MODELLING AND ANALYSIS OF A MEMS APPROACH TO DC VOLTAGE STEP UP CONVERSION

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Abstract
This paper studies the principle of a voltage step-up converter based on a micromachined variable parallel-plate capacitor in combination with an electrostatic actuator. Electrical equivalent circuit and system-level SIMULINK models have been developed. An analysis of design parameters serves as a starting point for a novel prototype implementation.
Possible areas of application are self-powered, standalone sensing systems, space applications and any kind of electrostatic or piezoelectric microsystem in general.
Key Words: *Electromechanical voltage conversion, electrostatic microstructures, MEMS modelling*

I. INTRODUCTION

A number of micro-devices could benefit from a fully integrated MEMS voltage converter that steps up the usually low dc input voltage to higher levels. For example, micro-resonators need high bias voltages to operate efficiently [1] and electrical noise levels in capacitive accelerometers can be reduced by using a high dc bias [2]. High dc voltages are also required in space applications such as scientific instruments [3] and micro-propulsion units [4] aboard satellites. The relatively low output voltage of solar panels and the trend towards microsatellites create a strong need for miniaturised voltage converters.

This paper proposes a micro-electro-mechanical voltage converter that exploits the interdependence of voltage and capacitance in a micromachined variable parallel-plate capacitor: the voltage of a charged and electrically isolated capacitor can be increased by reducing the capacitance while preserving its charge. The capacitance variation is achieved mechanically by moving one of the electrodes with an electrostatic micro-actuator. By periodically switching between two defined capacitance values, a bistable MEMS voltage converter can be realised.

This approach is novel and very little previous work exists about MEMS voltage converters. In reference [5] a converter is described that achieves the capacitance variation by means of resonant oscillations.

II. OPERATION PRINCIPLE

A schematic of the proposed MEMS voltage converter is shown in figure 1. The core element is the variable capacitor $C(x)$ which is mechanically coupled to an electrostatic micro-actuator. Operation of the switch Φ causes the actuator to change capacitance by moving one of the electrodes of the capacitor. The electrode movement is restricted to a minimum and a maximum displacement that corresponds to a capacitance of $C_{\min}$ and $C_{\max}$, respectively. Thus, the variable capacitor allows for a maximum voltage multiplication factor of

$$M_C = \frac{C_{\max}}{C_{\min}}. \qquad (1)$$

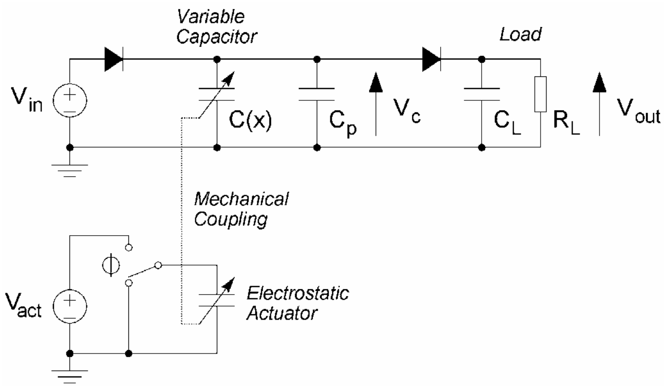

Figure 1. Schematic representation of the bistable voltage converter

The capacitance variation can either be based on a variable electrode gap (transverse structure) or by a change in effective electrode area (comb structure). Both approaches are suitable to serve both as capacitor and actuator. This leads to four possible capacitor-actuator combinations and each of them can be arranged in one of two different modes: In “active reduction” mode, the capacitor is charged and then reduced in capacitance by activation of the electrostatic actuator. Conversely, in the “active increase” mode, the electrostatic actuator is used to firstly increase the capacitance and at the same time to load the compliant mechanical suspension of the structure. Then, the capacitor is charged and subsequent deactivation of the actuator prompts the mechanical suspension to reduce the working capacitance and thus increase the voltage.

