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Low actuation-voltage shift in MEMS switch using ramp dual-pulse

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Abstract: This paper proposes a ramp dual-pulse actuation-voltage waveform that reduces actuation-voltage shift in capacitive microelectromechanical system (MEMS) switches. The proposed waveform as well as two reported waveforms (dual pulse, and novel dual-pulse) are analyzed using equivalent-circuit and equation models. Based on the analysis outcome, the paper provides a clear understanding of trapped charge density in the dielectric. The results show that the proposed actuation-voltage waveform successfully reduces trapped charge and increases lifetime due to lowering of actuation-voltage shift. Using the proposed actuation-voltage waveform, the membrane reaches a steady state on the electrode faster.

Keywords: charging, dielectric, MEMS, actuation, lifetime

Classification: Micro- or nano-electromechanical systems

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1 Introduction

In the recent years, RF MEMS switches have emerged as a promising technology for improving the performance of RF systems. RF MEMS switches offer low insertion loss, and extreme linearity with minimal power consumption. However, commercialization of RF MEMS switches is hindered by the need for continuing improvements in reliability and packaging such as creep of metal membrane, stiction, fatigue in membrane and dielectric charging [1, 2, 3, 4, 5, 8].

Dielectric charging is the main failure mechanism in lifetime of electrostatically actuated capacitive RF MEMS switches because the mechanical problems for RF MEMS switches are minimized due to the high advance technology. By actuating the membrane suspended electrostatically, it collapses on top of the dielectric [1, 2, 3, 4, 5, 6, 7, 8]. Due to the high actuation voltage required to actuate the switch, the electric filed across the dielectric can be higher than 10^8-V/m causing charge to readily tunnel from top and bottom electrodes into the dielectric which leads to an accumulation of trapped charge (Fig. 1 (a)). With repeated ON-OFF cycles, charges gradually build up in the dielectric, which shifts the actuation voltage [1, 2, 3, 6]. A simulation program with integrated circuit emphasis (SPICE) model is used to quantity dielectric charging [2]. This model can be used to predict charge injection and actuation-voltage shift under different unipolar waveforms.

In this paper, we investigate the accumulated charge, whereas two kind of actuation voltage waveforms are applied. An analytical method is used to compare charge injection for each waveform. Simulation results corroborate the theoretical analysis. Two popular software tools are employed: ADS, ANSYS. Then, we introduce a ramp dual-pulse (RDP) actuation-voltage waveform to reduce the charge buildup and therefore prolong lifetime. The RDP offers ultra-low charge injection in unipolar actuation-voltage waveforms.

2 Dielectric charging

Nowadays, a variety of researchers are attempting to explain the characteristic of dielectric charging. This phenomenon causes a shift of the actuation voltage, which leads to the failure of the switch [1, 2, 3, 7]. According to [2], the actuation-voltage shift due to dielectric charging can be calculated as

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follows:

$$\Delta V = \frac{qhQ}{\varepsilon_0 \varepsilon_r}. \tag{1}$$

Where h is the distance between the bottom electrode and trapped charge sheet of density Q, q is electron charge (1.60218E-19C) and $\varepsilon_0 \varepsilon_r$ is the permittivity of dielectric. ΔV is proportional to the amount of accumulated charge. Therefore, more charges are accumulated and ΔV increases in longer actuation time. More importantly, the hold-down voltage drops to below 0-V, causing the membrane being stuck when the voltage is removed [1, 3, 4, 6].

3 Dielectric charging due to prevalent actuation voltage

Dual pulse (DP) [6], and novel dual-pulse (NDP) [1] are the methods of actuation voltage are presented in this paper. Approaches to calculate total accumulated charge under complex control waveforms are equivalent-circuit model and equation-based model that are illustrated in the following section.

3.1 Equivalent-circuit model

A SPICE model was used to compute the dielectric charging under a complex actuation-voltage waveform. Two sets of RC circuits can be used to simulate accumulated charge density with different charging and discharging time constants (τ_C and τ_D) [1]. In order to correspond the resistances directly to the charging and discharging time constants, both capacitors were set to unity. The applied diodes in the circuit lead to direct charge flow. The sum of the accumulated charge in C_1 and C_2 present the total charge trapped in the dielectric. Exponential voltage dependence of the steady-state charge densities was implemented in the two voltage sources V_1 and V_2. The value of the voltage sources is determined by:

$$Q_J = Q_{0J} \times e^{(V/V_{0J})}. \tag{2}$$

Where Q_J is the steady-state charge density, V is the absolute value of the control voltage, Q_{0J} and V_{0J} are fitting parameters, and J is the type of trapped charge [2]. In RF MEMS switches, a low voltage can be used to hold the membrane in down-state position. Therefore, the DP actuation voltage is proposed to reduce charge injection, comprising a short high-voltage pulse (t_{ONP}) to actuate the switch membrane and a low-voltage pulse (t_{ONH}) to maintain the membrane at ON state ($t_{ONP} + t_{ONH} = t_{ON}$). The NDP voltage waveform was reported in [1]. In this approach, for minimum charge injection, the waveform is presented by decreasing the amplitude of the actuation voltage at the beginning of the ON time.

