

# Modeling of Dielectric Charging in RF MEMS 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 switch. The model provides for the direct incorporation of various physical factors known to impact dielectric charging, such as surface roughness, material inhomogeneity and electric field-dependent conduction in the dielectric. The values of the various parameters used in the model are extracted from experimental data. The proposed model serves as a generalization of various earlier models reported in the literature for the quantitative description of dielectric charging.

## I. INTRODUCTION

Dielectric charging is understood to mean the accumulation of electric charge in the insulating dielectric layer between the two electrodes of the capacitive RF MEMS switch. It can cause the switch to either remain stuck after removal of the actuation voltage or to fail to actuate under application of pull in voltage.

First experimental characterization of dielectric charging in capacitive RF MEMS switches was demonstrated 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 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. In the same paper it was also argued that conduction due to Frenkel-Poole emissions was responsible for charge accumulation. An experimentally fitted analytical model in [6] and a stretched exponential relaxation model in [7] are two of additional notable proposals for the quantitative modeling of dielectric charging.

More recently, a model was put forward in [8] to account for the impact of charge accumulation at both the top and the bottom metal-insulator interfaces in the capacitive RF MEMS switch. In the same work, the potential impact of surface chemistry on dielectric charging was acknowledged. The results reported in [8] suggest the need for further investigation

into the quantitative understanding of the governing physics of dielectric charging in capacitive RF MEMS switches. For example, impact of surface roughness and material inhomogeneity in the thin-film dielectric are two of the factors that one expects to impact dielectric charging. Process induced variations and the scale of these devices make these factors all the more important.

It is the objective of this paper to demonstrate a one-dimensional model for the quantitative description of dielectric charging with the following attributes:

- It constitutes a generalization of the various one-dimensional models reported in the literature to date;
- Utilizes experimentally-obtained data to assign specific values to the parameters used for the description of the electrical properties of the model;
- Enables the calculation and monitoring of the temporal evolution of charge accumulation at the top and bottom surfaces of the insulating dielectric film;
- Provides a means for the incorporation of the impact of the surface roughness of the dielectric interfaces on charge accumulation.

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 data obtained from the experimental characterization of metal-insulator-metal capacitor can be utilized for the assignment of appropriate values to the parameters in the electro-quasi-static model. Once these values have been assigned, the model is used for the quantitative investigation of charge accumulation for different stress voltages. Finally, we demonstrate a methodology for accounting for material surface roughness in the model.

## II. PHYSICAL DESCRIPTION OF DIELECTRIC CHARGING

A generic illustration of the cross sectional geometry of a typical RF MEMS capacitive switch can be found in [8]. Despite the indicated planarity of the material interfaces, process variations during deposition result in a material surface roughness, which, in turn are responsible for a non-

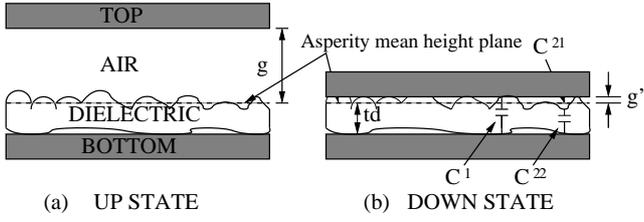


Fig. 1. UP and DOWN states of a non-ideal switch

planar contact between the dielectric and the two electrodes. This is pictorially described in Fig.1. Clearly, the contact between the top electrode and the dielectric surface during the DOWN state of the switch is not perfectly flat, leaving out air pockets. Thus, a very thin layer is formed between the electrode and the dielectric exhibiting spatial variation in its electric properties. Furthermore, process variations may lead to spatial variation in the electrical properties of the dielectric. It follows immediately from Gauss' law that spatial variations in the permittivity and conductivity are responsible for the accumulation of unpaired charge. Thus, a model aimed at the quantitative analysis of dielectric charging in RF MEMS switches must provide for the incorporation of such material inhomogeneities.

