Design and Control of a Zero Voltage Switching MEMS DC-DC Power Converter

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ABSTRACT

In this paper, we present the principle, the design, and the control of a DC-DC voltage converter using a MEMS variable capacitor. We developed a design strategy for a MEMS capacitor to be adequate with the converter input/output voltage specifications. We set up a control method based on a timing diagram synchronized with the capacitance variation. The converter operation of a 20V-10V step-down converter was simulated using Matlab/Simulink environment; efficiency up to 76% was obtained with a power density of almost 0.5mW/cm^2. The advantage of this new MEMS converter is that it can be completely integrated on silicon as it does not contain an inductor element as in conventional buck and boost converters. Our MEMS converter system is based on zero voltage switching enabling a high efficiency.

Keywords: MEMS, power conversion, variable capacitor, resonance.

1 INTRODUCTION

For portable applications like mobile phones and portable computers, the power supply is a low voltage battery that is converted to several voltage levels needed by the different functional blocs.

So far, this conversion is performed by the mean of conventional buck or boost or by switched capacitor converters. The inductive converters are complicated to integrate because of the difficulty to integrate the inductor element; the efficiency decreases as the miniaturization level increases because of resistive losses. The switched capacitor converters suffer from inherent switching losses and the dependence of the number of needed capacitors on the conversion ratio that implies a large chip area for a high conversion ratio.

Another alternative for dc-dc conversion is to store the transient energy in a mechanical form rather than storing it in an inductor or in a capacitor, by using, for example, an electrostatic MEMS structure. Previous research work about MEMS converters is not sufficiently developed; two modes of variable capacitor operation have been explored: bistable static mode [1] and resonant mode [2]. The bistable static mode requires an external voltage source to actuate the MEMS device. Both methods are focused on obtaining high output voltages for specific applications where efficiency is not important.

In our case, we propose a resonant MEMS converter optimized in terms of efficiency, where the MEMS device is actuated only by the input and output voltages in a zero voltage switching scheme.

2 VOLTAGE CONVERSION PRINCIPLE

In our previous work [3], we have presented in detail our novel conversion principle using a MEMS parallel plate capacitor (Fig.1).

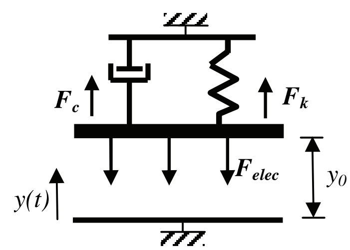

Figure 1: Simplified model of the MEMS variable capacitor

By applying sequentially on the MEMS structure only the input voltage, the output voltage and the open state (constant charge), we realized (by solving the energetic equations) that there is no solution enabling a periodic relative displacement of the electrodes when applying a zero voltage switching. Therefore we added an additional driving voltage based on the addition of the input and output voltages enabling a periodic operation with zero voltage switching. The operation cycle is presented in the following parts.

2.1 Step-down converter schematic

The circuit for a step-down converter using this principle is shown in Fig.2. Three essential blocks constitute the converter: the MEMS capacitor, the controller block and the switching part. V_i is the converter input voltage, V_o is output voltage across the load R_l, and C_f is the output filter capacitor. The switches S_i, S_o and S_{io} are used to put the variable capacitor C_{var} in series with respectively V_i, the output voltage V_o, and the sum of V_i and V_o. The controller block drives the switches and regulates the output voltage.

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2.2 Conversion cycle

The different steps of a conversion cycle, during the steady state operation, are shown through the *Q-V* diagram of the electromechanical system depicted on Fig.3. In this paper we focus our study only on the steady state which will be the normal operation cycle.