Crucial to the proper operation of the device is the condition of constant charge on the capacitor when its capacitance is reduced. This is ensured by a diode between input voltage and capacitor. The second diode ensures that the charge on the load capacitance C_L does not flow back into the converter when $C(x)$ is at its maximum. An interesting alternative to the diodes is the use of micromechanical switches that have to be timed properly to achieve the desired electrical isolation.

Any constant capacitance parallel to the conversion capacitor and between the diodes must be considered as parasitic and is modelled as an element C_p.

III. ELECTRONIC CHARACTERISTICS

The overall electronic behaviour of the bistable MEMS voltage converter is quite similar to the classic Dickson charge pump [6]. The device can be represented as an equivalent voltage source of magnitude

$$V_0 = \frac{M_C + C'_p}{1 + C'_p} \times V_{in} - \frac{M_C + 1 + C'_p}{1 + C'_p} \times V_D \qquad (2)$$

where $C'_p = \dfrac{C_p}{C_{\min}}$ is the relative parasitic capacitance and V_D the diode forward bias. The equivalent source resistance is

$$R_S = \frac{1}{\left(C_{\min} + C_p\right) f_{clk}} \qquad (3)$$

if the actuator is operated at a clock frequency f_{clk}. Obviously, the parasitic capacitance has a strong degrading influence and successful device design hinges on reducing this value. The forward bias V_D can be neglected if micromechanical switches are used instead of diodes.

In presence of a capacitive-resistive load, the output voltage reaches a stationary value of

$$V_{out} = \frac{R_L}{R_L + R_S} \times V_0 \qquad (4)$$

after an initial transient and retains a ripple of

$$V_R = \frac{V_0}{\left(R_S + R_L\right) C_L f_{clk}}. \qquad (5)$$

IV. SIMULINK MODELLING

A system-level SIMULINK library has been created to model the converter subsystems and to simulate complete system behaviour. The capacitors have been modelled as transducers that transform an electrical input current and a mechanical coordinate into an electrostatic force. The total charge Q_t stored on both $C(x)$ and C_p is the internal state variable of the capacitor model. The model calculates the fraction of Q_t that is stored on the main capacitance and uses it to find the resulting electrostatic force and voltage.

Figure 2 shows such a model at the example of the transverse capacitor. For the actuators, the stored charge does not have to be explicitly known and thus, a simplified voltage-controlled model was implemented.

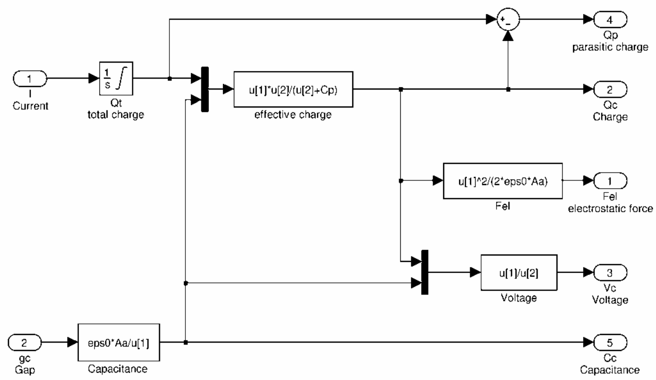

Figure 2. SIMULINK model of the transverse capacitor

The electromechanical coupling is implemented by a mass-spring-dashpot model that represents the inertia, compliant suspension and damping of the system. For the particular setup of a bistable system, the displacement variable in the mass-spring-dashpot model is limited to the range between the two values that correspond to the minimum and maximum capacitance positions. Figure 3 shows a complete core model at the example of a transverse capacitor and a transverse actuator in active reduction mode.

Finally, simple diode models have been added as threshold switches with a forward voltage drop. The system models were completed by a block representing the output load.

