A Compact Model for Dielectric Charging in RF MEMS Capacitive Switches

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***Abstract*— A unified, macroscopic, one-dimensional model is presented for the quantitative description of the process of dielectric charging in RF MEMS switches. The fidelity of the model relies upon the utilization of experimentally-obtained data to assign values to model parameters that capture the non-linear behavior of the dielectric charging process. The proposed model can be easily cast in the form a simple SPICE circuit. Its compact, physics-based form enables its seamless insertion in non-linear, SPICE-like, circuit simulators and makes it compatible with system-level MEMS computer-aided analysis and design tools. The model enables the efficient simulation of dielectric charging under different, complex control voltage waveforms. In addition, it provides the means for expedient simulation of the impact of dielectric charging on switch performance degradation.**

***Index Terms*— Dielectric charging, RF MEMS, capacitive switches, SPICE, system-level modeling.**

I. Introduction

The accumulation of electric charge in the insulating dielectric layer between the two electrodes of a capacitive RF MEMS switch is recognized as one of the most important switch performance degradation mechanism. The resulting dielectric charging can cause the switch to either remain stuck after removal of the actuation voltage or to fail to actuate under the application of pull in voltage. Because of its importance, the mechanism of dielectric charging has been the topic of significant research investigation. The following serves as a selective review of the most recent literature, which is by no means exhaustive. A more extensive overview is provided by the comprehensive lists of references that are included in the works noted below.

First experimental characterization of dielectric charging in capacitive RF MEMS switches was presented in [1]. It was qualitatively shown that switch lifetime depends exponentially on the applied voltage. This was attributed to Frenkel-Poole conduction [2], which depends exponentially on voltage. In [3] it was reported that dielectric charging was caused by charge injection. Through the development of a systematic and accurate procedure for the experimental investigation of charging and discharging current transients, a charging model was developed and used in [4] for the quantitative description of dielectric charging. In [5] it was demonstrated that the capacitive switch lifetime is a function of the applied voltage and the contact quality between the bridge and the dielectric. An experimentally fitted analytical model in [6] and a stretched exponential relaxation model in [7] are two of several additional notable proposals for the quantitative modeling of dielectric charging. A SPICE circuit model was proposed in [8] to provide for efficient numerical simulation of dielectric charging. One useful application of such a model is in the investigation of complex bipolar control voltage waveforms for reducing the effect of dielectric charging [9].

On-going efforts in the pursuit of the quantitative understanding of dielectric charging and its dependence on material properties, operating conditions, and device geometry are complemented by research in the advancement of the sophistication of computer models for dielectric charging. In addition to representing accurately the governing physics, these models must be compact enough to enable computer-aided device optimization. This in turn, requires the seamless interfacing of such a model with system level simulators for MEMS devices, in order to couple the effect of dielectric charging with electromechanical performance of the switch.

In this spirit, a one dimensional model was introduced in [10] to facilitate a macroscopic description of dielectric charging that allowed for incorporation of several physical factors known to impact dielectric charging. It is the objective of this paper to improve further upon the model in [10], toward the development and demonstration of a compact, one-dimensional model for the quantitative description of dielectric charging with the following attributes:

- It utilizes experimentally-obtained data to assign specific values to the parameters used in the governing equations for the model;
- It enables the calculation of the temporal evolution of charge under any complex waveform;
- It enables accurate and efficient simulation for lifetime assessment;
- It lends itself to convenient insertion into existing MEMS system-level, computer-aided analysis tools, thus providing for predictive analysis of the impact of dielectric charging during switch operation.

The paper is organized as follows. We begin with the discussion of the use of an electro-quasi-static model for the physics involved in the dielectric charging during the operation of the RF MEMS capacitive switch. Next, we show how switch physical attributes as well as data obtained from experiment are combined and used for decide the values of the parameters in the electro-quasi-static model. Once these values have been

