Numerical Simulations of Novel Constant-Charge Biasing Method for Capacitive RF MEMS Switch

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ABSTARCT

This paper presents numerical simulation results for a novel constant-charge (CC) biasing method for automatically controlling the voltage across the dielectric of the capacitive RF MEMS switch. An electromechanical 1-D nonlinear model that takes into account variable damping of the medium (e.g, air) and contact forces of the surface of the dielectric was used for numerical simulations. Numerical simulation results for the CC biasing method are compared with those of the constant-voltage (CV) biasing method for doubly-clamped capacitive RF MEMS switch. It was found that the higher initial voltage of the CC biasing scheme results in faster switching times while the maximum electric field across the dielectric with CC biasing is significantly less than CV biasing. Such a reduced electric field of CC biasing is considerably less prone to dielectric charging resulting in a significant improvement in reliability.

Keywords: RF MEMS, Switch, Constant-charge, Simulation

1 INTRODUCTION

Recently, there have been many investigations on radio frequency (RF) microelectromechanical systems (MEMS) switches to develop low power consumption, low cost and ultra-low loss switches with a goal of replacing traditional electronic switching components (such as *pin* diodes) in RF/microwave/millimeter-wave applications. The development of capacitive RF MEMS switch was phenomenal. To date, there have been several demonstrations where RF MEMS have demonstrated ultra-low loss phase shifters at frequencies from X-band through Ka-band [1, 2]. RF MEMS filters have also enabled significant reduction in size and weight while maintaining competitive performance to more conventional technologies.

Despite this phenomenal development, there are several issues that need be addressed if RF MEMS switches are to be a commercially viable technology. The forefront of the development of the RF MEMS switches includes reliability and packaging issues. Ohmic contact switches suffer from a degradation of the switch contacts with repeated cycling. Capacitive switches, designed to bypass the issues associated with metal-metal contacts, are affected by dielectric charging issues. For the capacitive switches, it has been shown that every *5 volts* of increased actuation voltage decreases the lifetime by an order of magnitude when a conventional constant-voltage (CV) biasing scheme is used [3]. This is due to high electric field (typically in the order of 1 ~ 5 MV/cm) across the dielectric layer when the membrane is closed. Development of an innovative method to minimize dielectric charging while maintaining top-notch RF performances is desirable. In this paper, a novel method for automatically controlling the voltage across the dielectric of the capacitive RF MEMS switch is proposed and numerical simulation for such a method is reported.

2 NOVEL CONSTANT-CHARGE BIASING

A novel approach for biasing capacitive RF MEMS switches (Figure 1) can be achieved by applying a constant-charge (CC) instead of a conventional constant-voltage (CV). The CC method has been used to characterize the quality of the dielectric layer [4] and MEMS electrostatic actuators [5]. In the latter, current pulse drive was used to demonstrate the extended stable travel range beyond the pull-in point in electrostatic actuator operation.
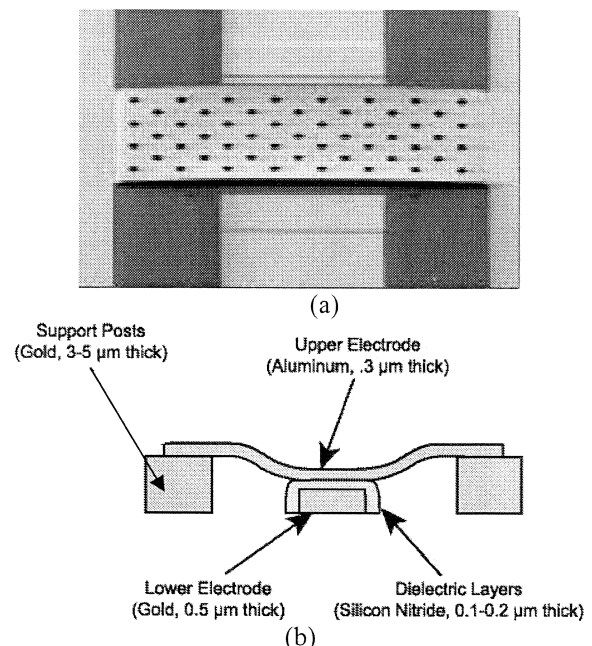

(a)

(b)

Figure 1. Doubly-clamped capacitive RF MEMS SW: (a) SEM photomicrograph [6]; (b) a schematic diagram for cross-sectional view of the SW that shows materials used in the simulation.