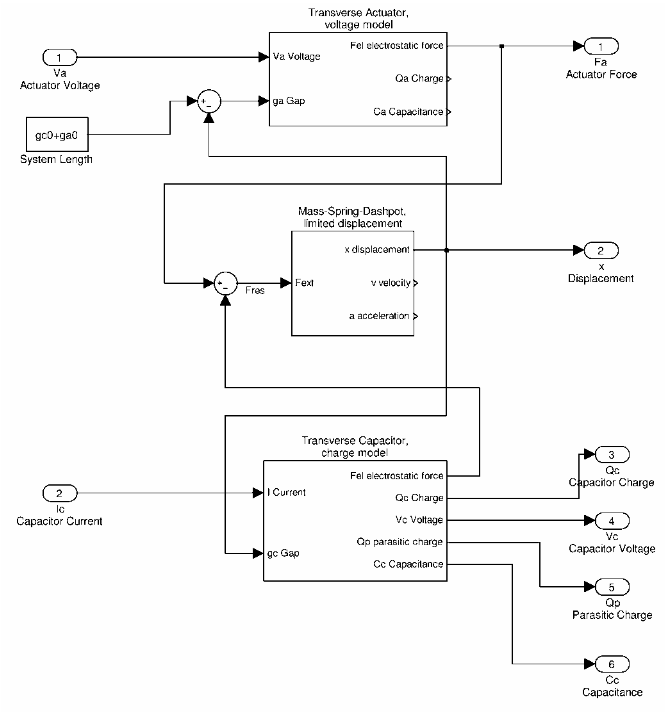

Figure 3. Example of a core SIMULINK model

V. DESIGN ANALYSIS

The capacitor dimensions are straightforward to choose when assuming that certain parameters of a fabrication process are known such as structure thickness and aspect ratio. A likely set of predetermined design specifications are the targeted multiplication factor and the minimum working capacitance. To complete the converter design, a spring stiffness value and the actuator dimensions have to be found, preferably in a way that optimises system size and speed.

For the active reduction topology, an approach was considered that places the rest position of the system near the position of minimum capacitance. This implies that the capacitor has to perform an actuation task while being charged in order to move the system into its maximum capacitance position. Also, an upper limit for the spring stiffness can be derived in this case. The benefit of this approach is that the spring never opposes the actuator movement and can even help in the conversion task, leading to smaller size requirements for the actuator.

In order to find optimal actuator dimensions, a force minimisation approach was devised for each topology. A series of design calculations then identified the most area efficient topology for the active reduction mode: a combination of a transverse capacitor and a comb-drive actuator yielded the smallest actuator dimensions when compared to the other topologies. Figure 4 shows a simulation result without output load for this particular combination. The dimensions were chosen to achieve a voltage multiplication factor of 10 and a minimum capacitance of $0.5pF$. The input voltage is $24V$ and the clock frequency $1kHz$. An actual implementation, for example on a 50 micron SOI-wafer, would need approximately $2mm^2$ of surface area.

A complete system simulation including the output load was also performed and yielded results for stationary voltage and output ripple that were in good agreement with equations (4) and (5) in section III.

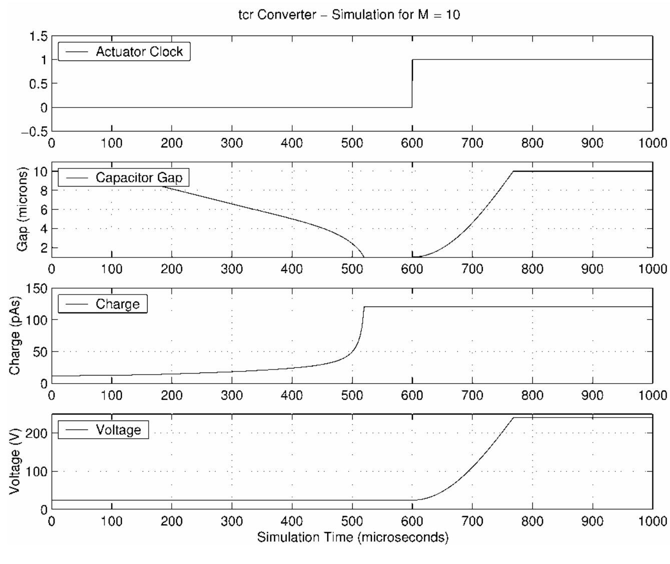

Figure 4. Simulation result for transverse capacitor and comb-drive, active reduction