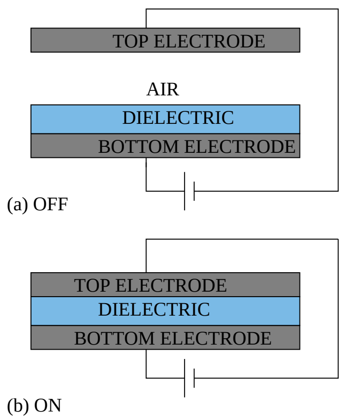


Fig. 1. 1D Model : OFF and ON states of an ideal capacitive switch

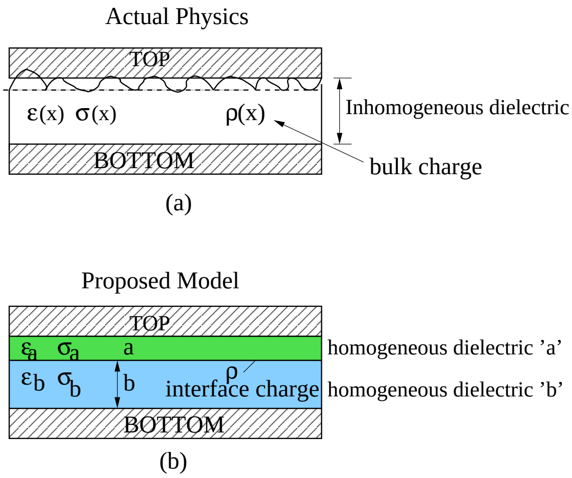


Fig. 2. ON state : Macroscopic model of dielectric charging

obtained, the use of the model for the quantitative investigation of charge accumulation for different stress voltages and waveforms is demonstrated. This is followed by the development of a SPICE equivalent circuit description of the proposed model.

II. Macroscopic model of dielectric charging

A generic illustration of the cross-sectional geometry of a typical RF MEMS capacitive switch can be found in [11]. Illustrated in Fig. 1 is the one-dimensional (1D) compact model used for system level modeling of such MEMS switches. It highlights the kind of model that will be needed for dielectric charging. This model represents an ideal switch. However, processing conditions result in inhomogeneities and imperfections in both the electrodes and the insulating dielectric. For example, due to surface roughness the interface between the metal and the dielectric is not perfectly planar (Fig. 2a). Macroscopically, this can be viewed as a spatial variation in the electrical properties of the dielectric, namely, its electric permittivity and its conductivity. As is well known, surfaces of discontinuity of the material electrical parameters become regions of accumulation of charge. In a similar manner, defects within the volume of the dielectric material itself and, more generally, the presence of variations in its macroscopic electric properties, lead to accumulation of charge throughout the bulk of the dielectric (Fig. 2a). For modeling simplicity and in the context of 1D modeling, we will use a single sheet of charge, located at a certain distance b from the bottom electrode (Fig. 2b), to account for this bulk charge in the model. Based on the discussion above, for charge to accumulate at this plane the electrical properties of the dielectric must exhibit a discontinuity across the plane (Fig. 2b). The physics of charge accumulation can then be quantified through the mathematical analysis of the resulting, two-layer Maxwell capacitor configuration [10].

Let $V(t)$ be the impressed voltage between the two electrodes (Fig. 3). The one-dimensional nature of the proposed model and its piece-wise homogeneous material properties imply that the electric field is uniform in each layer. Let ρ_{ab} represent the surface charge density at the interface. It is, then,

$$\rho_{ab} = (\epsilon_a E_a - \epsilon_b E_b) \tag{1}$$

where ϵ_i, $i = a, b$, are the electric permittivities of the two layers. Application of charge conservation at the dielectric interface yields

$$(\sigma_a E_a - \sigma_b E_b) + \frac{\partial(\epsilon_a E_a - \epsilon_b E_b)}{\partial t} = 0 \tag{2}$$

where σ_i, $i = a, b$, are the conductivities of the two layers. Finally, the equation

$$aE_a + bE_b = V(t) \tag{3}$$

closes the system for the determination of the temporal variation of $E_a(t), E_b(t)$.

More specifically, given $V(t)$ the system of (1)-(3) can be solved for the calculation of the electric fields in the two layers, which, in turn, through (1),(2), can be used to obtain the temporal variation of the charge accumulation. The above equations can be simplified to arrive at a charging equation of the form,

$$\frac{\partial \rho_{ab}}{\partial t} + B\rho_{ab} = A \tag{4}$$

where A and B are given by,

$$A = \frac{\sigma_b \epsilon_a - \sigma_a \epsilon_b}{b\epsilon_a + a\epsilon_b} V \tag{5}$$

$$B = \frac{b\sigma_a + a\sigma_b}{b\epsilon_a + a\epsilon_b} \tag{6}$$

Finally, using well-known results, the shift in actuation voltage due to charge accumulation is given by,

$$\Delta V = \frac{b\rho_{ab}}{\epsilon_b}. \tag{7}$$

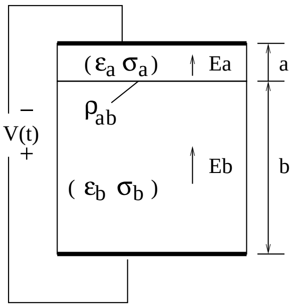


Fig. 3. Proposed Two-layer Maxwell capacitor

TABLE I
MODEL PARAMETERS

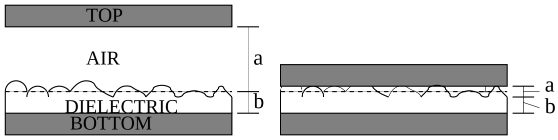
	OFF or UP state	ON or DOWN state
a	2.2 μm	0.05 μm
b	0.3 μm	0.30 μm
ϵ_a	ϵ_0	$2.2\epsilon_0$
ϵ_b	$5.5\epsilon_0$	$5.5\epsilon_0$
σ_a	0	Experimentally defined
σ_b	Experimentally defined	Experimentally defined

