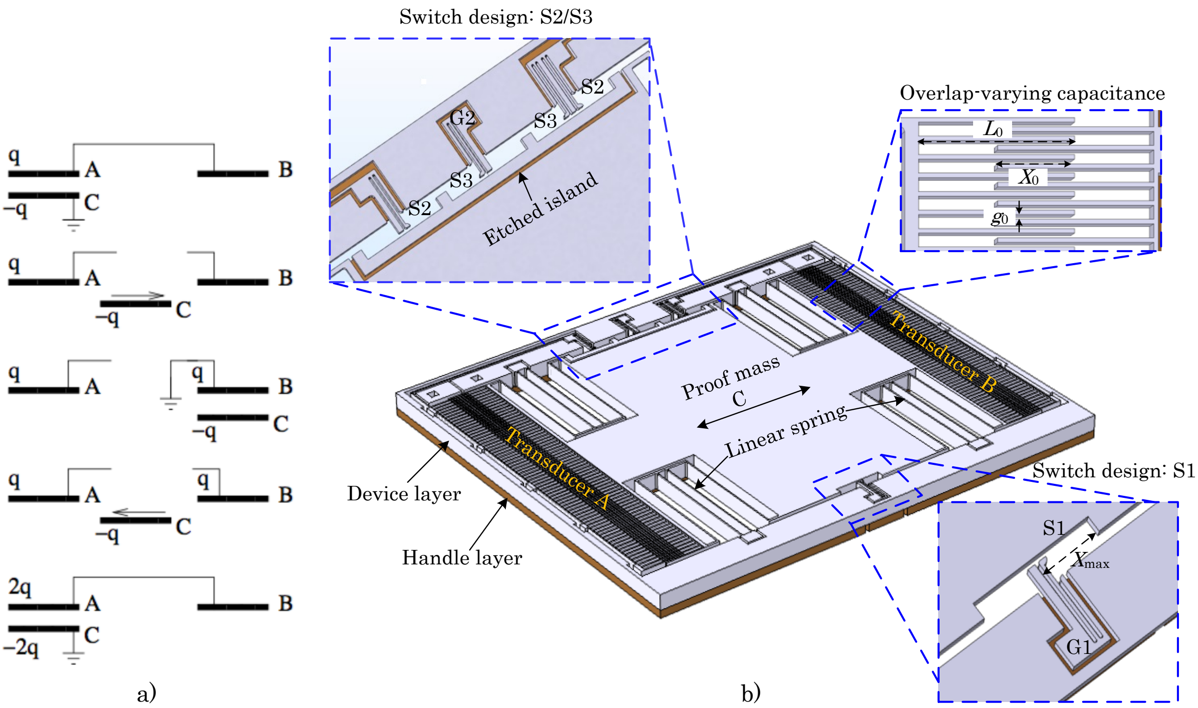

Figure 1. a) Principle of Nicholson influence machine and b) Schematic design for MEMS-implementation of influence machine using standard silicon-on-insulator(SOI) process.

possible to operate without an electric control circuit. A macroscale rotating doubler [11] was capable of increasing output voltage to hundreds volt from an initial voltage of 9.0 V. Several designs for small scale generators have shown doublers of electricity with one single capacitor or two anti-phase capacitors [12, 13, 14]. However, their circuits rely on diodes that result in reduced charging current and a large required minimum precharge voltage.

In this work, a MEMS generator concept proposed overcomes these challenges by reverting to electromechanical switches. By design, the leakage current due to the diode switches can be avoided so that the charging current is improved over the conventional topology. The electromechanical switches enables operation of the bootstrapping generator from a low precharging level.

2. Design description

Details of the microscale design are shown in figure 1b. The necessary functionality can be realized with standard microfabrication structuring of an SOI wafer. Both handle and device layers need to be patterned. The three capacitor plates A-B-C in Nicholson's device are made of two ordinary overlap-varying transducers in the device layer. For a design constrained by minimum feature size, it is advantageous to choose the device layer thick to increase the nominal capacitance and its variation. We choose the device layer thicker than the handle layer.