In the case of the active increase mode, the system enters harmonic oscillations in the conversion phase, when it is released from its maximum capacitance position. A static analysis of the energy stored in the system was undertaken to find the rest position of the spring such that the oscillation amplitude just reaches the position of minimum capacitance. The spring needs to be much stiffer in this mode in order to exert enough force against the electrostatic attraction of the capacitor electrodes.

The actuator design followed the same rules as before, minimising the total system force and thus actuator size. The two topologies that use a transverse capacitor emerged as the most promising ones. The wafer surface requirements for the active increase mode were slightly higher than for active reduction. However, active increase systems have been determined to allow for a slightly higher maximum clock frequency.

VI. PROTOTYPE DESIGN

As a starting point for prototype design and further study, a fabrication process was considered that uses SOI-wafers, etched with deep reactive ion etching (DRIE) and released in HF. Such a process has been described in ref [7]. The high attainable aspect ratio of DRIE should prove beneficial for the creation of large electrodes perpendicular to the wafer plane, thus optimising volume utilisation.

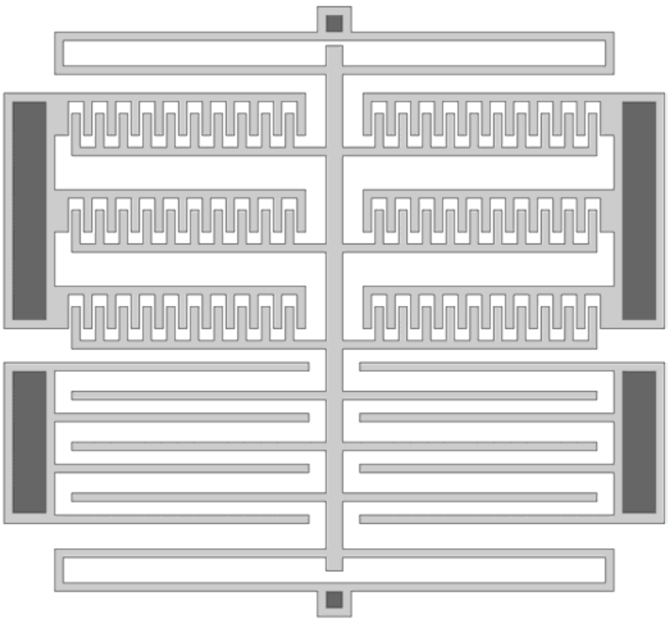

Figure 5. Suggestion for a prototype layout

A design suggestion for a prototype MEMS voltage converter is shown in figure 5. The layout is not to scale but illustrates the principle: A central beam is suspended by folded flexures and connected to electrical ground potential. In the lower section it carries a number of electrode fingers that form a transverse capacitor. The upper section is a comb-drive actuator that is used to perform an active reduction of the working capacitance. The darker shaded areas are anchors of oxide while the lighter coloured parts are released from the substrate and free to move. The layout is modular and can be adapted for any of the converter topologies mentioned in this paper.

Potential problems of this layout include that each electrode of the transverse capacitor has an electrostatic field on both sides which leads to a significant reduction of the voltage multiplication factor and the oxide anchors introduce a relatively high parasitic capacitance.

VII. CONCLUSIONS

The principle of a micro-electro-mechanical voltage step-up converter has been introduced in this paper. This type of voltage converter holds potential benefit for applications that hinge on process integration and miniaturisation.

The electrical properties of MEMS voltage converters have been analysed in analogy to the charge pump and a SIMULINK model library has been implemented. A design approach focussing on miniaturisation was developed and has been verified by system simulations. Prototype layouts have been suggested and further work should mainly concentrate on the fabrication and characterisation of actual devices.

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