The CC biasing scheme can also be used for capacitive RF MEMS switches. In the capacitive switches, because the total charge remains constant in the CC biasing, as switch capacitance increases the resulting voltage automatically decreases. In this manner, the voltage present when the membrane contacts the dielectric is very low, resulting in significant improvement of reliability of the switch.

The energy stored in the capacitive switch with an applied voltage V and charge Q is given by:

$$W = \frac{1}{2}CV^2 = \frac{Q^2}{2C} .$$ (1)

The electrostatic force in the out-of-the plane direction is given by:

$$F_{el} = \frac{\partial}{\partial z}\left(\frac{Q^2}{2C}\right) .$$ (2)

The minimum charge required for pull-in behavior is called pull-in charge (Q_{PI}) and it is given by:

$$Q_{PI} = \sqrt{2\varepsilon_0 A k g_0} ,$$ (3)

where A is the area, k is the spring constant of the switch membrane and g_0 is the initial air gap between the switch membrane and the dielectric layer. The corresponding voltage for the constant-charge Q_{PI} is given by:

$$V_Q = \frac{Q_{PI}}{C_0} = \sqrt{\frac{2kg_0^3}{\varepsilon_0 A}} ,$$ (4)

where C_0 is the initial capacitance before the movement of the switch membrane. This pull-in voltage for conventional CV biasing method is given by:

$$V_{PI} = \sqrt{\frac{8kg_0^3}{27\varepsilon_0 A}} .$$ (5)

It can be found that CC biasing method requires a factor of 2.6 larger effective voltage applied to the capacitive switch than CV biasing method.

3   1-D NONLINEAR DYNAMIC MODEL

In order to assess the behavior of CC-biased capacitive RF MEMS switch, electromechanical 1-D nonlinear dynamic model that takes into account variable damping of the medium (e.g, air) and contact forces of the surface of the dielectric [7] was used for numerical simulations.

For the CC biasing method, the electrostatic force of the switch membrane which is proportional to the square of

applied voltage is a function of time since the voltage is changed as the switch membrane moves down. Therefore, the electrostatic force of the membrane is given by:

$$F_{el} = \frac{1}{2}C_{sw}'(t)\left[\frac{Q_0}{C_{sw}(t)}\right]^2 ,$$ (6)

where $C_{sw}(t)$ is the capacitance of the switch and Q_0 is the applied constant-charge.

The 1-D dynamic equation of motion of the switch membrane is given by:

$$m\frac{d^2z}{dt^2} + b\frac{dz}{dt} + kz = F_{el} + F_c ,$$ (7)

where m is the mass of the membrane, z is the amount of the displacement of the membrane in the out of the plane direction, b is the variable damping coefficient, and F_c is the contact force of the surface of the dielectric layer. The contact force of the surface of the dielectric layer has two components: attractive Van der Waals forces and repulsive nuclear contact forces. The dynamic equation of the motion of the switch membrane which is a nonlinear differential equation can be solved by any nonlinear differential equation solver.

The variable damping coefficient is derived from Reynolds gas-film equation for rectangular parallel-plate [7] which is given by:

$$b \cong \sqrt{2}\mu_{air}l\left(\frac{w}{g_0 - z}\right)^3 ,$$ (8)

where μ_{air} is the viscosity of air ($\approx 1.8 \times 10^{-5}$ kg/m^3), l and w are the length and width of the switch membrane. Figure 2 shows variation of the damping coefficient as a function of displacement of the switch membrane.

In this modeling, in order to avoid a singularity when the gap between the membrane and the dielectric layer is zero, the variable damping coefficient is assumed to have a single value. Further, in order to make the problem simple, three approximate values are used for different range of the gap as shown in the Table 1.

