Novel Dual-Pulse Actuation Voltage for Longer MEMS Switch Lifetime

C. H. Lai and W. S. H. Wong

***Abstract*—A novel dual-pulse actuation voltage has been proposed to reduce dielectric charging in micro-electromechanical system (MEMS) switch, leading to a longer switch lifetime. Mathematical and transient circuit models have been utilized to simulate dielectric charging in the RF MEMS switch, enabling the analysis of charge built-up at the switch dielectric and substrate brought about by the actuation voltage curve used. The proposed dual pulse actuation signal has shown to improve the lifetime of the RF MEMS switch as it minimizes the charge built-up.**

***Index Terms*—charging, dielectric, lifetime, reliability, Radio frequency (RF) Micro-electromechanical system (MEMS).**

I. Introduction

Micro-electromechanical Systems or MEMS switch is becoming the preferred choice for RF switching due to its outstanding performance when compare to the conventional solid state RF switch such as p-i-n diodes or FET transistor. RF MEMS switch has very low insertion loss but high isolation and consumes minimal power in the microwatts rather than the miliwatts that solid state switches require. However, unlike its solid state counterparts, due to the electro-mechanical nature the MEMS switch suffers from shorter lifecycle ranging from 100 million to 10 billion cycles only [11].

In capacitive membrane switches, the main life-limiting mechanism is dielectric charging trapped within the switch dielectric layer due to the high actuation voltage required to actuate the switch [2]. Capacitive membrane switch is generally consists of a thin metal membrane suspended microns above a dielectric layer. When sufficient actuation voltage is applied to the electrodes beneath the membrane, the membrane is pulled down towards the dielectric layer by electrostatic force, creating a capacitive short. Over time and repeated ON-OFF cycles charges are trapped in the dielectric layer and the substrate of the switch, pulling the membrane to the dielectric even without any actuation voltage applied.

This paper analyzes the charge trapped in the switch using mathematical and transient circuit models of the charge built-up [6]. Then the implementation of a novel dual-pulse actuation voltage which reduces charge built-up and therefore extends the lifetime of the switch will be presented.

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II. Dielectric Charging

A typical capacitive membrane switches generally require 30V to 50V of actuation voltage which will form a very high electric field in a region of 100MV/m across the dielectric layer. In this condition, it is possible for charges to tunnel across the dielectric and become trapped within the dielectric layer through a process similar to that of Frenkel-Poole emissions in thin insulating films [2], where the charged trapped is exponentially related to the applied electric field.

During switching ON, charges will be accumulated on the surface of the dielectric or even on the bulk of the substrate since the recombination time for these charges can be very long and there is a lack of conduction path to drain off the trapped charges. When the trapped charges build up to a level that is just enough to hold the membrane to the dielectric layer even without the presence of actuation voltage, the switch is stuck at the ON state.

The built-up charge also affects the pull-in voltage V_{pi} and pull-out voltage V_{po} of the switch. Pull-in voltage V_{pi} is the threshold voltage that the actuation voltage must exceeds so that the electrostatic force generated will be greater than the restoring force of the switch membrane and closes the switch. Once the switch closes, the electric field will be higher due to the smaller gap between the membrane and electrodes. Hence, the switch will only open when the applied voltage is reduced to below the pull-out voltage, V_{po}.

The trapped charges change the magnitude of the electric field present in the dielectric layer and thus the generated electrostatic force. In case of a positive actuation voltage, positive charges will tunnel into the dielectric layer due to the high electric field across the gap. The trapped charges

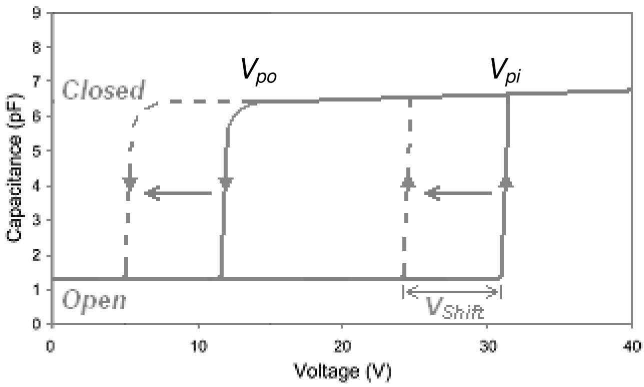

Fig. 2: C-V curve of capacitive RF MEMS switch before (solid line) and after continuous actuation (dotted line) [5].

will generate electrostatic force itself and increase the net amount of electrostatic force between the membrane and electrodes. This reduces the amount of external force / voltage needed to pull down the switch membrane. The net effect of injected positive charges is therefore a negative shift of the switch C-V curve as shown in figure 2, which in turn affects the pull-in and pull-out voltages where $V_{pi} = V_{pi} - V_{shift}$ and $V_{po} = V_{po} - V_{shift}$. Since V_{shift} is proportional to the amount of trapped charge, the longer the switch has been in operation, the more charges are accumulated and V_{shift} increases. The switch will fail when V_{po} in positive region becomes negative. In that case, the switch will be in the closed state even at 0 V.