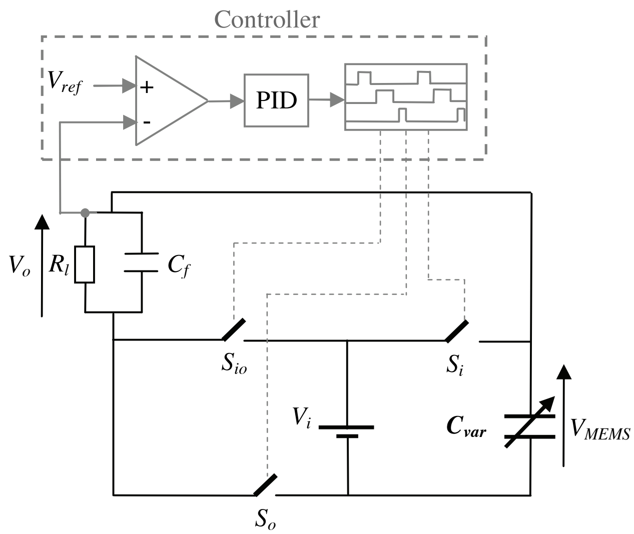

Figure 2: Step-down MEMS converter

The cycle starts at point 1 where the charge stored on the variable capacitor C_{var} is minimal Q_{min}, at this moment C_{var} is connected to the input source V_i, this induces an electrostatic force that attracts the mobile plate and increases the capacitance, thus during the path 1-2 the charge on C_{var} increases ($Q=C.V$), the electromechanical system gets energy from the input.

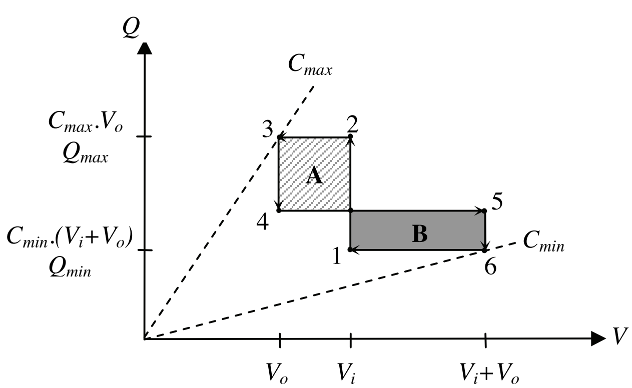

Figure 3: Q-V diagram representing a conversion cycle

At point 2 the capacitor is isolated and the capacitance continues to increase under constant charge, so the capacitor voltage decreases during path 2-3 until it reaches V_o at the same time that the capacitance reaches its maximum C_{max} at point 3. Then the capacitor is connected to the output while the capacitor plates are pulling apart (path 3-4), the charge on C_{var} decreases and a part is transferred to the output. After that, the capacitor is isolated to let the voltage increase under constant charge while the capacitance is decreasing (path 4-5), when the capacitor voltage reaches V_i+V_o the capacitor C_{var} is connected to the input and the output voltage in series. During this phase 5-6 the remaining part of the gained charge during 1-2 is transferred to the output and returned back to the input, the capacitance decreases until it reaches C_{min} at point 6, at this moment the mobile plate starts moving towards the fixed plate (path 6-1) and the capacitance increases under constant charge, the voltage thus decreases until it reaches V_i at point 1 to start a new cycle.

The net energy of the whole cycle is zero (form "8" cycle); the gained energy by the electromechanical system during a part of the cycle (shaded area A) is restituted during the other part of the cycle (area B) enabling a periodic operation, after the transient state. The MEMS variable capacitor is the fundamental part of the converter; its design is presented in the next section.

3 MECHANICAL STRUCTURE DESIGN

The variable capacitor is actuated at its mechanical resonant frequency f_r in order to maximize the vibration amplitude, and therefore to obtain a high capacitance variation C_{max}/C_{min} which is necessary to achieve high voltage conversion ratio as well as to maximize the conversion efficiency. The design of the variable capacitor is optimized to obtain large amplitude oscillations while avoiding the resonant pull-in phenomenon [4]. The capacitor consists of a clamped-clamped silicon beam moving in front of a fixed electrode spaced by a gap y_0.

For a step-down converter (20V-10V), the proposed design steps for a MEMS capacitor are as following:

1- We start by defining the capacitance value at rest position; this capacitance should be much higher than the parasitic capacitances of the MOSFET transistors forming the switches. We will suppose C_0 equal to 100pF, although it can be higher to increase the converter output power capability.
2- Then we choose the desired capacitance variation. The capacitance variation should be at least greater than the voltage conversion ratio. In addition a large capacitance variation is advantageous to maximize the efficiency. We choose C_{max}/C_0 equal to 5.
3- At this step we will choose the minimal gap, this parameter is limited by the electrical discharge phenomenon or more specifically by the field emission phenomena for gaps between 5nm and 5μm. Because we aim a high power density, we choose the minimal achievable gap. In the modified Paschen's curve [5], the field emission is about 75V/μm; hence the minimal gap y_1 should be greater

than V_s/75, in our case 0.13μm. For safety and fabrication reasons we set this value to 0.4μm.