3.2 Equation-based model

Equation-based model can be used to analyze trapped charge under different actuation-voltages [2]. We can formulate the dielectric charging for each ON time of the operating cycle as follows:

$$Q(t + t_{ON}) = Q_S \times \left(1 - e^{-(t_{ON}/\tau_C)}\right) + Q(t) \times e^{-(t_{ON}/\tau_C)}. \tag{3}$$

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Where Q_S is the source charge-injection, and $Q(t)$ is the initial charge on the dielectric before the ON time starts. In the interest of clarity, the subscript "J" is temporarily omitted. The charge left on the dielectric after the OFF time is:

$$Q(t + t_{ON} + t_{OFF}) = Q(t + t_{ON}) \times e^{-(t_{OFF}/\tau_D)}. \tag{4}$$

It is assumed that the pristine switch is used to compare charge density under different actuation-voltages ($Q(t) = 0$). If $t_{ON} \ll \tau_C$ and $t_{OFF} \ll \tau_D$, Eq. (3) and Eq. (4) reduce to:

$$Q(t_{ON}) \cong Q_S \times (t_{ON}/\tau_C). \tag{5}$$

$$Q(t_{ON} + t_{OFF}) \cong Q(t_{ON}) \times (1 - (t_{OFF}/\tau_D)). \tag{6}$$

All waveforms are different in ON time, so accumulated charge density is investigated in the same interval. Eq. (7) and Eq. (8) specify sources charge-injection for dual pulse, and novel dual-pulse waveforms, respectively:

$$Q_S = \begin{cases} Q_P & t \leq t_{ONP} \\ Q_H & t_{ONP} < t \leq t_{ONP} + t_{ONH} \end{cases}. \tag{7}$$

$$Q_S = \begin{cases} Q_H + (Q_P - Q_H)(1 - e^{-(t_{ONP}/\tau_C)}) & t \leq t_{ONP} \\ Q_H & t_{ONP} < t \leq t_{ONP} + t_{ONH} \end{cases}. \tag{8}$$

Where Q_P is the maximum charge-injection density in t_{ONP}, and Q_H is the charge-injection density in t_{ONH} ($Q_P - Q_H = \Delta Q$). Eq. (9) and Eq. (10) can be used to calculate accumulated charge density for dual pulse, and novel dual-pulse waveforms, respectively:

$$Q(t_{ONP} + t_{ONH}) \cong Q_P \times (t_{ON}/\tau_C) - \Delta Q \times (t_{ONH}/\tau_C). \tag{9}$$

$$\begin{aligned} Q(t_{ONP} + t_{ONH}) \cong\ & Q_P \times (t_{ON}/\tau_C) - \Delta Q \times (t_{ONH}/\tau_C) \\ & - \Delta Q \times e^{-(t_{ONP}/\tau_C)} \times (t_{ONP}/\tau_C). \end{aligned} \tag{10}$$

4 RDP actuation voltage

Ramp dual-pulse is a new method to enhance the lifetime of the switch. The RDP actuation voltage increases with constant slope at the beginning of the ON period (Fig. 1 (b)) instead of the NDP pulse. The proposed actuation-voltage causes the less injected charge into the dielectric. This minimizes the time that high voltage is used to actuate a switch.

4.1 Equivalent-circuit model

The proposed actuation-voltage curve is that obtained by adding a circuit after the peak voltage source, as shown in Fig. 1 (c). The proposed actuation-circuit can be easily implemented with analog circuit; this is suitable for any capacitive MEMS switch. Fig. 1 (d) shows the comparison of the dielectric charging effect between a 100-Hz DP actuation signal, a 100-Hz NDP actuation signal, and a 100-Hz RDP actuation signal with equal duty cycles. From this figure, it is shown that the RDP waveform successfully reduces the accumulated charge and increases lifetime due to less actuation-voltage shift.