III. Modeling of Dielectric Charging

Dielectric charging for each ON time of the operating cycle can be modeled as [4]:

$$Q_C = \sum_{J=1,2} Q_J \times \left(1 - \exp\left(-\left(t_{on} + t_{eJ}\right) \Big/ \tau_{CJ}\right)\right) \quad (1)$$

where Q_J is the steady state charge density for J^{th} trap species (there are two types only, $J = 1$ and $J = 2$), t_{on} is the ON time duration for one cycle, τ_{CJ} is the charging time constant for J^{th} trap species and t_{eJ} is the equivalent time required to charge the dielectric to the value just before the present ON time. The steady state charge density Q_J for the J^{th} trapped species when absolute voltage V is applied is given by:

$$Q_J = Q_{0J} \times \exp\left(V \big/ V_{0J}\right) \quad (2)$$

where Q_{0J} and V_{0J} are fitting parameters. Dielectric discharging can be model as:

$$Q_D = \sum_{J=1,2} Q_{PREVJ} \times \exp\left(-t_{off} \big/ \tau_{DJ}\right) \quad (3)$$

where Q_D is the charge accumulated after the OFF time duration, Q_{PREVJ} is the amount of charges trapped in the dielectric just before the OFF time for J^{th} trap species, t_{off} is the OFF duration and τ_{DJ} is the discharging time constant for J^{th} trap species. By iterating equation (1) and (3), the accumulation of charge over many operating cycles can be obtained. Figure 3 depicts the dielectric charging and discharging curve under a square wave ON-OFF actuating voltage [4]. The trapped charge at the beginning of each operating cycle can be somewhere between empty and full, represented by point A on the charging curve. When the switch is turned ON, the amount of charges increases to point B (Q_C) at the end of the ON time, which can be calculated by using Equation (1). Once the switch is turned OFF, the charges trapped inside the dielectric start to discharge from point C on the discharging curve. At the end of the OFF time, the dielectric is discharged to point D (Q_D) which can be calculated by Equation (3). For the next cycle, point D is mapped back onto point E on the charging curve. Thus, the net amount of charges accumulated on the dielectric after one operating cycle is equals to point E minus point A.

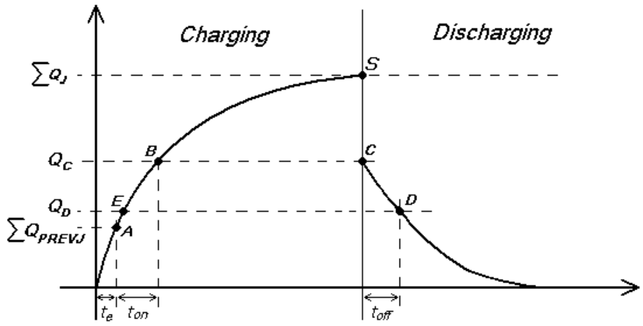

Fig. 3. Dielectric charging and discharging under square wave actuation voltage after one operating cycle, where the charge density increases from the initial-state A to the end-state E.

Figure 4 shows the accumulated charge calculated using the above model over a long operating cycles. The switch model used is similar to that in [4]. The switch is operated using square wave of 100Hz, 50% duty cycle.

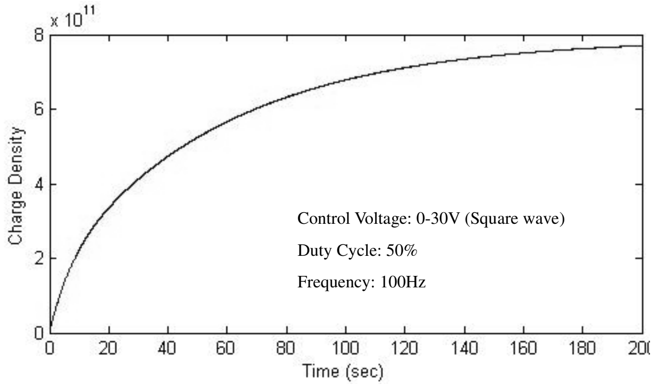

Fig. 4. Dielectric charge density accumulated over 200 seconds stressed by 0-30V square wave actuation signal.