The proof mass C suspended by linear folded-springs is excited laterally by vibrations. Three electromechanical switches S1-S2-S3 can close at contact between flat surfaces and cantilevers with bumps when the proof mass moves to either of two extremes. A small, electrically isolated island on the proof mass is etched through the device layer for the switches S2/S3. This island is then supported by the handle layer which must be present on the proof mass. The switching arrangement allows three terminals differently connected or grounded to G1/G2 at the maximum displacement amplitude $X_0 = 500$ μm. The charge will increase by a factor $r(\alpha) \in (1, 2)$ on

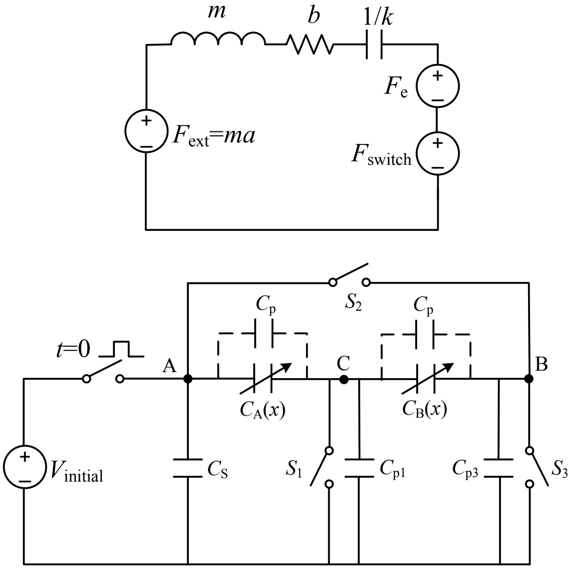

Figure 2. Equivalent circuit lumped-model of the bootstrapping generator.

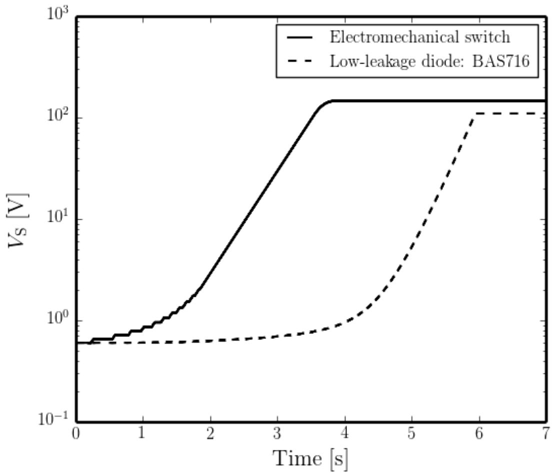

Figure 3. Comparison between two doubler-circuit configurations: i) electromechanical switch and ii) low-leakage diode BAS716 for $A = 1.0g$ and $V_{\text{initial}} = 0.6$ V.

each cycle, where $\alpha = \frac{C_{\text{max}}}{C_{\text{min}}}$ including parasitic capacitances C_{p}. The mathematical form $r(\alpha)$ can be found in the previous analysis by [11]. In the following analysis, we consider a device with total active area 1.2 cm^2, device layer thickness 400 μm, handle layer thickness 50 μm, proof mass $m = 60.6$ mg, stiffness $k = 215.3$ N/m, mechanical damping $b = 2.28 \times 10^{-4}$ Ns/m, nominal capacitance $C_0 = 8.4$ pF and $\alpha = 4.35$ with $C_{\text{p}} = 5.0$ pF. The resonant frequency is then $f_0 = 300$ Hz. Each cantilever of the switches has a stiffness $k_{\text{s}} = 891.2$ N/m.

3. Lumped-model

The bootstrapping generator is represented by equivalent circuits for mechanical and electrical domains in figure 2. The generator is driven by an external force $F_{\text{ext}} = ma$ and the electrostatic force acting on the proof mass is $F_{\text{e}} = \frac{1}{2}\left(\frac{1}{C_{\text{A}}(x)+C_{\text{p}}}\right)' Q_{\text{A}}^2 + \frac{1}{2}\left(\frac{1}{C_{\text{B}}(x)+C_{\text{p}}}\right)' Q_{\text{B}}^2$, where Q_{A} and Q_{B} are the total charges on the transducers A and B respectively, and $C_{\text{A,B}}(x) = \frac{C_0}{1 \pm \frac{x}{X_0}}$. F_{switch} is the force acting on the proof mass when the switch cantilevers contact the proof mass at two extreme positions.

The doubler circuit with the electromechanical switches is shown in the bottom of figure 2. The circuit includes stray capacitances for the switches $C_{\text{p1}} = C_{\text{p2}} = 2.0$ pF. The voltage source V_{initial} is a way to include a precharging function in the simulation in order to initiate operation of the bootstrapping generator. The output is connected to a capacitor $C_{\text{S}} = 1.0$ nF as an energy reservoir.