Table 1. Variable damping for different gap distance of the capacitive RF MEMS switch

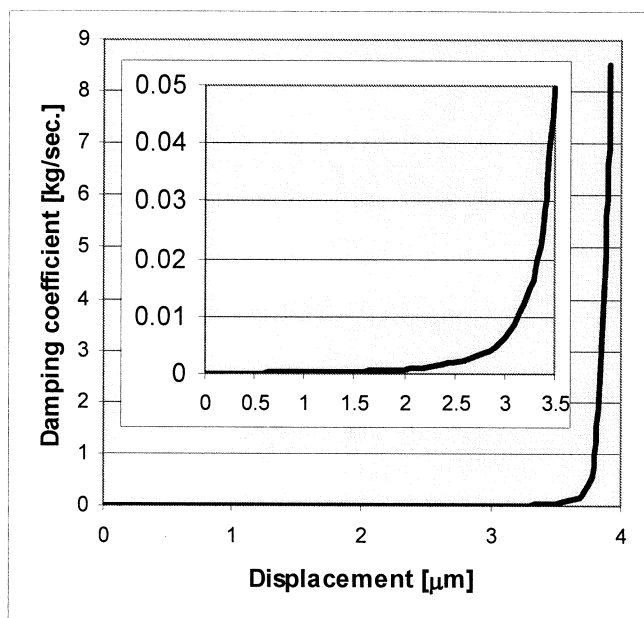| Gap (g_0 -z) [μm]	b [kg/sec]
0 ~ 0.5 g_0	10^{-6}
0.5 g_0 ~ 0.99999 g_0	10^{-4}
0.99999 g_0 or larger	0.5

Figure 2. Damping coefficient as a function of displacement of the membrane.

4 ANALYSIS OF THE CC BIASING METHOD

In this work, simulations of CC (biasing at *2.42 pC* of charge generated by *70 volts* momentarily across *35 fF*) and CV (*30 volts*) methods for doubly-clamped capacitive RF MEMS switch have been carried out using the nonlinear differential equation solver *Mathematica™*. Parameters used in these simulations are as follows: the mass of the membrane is *329* x *10⁻¹²* g; the spring constant of the membrane is *4 N/m*; the area of the membrane is *(125 μm)²*; the thickness of the dielectric layer is *0.2 μm*; and the initial gap between the membrane and the dielectric layer is *4 μm*.

Figure 3 shows simulation results of CC and CV biased pull-down behavior. It was found that the higher initial voltage (*70 volts*) of the CC biasing scheme results in 36% faster switching times (*18 μsec*). Note that there is no oscillation in this graph when the membrane approaches to the surface of the dielectric layer. It is due to the fact that this model incorporates contact forces and variable damping with three approximated values for different ranges of the displacement.
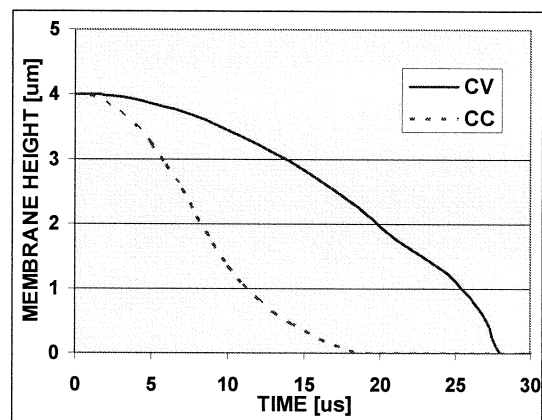

Figure 3. Electromechanical 1-D nonlinear simulation results for capacitive RF MEMS SW, membrane height as a function of time.