4- The initial gap y_0 is equal to 2μm as $C_{max}/C_0=5$, we can calculate therefore the electrode area knowing that the capacitance of a parallel plate capacitor is given by $C_0 = (\varepsilon_0 A_e)/y_0$. A_e is equal to 24mm^2, we choose an electrode area of 4*6mm² so that the whole device occupies a minimal area.

5- Then we calculate the beam stiffness k. When the beam or the moveable electrode is at the position of minimal gap y_1, the spring force should be higher than the electrostatic force in order to avoid pull-in effects. To keep a security margin, we will suppose a ratio of 4 between the two forces, $F_k/F_{elec}=4$, which gives a stiffness of 156 kN/m.

$$F_k = 4 \times F_{elec} \Rightarrow k(y_0 - y_1) = 4 \times \frac{1}{2} \frac{\varepsilon_0 A_e V_s^2}{y_1^2} \qquad (1)$$

6- After that, we size the beam. We choose a beam width w equal to the electrode width of 6mm and a beam length L (10mm) about 3 times the electrode length in order to have a parallel plate displacement. Finally by using (2) we can deduce the beam thickness t that gives the required stiffness.

$$k = m(2\pi fr)^2 = \frac{Ew}{12}\left(\frac{t}{L}\right)^3 (4.7)^4 \qquad (2)$$

Where E is the Young's modulus.

The capacitor design parameters obtained using the above strategy, are given in table 1.

Symbol	Parameter	Value
E	Young's modulus	169GPa
ρ	Silicon density	2330kg/m^3
C_0	Capacitance at rest	100pF
y_0	Gap at rest position	2μm
A_e	Electrode area	24mm^2
k	Stiffness	156kN/m
L	Beam length	10mm
w	Beam width	6mm
t	Beam thickness	150μm

Table 1: Variable capacitor parameters

The total area used by the device is almost 85mm^2 (including the anchors area). For an advanced implementation we can use other variable capacitor structures having a better capacitance density, like comb structures.

Now we have designed the variable capacitor appropriate to be used in the MEMS converter. We will study the control block that applies the electric cycle on the mechanical structure.

4 ELECTRICAL CONTROL

In a buck converter, for example, the control is achieved by a Pulse Width Modulation (PWM) signal applied to a switch. For a desired conversion ratio, the duty cycle of the PWM output is directly dependent on the voltage conversion ratio and adjusted by comparing the output voltage to a reference voltage. In our case the control is more complicated; three signals are created to control the three switches. Their duty cycles depend on the energy equilibrium (energetic balance of the MEMS structure should be zero) and on the capacitor voltage evolution (the duration needed by the voltage to vary from V_i to V_o for example). These elements are related to the conversion ratio and to the MEMS device parameters.

The switch control times shown on Fig.4, are deduced from the energy equilibrium between the energy gained by the MEMS device and the energy that it restitutes (3). These times correspond to the transition from one operation phase to one other (t_1 corresponding to the point 1 and t_2 to the point 2 on Fig.3).

$$\begin{cases} E_{C\min} = E_{C\max} - E_{restored} \\ E_{C\max} = E_{C\min} + E_{\text{supplied}} \end{cases} \qquad (3)$$

Where $E_{restored}$ is the energy transferred from the variable capacitor to the output and returned to the input, $E_{supplied}$ is the energy supplied by the input source to the variable capacitor. E_{Cmin} and E_{Cmax} are respectively the total energy (mechanical and electrical) stored in C_{var} when the capacitance is minimal/maximal.

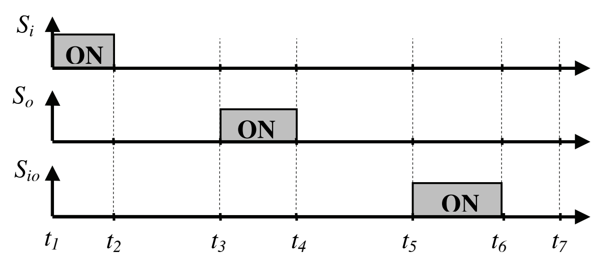

Figure 4: Timing diagram used for switching

The transition times from one operation phase to another are deduced from the elementary trajectories of the different operation phases. The trajectories are calculated by numerically solving the motion equation (4) for each of the operation phases by substituting F_{elec} by its expression at constant charge or at constant voltage depending on the operation phase. Then the duty cycle for each one of the switches can be calculated to deduce the timing diagram shown on Fig.4. This timing diagram is adjusted by a PI controller in a feedback loop (Fig.2) to regulate the output voltage.

$$m\frac{d^2 y(t)}{dt^2} + c\frac{dy(t)}{dt} + k\,(y_0 - y(t)) = F_{elec} \quad (4)$$

Where $y(t)$ is the instantaneous position of the mobile electrode with respect to the fixed electrode, c is the damping coefficient, m is the beam mass.