IV. Equivalent Circuit Model

In order to analyze the dielectric charging under complex actuation voltage waveform, a SPICE model was implemented by *Yuan et. al.* by using 2 RC sub-circuits to simulate the charging and discharging behavior of the dielectric [6]. As shown in Figure 5, the two sets of RC circuit represent the two trapped species with different charging and discharging time constants. Dielectric charging is represented by the charging of both capacitors, C_1 and C_2. Both capacitors were set to unity so that the resistances directly correspond to the charging and discharging time constants. R_{C1} and R_{D1} represent the charging and discharging time constants for $J = 1$, and R_{C2} and R_{D2} represent the charging and discharging time constants for $J = 2$. Diodes in the circuit were used to direct charge flow. The total charge trapped in the dielectric can be obtained by adding the charge accumulated on the unity capacitors (C_1 and C_2). Two voltage sources, V_1 and V_2 were implemented to represent the steady state charge density for different trap species. The value of the voltage sources are determined by equation (2).

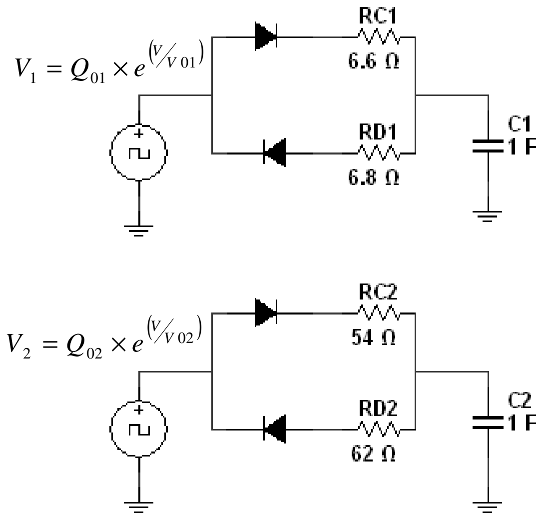

Fig. 5. Equivalent-circuit model for transient circuit simulation. Voltage dependence of the steady-state charge densities was implemented in the two voltage sources V_1 and V_2.

The simulated result by using the equivalent circuit model is shown in Figure 6. Result in figure 6 shows that the readings from the equivalent circuit model are very close to the one predicted by the equation-based model. Hence, dielectric charging effect for complex waveform such as dual-pulse actuation signal can be obtained using the Transient SPICE model by simply changing the shape of the two voltage sources V_1 and V_2.

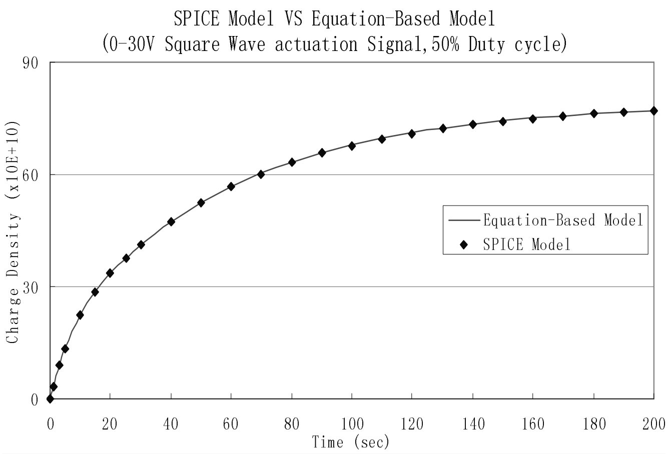

Fig. 6. Dielectric charging curve over 200 seconds modeled by using equation-based model compared to the spice model.

The voltage shift due to dielectric charging can then be calculated by using equation [4]:

$$\Delta V = \frac{dQq}{\varepsilon_o \varepsilon_r} \tag{4}$$

where, ΔV is the voltage shift V_{shift} due to dielectric charging, d is the distance between the centroid of the charge sheet (dielectric) and the top electrode (switch membrane), Q is the charge density modeled by the SPICE model, q is the electron charge, $\varepsilon_O \varepsilon_r$ is the permittivity of dielectric. This equation calculates how much the V_{pi} and V_{po} have been shifted based on the density trapped charge.

V. Novel Dual pulse actuation signal

In order to improve the lifetime of the switch further, a modified dual-pulse waveform as shown in Figure 7 has been proposed. The novel actuation waveform reduces dielectric charging by gradually increase the actuation voltage (peak) at the beginning of the charging period instead of applying a sharp square wave as proposed by *Goldsmith* [2]. Experimental results show that the dielectric charging is exponentially related to the applied voltage across the membrane and substrate [4]. The proposed novel dual-pulse waveform reduces the dielectric charging by minimizing the time where high voltage is applied across the gap of two electrodes.