Figure 4 shows simulation results for the electric field across the dielectric layer as a function of time. The electric field across the dielectric layer with CC biasing is constant since the overall charge is constant. The electric field across the dielectric layer is notably small (*0.17 MV/cm*). However, the electric field across the dielectric layer for the CV biasing method shows very low initial electric field and huge increase after the membrane snaps down to the dielectric layer. Once the pull-in is occurred, the maximum electric field is ~ *1.5 MV/cm*. It was found that CC biasing scheme results in considerably lower electric field across the dielectric layer, which in turn significantly improves the reliability of the capacitive RF MEMS switch.
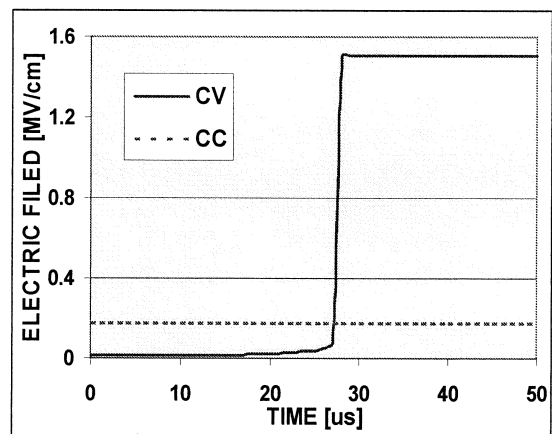

Figure 4. Electromechanical 1-D nonlinear simulation results for capacitive RF MEMS switch, electric field across the dielectric layer as a function of time.

Figure 5 shows the voltage as a function of time and it shows the voltage automatically decreases as the gap between the membrane and the dielectric layer gets narrower for the CC biasing scheme while the voltage is constant for the CV biasing scheme.
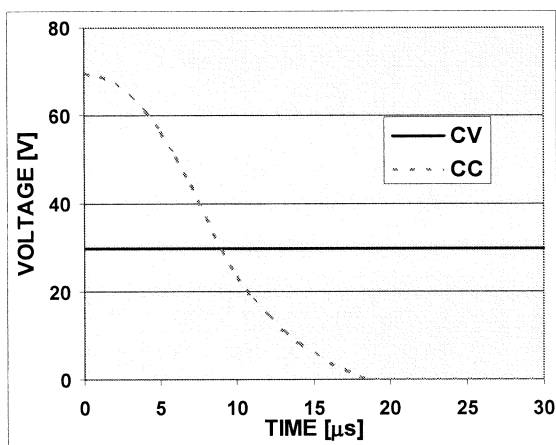
Figure 5. Electromechanical 1-D nonlinear simulation results for capacitive RF MEMS switch, voltage as a function of time.

Figure 6 shows simulation results for the capacitance change as a function of time for both CV and CC biasing schemes. Since the initial voltage applied to the CC biasing method is higher, it results in a faster switching as shown in Figure 3 that corresponds to the faster capacitance change.
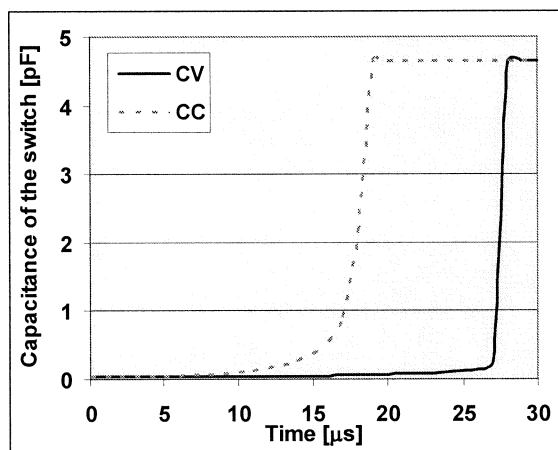

Figure 6. Electromechanical 1-D nonlinear simulation results for capacitive RF MEMS switch, capacitance of the switch as a function of time.

5   CONCLUSIONS

This paper presents theoretical analysis of a novel constant-charge biasing method for the capacitive RF MEMS switch. A nonlinear 1-D electro-mechanical model for the capacitive RF MEMS switch was developed. Such model has been solved by a nonlinear differential equation solver. Novel constant-charge biasing simulation results show that there is a substantial increase in the switching speed and significant decrease in the maximum electric field across the dielectric layer. The novel constant-charge

biasing scheme can be used to significantly improve the reliability of the capacitive RF MEMS switch.

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