4. Simulation results

Figure 3 shows increase of the voltage on the reservoir capacitor for $V_{\text{initial}} = 0.6$ V and an acceleration amplitude $A = 1.0g$. For comparison to the diode doubler, a circuit with the low-leakage diode BAS716 is simulated with the same transducer design. The diode has a junction capacitance of the same magnitude as the parasitic capacitance of the switches. The comparison shows that the mechanically switched device bootstraps to the voltage $V_{\text{s}} = 145$ V in $t = 3.8$ s, while these values are $V_{\text{s}} = 110$ V in $t = 5.9$ s for the diode scheme. The initial voltage of 0.6 V

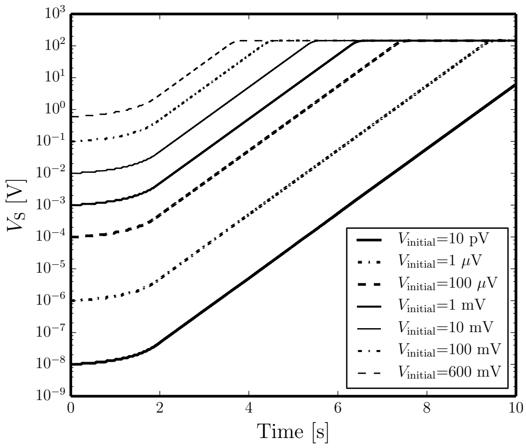

Figure 4. Voltage on reservoir capacitor for various initial voltages and $A = 1.0g$.

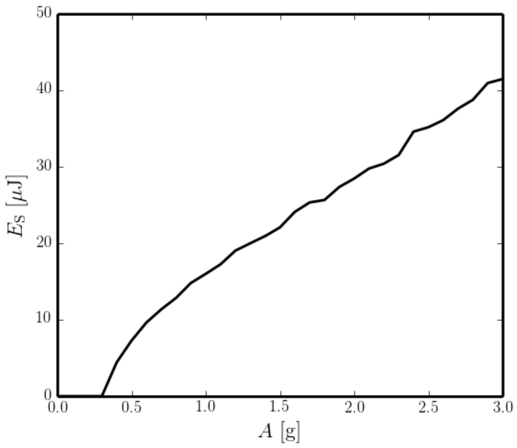

Figure 5. Energy storage on C_s vs. acceleration amplitudes for $t = 10$ s and $V_{initial} = 1.0$ mV.

used in the comparison is approximately the minimum threshold for the diode doubler to allow the operation.

Figure 4 shows an advantage that the design of the electromechanical switches can bootstrap to high voltages even when very small initial voltages are applied. The precharging voltage in range of mV, μV or even pV can enable the bootstrapping operation, but the smaller $V_{initial}$ needs longer time to reach the maximum level. With respect to realistic devices, it shows that a miniscule voltage difference or charge imbalance is sufficient to make the output voltage increase based on the doubler mechanism. In practice the lower limit will possibly be limited by leakage. However, with the mechanical switches, such a leakage will be orders of magnitude less than for a diode.

Figure 5 shows energy obtained in $t = 10$ s under increase of acceleration amplitudes for $V_{initial} = 1.0$ mV. For low acceleration amplitudes, the proof mass displacement is insufficient to achieve a capacitance variation α beyond the required lower limit for the operation. It takes an acceleration amplitude beyond a certain critical value A_c to initiate the bootstrapping. We found $A_c = 0.3g$ for this design. The obtained energy increases with the acceleration amplitude, e.g. $E = 41.8$ μJ for $A = 3.0g$.

5. Concluding remarks

A first analysis of a MEMS electrostatic influence machine, or doubler of electricity, based on a standard silicon-on-insulator(SOI) process was made. The doubler circuit relies fully on electromechanical switches to improve the charging current and to minimize the precharging voltage. The advantages overcome the challenges of a diode-based doubler configuration. The output can be bootstrapped to the maximum voltage from extremely small voltages. This opens up for the possibility to use priming techniques for electrostatic energy harvesters that in themselves provide an insufficient bias. The use of work-function differences for example, will provide a best case priming voltage of only a few volts [5] if the device is optimized for it. However, with the doubler configuration, this or other techniques that can provide a charge imbalance would be useful even if only a mV or lower bias voltage can be achieved.

Acknowledgments
This work was supported by the Research Council of Norway through the Grant no. 229716/E20.

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