This waveform can be simply generated by adding a simple R-C low pass filter after the peak voltage source as shown in figure 8. Therefore, it is easily implemented in the actual circuit rather than using active component such as microcontroller and sensing circuit. The R-C value has to be properly tuned to get the most suitable waveform for a particular switch. By adding the low pass filter, the charge contributed by the actuation voltage can be further reduced as shown in figure 9.

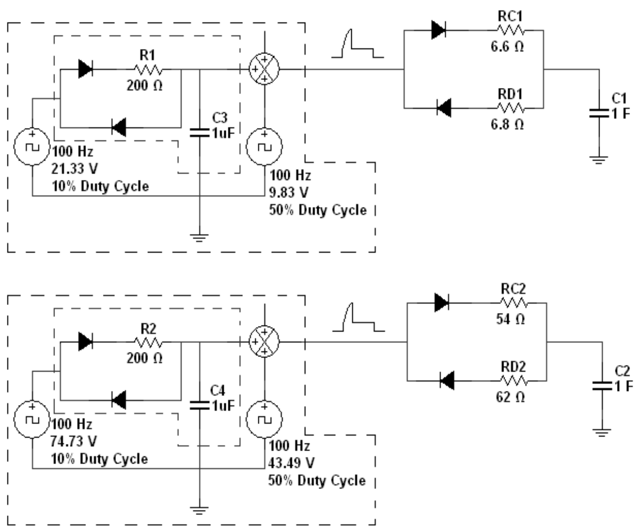

Fig. 8. Equivalent circuit model for modified dual pulse actuation signal. A simple R-C low-pass filter is place after the peak voltage sources.

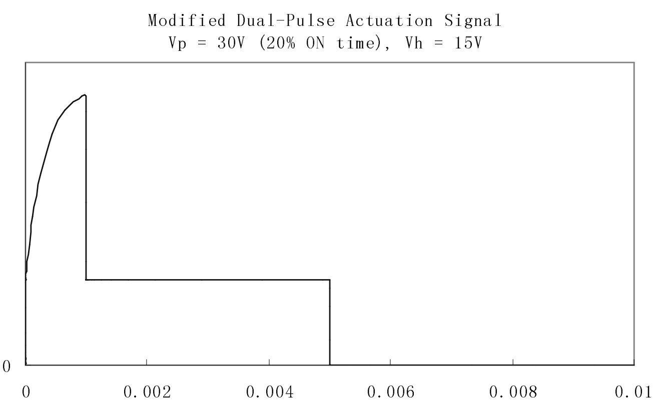

Fig. 7. A Novel dual pulsed actuation signal. A sharp peak voltage is replaced by a gradually increasing voltage.

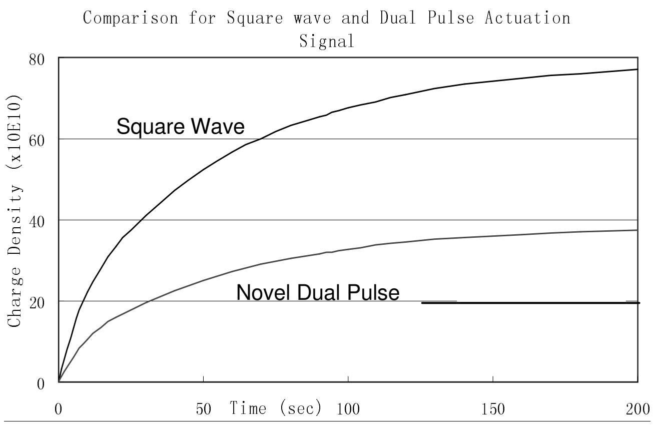

Fig. 9. Comparison of dielectric charging effect between a 100Hz, 0 to 30V square wave actuation signal and a 100Hz dual pulse actuation signal as in figure 7.

VI. CONCLUSION

A model of dielectric charging in a MEMS switch has been presented. Using this model, a novel dual pulse actuation signal has been proposed to reduce the effects of dielectric charging in RF micro-electromechanical system (MEMS) switch. Both the mathematical model and the transient circuit model have shown that the proposed novel dual pulse actuation signal is able to reduce the dielectric charging, therefore prolonging the life the MEMS switch. And more importantly, it shows that it is not necessary to applied square wave to actuate the switch but can be any waveform that suits the particular switch.

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