III. Definition of Model Parameters

Next, we describe the process we adopt for defining the model parameters. For the purpose of illustration, we consider the switch used in [9]. This process can be repeated for any switch where such data is available. For definition of model parameters, we rely on both the switch physical attributes and data obtained from the experimental characterization of the dielectric. We consider two distinct states of the switch, ON (or CHARGING, or DOWN) state, and OFF (or DISCHARGING, or UP) state. The two layers *a* and *b* are shown in these two states (Fig. 4). For layer *b*, we take its thickness to be the thickness of the dielectric, and its permittivity ϵ_b to be the permittivity of silicon dioxide which is 5.5. For layer *a*, in the UP state, thickness is the same as the air gap while permittivity is taken to be the permittivity of air. Its conductivity is taken to be zero. In the DOWN state, its permittivity is taken to be

$$\epsilon_a = \frac{3\epsilon_b}{\epsilon_b + 2}\epsilon_0 \tag{8}$$

This expression is motivated by the well-known effect of the induced polarization in a dielectric sphere in the presence of an external electric field [12]. In this case, it is the hemispherical asperities representing the roughness at the metal/insulator interface that are taken into account in a macroscopic manner through the assignment of the (8) for the permittivity of layer *a*. Its thickness is taken to be 0.05 μm, a value dictated by information about the roughness of metal/insulator interface. The only parameters that now remain to be defined are the conductivities of layer *b* in the two states. For this we make use of data obtained from experimental characterization of the dielectric. More specifically, useful experimental inputs for the definition of these parameters include transient current measurements, transient capacitance measurements, and measured actuation voltage shifts.



(a) UP STATE or OFF (b) DOWN STATE or ON

Fig. 4. ON and OFF states : definition of model parameters

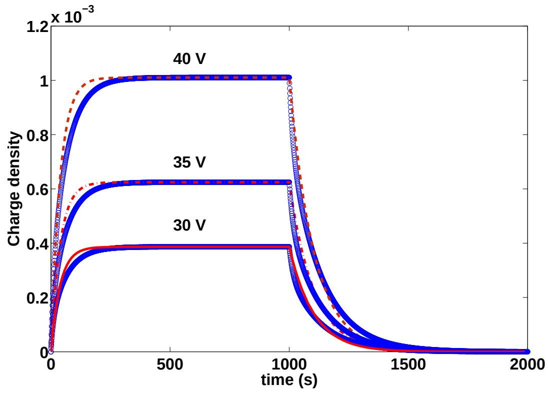


Fig. 5. Comparison of model prediction with experimentally obtained charge density.

For the purposes of this paper, we will make use of measured data of dielectric charge density accumulation, $Q(t)$, obtained from transient current measurements [9]. A plot of $Q(t)$ for different voltages reported in [9] is shown in Fig. 5 (blue line). It is important to note that measured actuation shifts in voltage can also be used as they can be readily transformed into this graph through (7). The following strategy is used for obtaining the conductivities of the two layers.

- Pick a curve for the accumulated charge density $Q(t)$ for a particular voltage.
- Calculate model parameters A and B through a non-linear least squares algorithm like Levenberg-Marquardt [13]. A and B, in turn, yield the conductivities through (5)and (6) as all other model parameters are already defined.
- Note that A is related to the steady state value while B is related to the time constant of the charge density accumulation. It has been experimentally observed that time constant does not vary with the applied voltage [4].
- Once B is found for one voltage, for other voltages only A needs to be determined. Thus, only steady-state values of charge/actuation voltage shift are needed for determining A.

The above methodology was used to define the conductivities in the proposed model using the data in [9]. The model was then used to calculate charge accumulation and was compared to the experimentally obtained results. Figure 5 depicts the comparison. Very good agreement is observed. Plotted in Fig. 6 is the conductivity of layer *b*, illustrating its non-

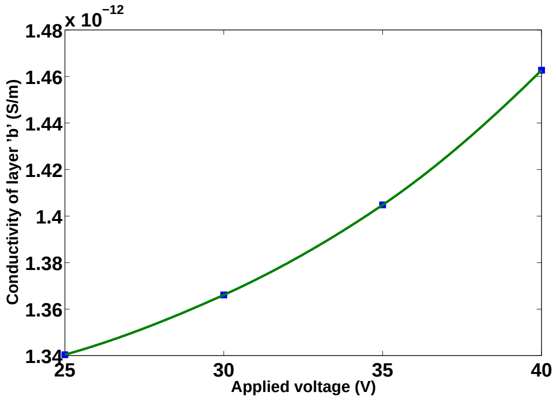


Fig. 6. Voltage-dependent conductivity of layer *b*.