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4.2 Equation-based model

Source charge-injection is determined by Eq. (11) for ramp dual-pulse waveform:

$$Q_S = \begin{cases} Q_H + (Q_P - Q_H)(t_{ONP}/\tau_C) & t \leq t_{ONP} \\ Q_H & t_{ONP} < t \leq t_{ONP} + t_{ONH} \end{cases}. \tag{11}$$

Accumulated charge density for the proposed actuation-voltage in ON

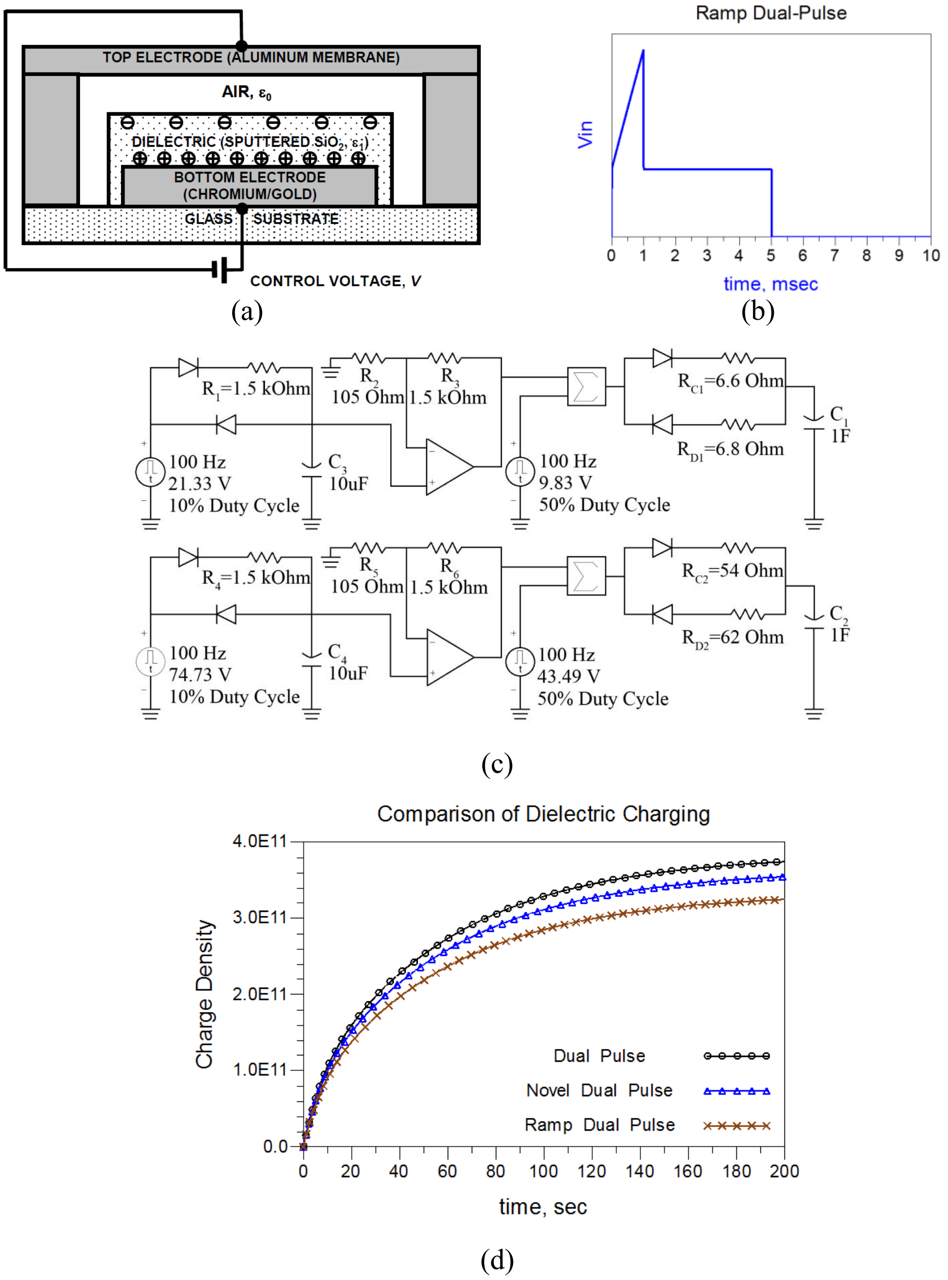

Fig. 1. (a) Schematic cross-section of a capacitive RF MEMS switch [3]. (b) A 100-Hz RDP actuation voltage with 30-V peak voltage and 15-V holding voltage. (c) Equivalent-circuit model for RDP waveform. (d) Comparison of dielectric charging effect between DP, NDP, and RDP.