We have simulated in Matlab/Simulink environment the operation of a 20V-10V converter using the designed capacitor described in Table.1 and by controlling the switches using the deduced timing diagram, we obtained an efficiency equal to 76%. The power losses taken into account are the damping losses, the conduction losses in the ON resistances of the switches and their gate control losses. The output power is equal to 0.4mW so the power density is almost equal to 0.5mW/cm^2. In Fig.5 are shown the mobile electrode displacement and the capacitor voltage V_{MEMS} during the steady state.

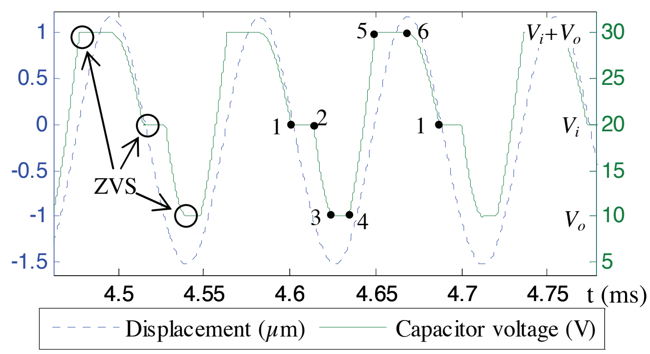

Figure 5: Displacement and capacitor voltage evolution

The transition points corresponding to the conversion cycle (see Fig.3) are shown on one period. The zero voltage switching (ZVS) is also illustrated. A constant voltage is applied by turning ON the suitable switch only when V_{MEMS} has reached this voltage value. Thus a switch is turned ON only when the voltage across it is zero.

5 STRUCURE FABRICATION

A prototype based on the optimized design is under fabrication following the process described in Fig.6. A 4" Borofloat^C 33 glass wafer, with thermal expansion coefficient (3.25 10^{-6}K^{-1}) adapted to silicon is used as a substrate. For the beam we used a 4" silicon wafer N-doped with a resistivity <5mOhm.cm.

For the HF etch, we deposited a 180nm chrome-gold mask layer (30 nm Cr, 150 nm Au) onto the glass substrate by evaporation. The glass wafer is etched in 10% HF to a 2 μm depth. Afterward, a thin gold electrode (50nm) is deposited in the bottom centre of the cavity to form the fixed electrode. For the anodic bonding, a Karl Suss SB6 bonder was employed. The wafers are heated to 320°C, a bonding pressure of 300mbar is applied, and a negative DC voltage of 500V magnitude is applied for 25 minutes on the glass wafer (with respect to the silicon wafer). The Si wafer is then thinned down to 150μm thickness by grinding followed by CMP (Chemical mechanical polishing) to improve the surface roughness, and finally the beams are formed by DRIE etching.

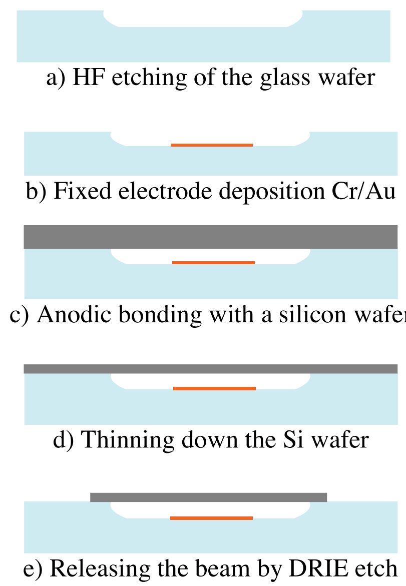

Figure 6: Schematic fabrication process flow

With this process we can obtain a variable capacitor with almost zero parasitic capacitance as the glass is non conductive.

6 CONCLUSION

The optimized MEMS capacitor design, along with the lossless switching control, has led to a yield and a power density higher than previous dc-dc converters based on MEMS. However these results can be improved by further miniaturisation. For a clamped-clamped beam with a gap of few nanometres, the converted power density reaches up to 1W/cm^2. Moreover our converter is useful in low power portable applications as it can be completely integrated on silicon.

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