TABLE II
BIPOLAR CONTROL VOLTAGE WAVEFORMS

t/T(%)	10	30	40	20
W_1	35	0	-35	0
W_2	30	0	-30	0
W_3	35	0	-30	0

linear dependence on the voltage. With all parameters defined, the model lends itself to the calculation of dielectric charge accumulation for any control voltage waveform. This is the topic of the next section.

IV. Simulation under different waveforms

Bipolar control voltage waveforms have been proposed as a means to limit dielectric charging [9]. The proposed model provides for a computationally efficient way for evaluating dielectric charging under different control voltage waveforms and its impact on actuation voltage. Following [9], the change is actuation voltage versus time was computed using our model for three waveforms. The attributes of the three control waveforms, W_i, $i = 1, 2, 3$, are summarized in table II. Each column entry represents the value of the voltage applied for that $\%$ of the time period T. The predictions from our model (solid lines in the graph) are in excellent agreement with the experimental values reported in [9] (Fig. 7). Waveform 3 is seen to minimize the effect of dielectric charging.

V. SPICE equivalent circuit model

The proposed model can be cast in the form of a SPICE circuit consisting of a capacitor, a variable resistor and a voltage controlled current source. The capacitance value is taken to be

$$C_0 = \frac{b}{\epsilon_b} \tag{9}$$

so that the voltage at node 1 directly measures the shift in pull in voltage. The value of the resistor is taken to be BC_0. It has two discrete values depending on if it is ON or OFF. Note that B is independent of the value of the voltage. This

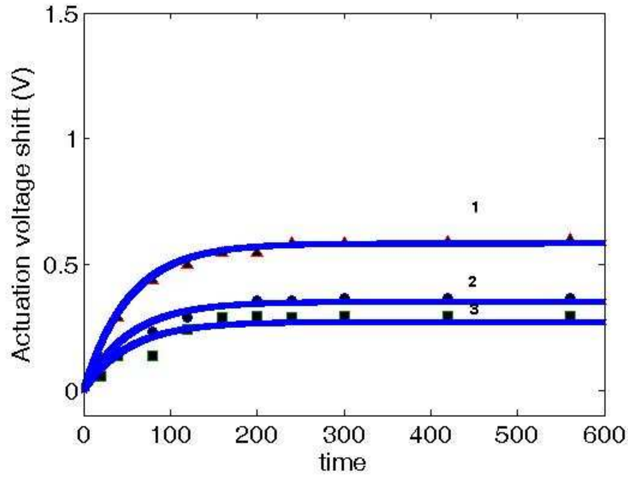


Fig. 7. Bipolar waveforms: comparison of model prediction with results from experiment [9].

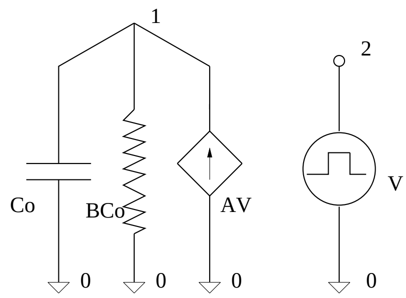


Fig. 8. SPICE equivalent circuit

greatly simplifies the analysis. The voltage controlled current source is given by,

$$VCCS_{val} = \frac{\sigma_b \epsilon_a - \sigma_a \epsilon_b}{b\epsilon_a + a\epsilon_b} V(2) \tag{10}$$

This model is very efficient to simulate using a nonlinear, SPICE-like, circuit simulator. For example, the simulation for the prediction of dielectric charge accumulation after four million cycles requires 600 s of computation time on a PC with 1 GB RAM and 1.76 GHz Intel Pentium M processor.

VI. Conclusions

To conclude, we have presented a one-dimensional compact model for the macroscopic, quantitative description of the process of dielectric charging in RF MEMS capacitive switches. The proposed model relies on experimentally-obtained data for the definition of its parameters, thus allowing for non-linearities in material electrical properties to be incorporated in its definition. The compactness of the model lends itself to the efficient and accurate simulation of dielectric charging under complex control voltage waveforms. It is easily cast in the form of a SPICE circuit, which can be used to expedite the computer-aided assessment of the impact of dielectric charging on the performance of the switches. In addition, because of its physics-based description, the proposed model should be found useful for incorporation in the electro-mechanical models for MEMS switches used in system-level MEMS simulation tools.

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