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time can be calculated as:

$$Q(t_{ONP} + t_{ONH}) \cong Q_P \times (t_{ON}/\tau_C) - \Delta Q \times (t_{ONH}/\tau_C) \\ - \Delta Q \times (t_{ONP}/\tau_C). \tag{12}$$

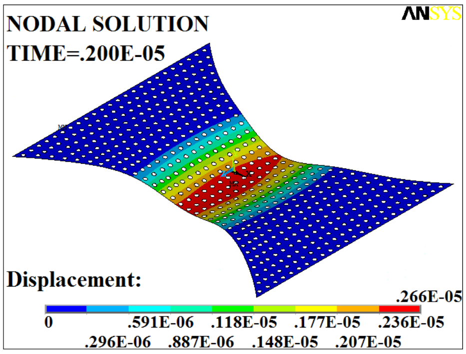
Comparison between Eq. (9), Eq. (10) and Eq. (12) shows that the RDP has the lowest accumulated charge in all waveforms.

5 Switching time impressible by different actuation-voltages

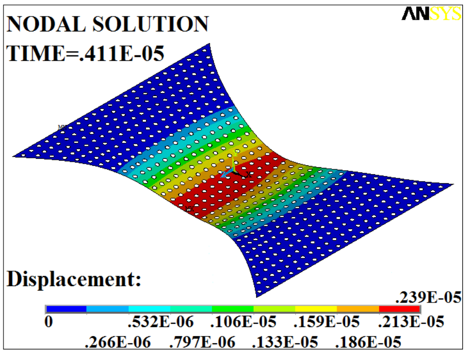
The switching time is investigated for the considered waveforms. The electrostatic force applied to the membrane is [4]:

$$F_{electrostatic} = \frac{1}{2}\frac{\varepsilon_0 AV^2}{g^2}. \tag{13}$$

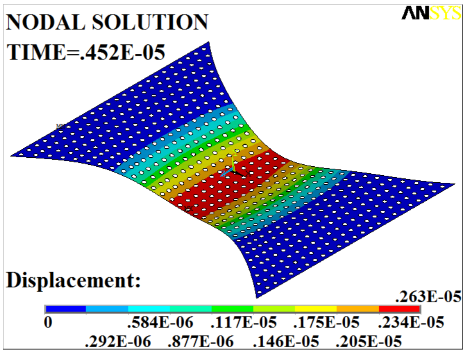
Where ε_0 is the permittivity of air, A is the actuation area, V is the applied voltage, and g is the height of the membrane above the electrode. The mechanical parameters of switch are similar to that in [9]. There are 24355 nodes on the actuation area and maximum electrostatic force is 9.56×10^{-6}-N downward. For the considered structure, Fig. 2 shows the simulated membrane displacement when different actuation-voltage waveforms are applied. The gap between the membrane and the dielectric is about 2-μm. In dual pulse waveforms, maximum electrostatic force occurs immediately. Thus, calculated switching time is approximately 2-μs (Fig. 2 (a)).



(a)



(b)



(c)

Fig. 2. Switching time simulation under different actuation-voltage: (a) Dual pulse. (b) Novel dual-pulse. (c) Ramp dual-pulse.

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Table I. Performance comparison of different actuation-voltage waveforms.

Actuation-Voltage Waveform	Q_{MAX} (q/cm^2)	ΔV (V)	Switching Time (µs)
Dual Pulse	3.743E11	1.862	2
Novel Dual-Pulse	3.545E11	1.764	4.11
Proposed Waveform (RDP)	3.248E11	1.616	4.52

NDP and RDP waveforms gradually increase the actuation voltage, therefore the membrane reaches the contact later than the DP waveform. NDP and RDP switching times are approximately 4.1-μs and 4.5-μs, respectively (Fig. 2 (b) and Fig. 2 (c)).

The NDP and RDP waveforms increase the switching time, whereas these waveforms decrease the settling time due to lower velocity of membrane at contact. Therefore, the membrane achieves a steady state on electrode faster. Finally, Table I summarizes the performance of the RDP actuation voltage along with results from previously introduced actuation-voltage for comparison. It is clear that, with the proposed waveform, reduction of the accumulated charge density in capacitive MEMS switch is demonstrated exclusively, leading to less voltage shift and eventually increasing the lifetime of the MEMS switch.

6 Conclusion

The dielectric charging generated by different types of actuation-voltage waveforms is analyzed by analytical and transient circuit model of dielectric charging. The amount of accumulated charge depends on the types of actuation voltage. Dual pulse actuation voltage reduces the accumulated charge significantly. The proposed method (RDP) is a type of dual pulse actuation voltage which reduces the accumulated charge density by 13.5% while the NDP method reduces 5.3% compare to DP method. Also, the switching time of the proposed actuation voltage is almost the same as NDP. Therefore, the proposed waveform is well suited for long life capacitive MEMS switch.

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