To provide for such a model we propose the three-layer, piece-wise homogeneous planar model depicted in Fig.2. The imperfect contact at the top of the dielectric are modeled as a layer 'a' with permittivity and conductivity different from that of the bulk dielectric. The effects of different applied voltage and changes in the quality of the contact (due to surface roughness) are captured through the use of appropriate values of the permittivity and conductivity of this layer, which are different from those in the bulk. Layer 'b' represents the bulk of the dielectric. Finally, layer 'c' represents the imperfect contact at the bottom side of the dielectric.

Let  $V(t)$  be the impressed voltage between the two electrodes. It is assumed that the time variation is slow enough for an electro-quasi-static model suffices for the analysis of the response of the structure to the applied voltage. Furthermore, the one-dimensional nature of the proposed model and its piece-wise homogeneous material properties imply that the electric field is constant in each one of the three layers. Let  $\rho_{ab}$  and  $\rho_{bc}$  represent the charge densities at the top and bottom interfaces, respectively, between the bulk layer and the top and bottom layers. It is, then,

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

$$\rho_{bc} = (\epsilon_b E_b - \epsilon_c E_c) \quad (2)$$

where  $\epsilon_i$ ,  $i = a, b, c$ , denotes the electric permittivity of each layer. Application of charge conservation at each one of the two dielectric interfaces yields

$$(\sigma_a E_a - \sigma_b E_b) + \frac{\partial(\epsilon_a E_a - \epsilon_b E_b)}{\partial t} = 0 \quad (3)$$

$$(\sigma_b E_b - \sigma_c E_c) + \frac{\partial(\epsilon_b E_b - \epsilon_c E_c)}{\partial t} = 0 \quad (4)$$

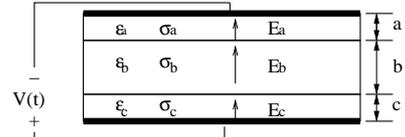


Fig. 2. Three-Layer Model

where  $\sigma_i$ ,  $i = a, b, c$ , denotes the conductivity of each layer. Finally, the equation

$$aE_a + bE_b + cE_c = V(t) \quad (5)$$

closes the system.

Given  $V(t)$  the system of (3)-(5) can be solved for the calculation of the electric fields in the three layers, which, in turn, through (1),(2), can be used to obtain the temporal variation of the charge accumulation. Finally, using well-known results, the shift in actuation voltage due to charge accumulation is given by,

$$\Delta V = \frac{h_T \rho_{ab} + h_B \rho_{bc}}{\epsilon_b} \quad (6)$$

where  $h_T$  and  $h_B$  are, respectively, the distances of the top and bottom dielectric interfaces from the surface of the bottom electrode.

### III. SIMULATIONS

Experimental results reported in [8] have been used for guiding the assignment of values to the various parameters for this model. Thus, for our purposes it is assumed that the dielectric used is silicon dioxide; however, the proposed methodology is applicable to any other insulating material, provided that experimental data like those in [8] are available for the definition of the appropriate model parameters. The thickness of the dielectric layer is taken to be  $0.25 \mu\text{m}$ , while its relative dielectric constant is 4.0. The top electrode is a  $0.3 \mu\text{m}$  Al membrane that is grounded whereas the bottom electrode is Cr/Au. The air gap between the top electrode and the dielectric is  $2.5 \mu\text{m}$ . Actuation voltage shifts reported for different control voltages are as follows,  $\Delta V = 1.25V$  for  $V = 30V$ ,  $\Delta V = 3.00V$  for  $V = 40V$ , and  $\Delta V \approx 0.0V$  for  $V = 50V$ .

The values of the various parameters used in the model are presented in Table I. For the Down state (or Charging state),  $a = 0.04 \mu\text{m}$ ,  $b = 0.25 \mu\text{m}$  and  $c = 0.01 \mu\text{m}$ , whereas for the Up state (or Discharging state),  $a = 2.50 \mu\text{m}$  (which is the air gap), with  $b$  and  $c$  remaining the same as expected.  $h_T$ ,  $h_B$  are then found to be  $0.26 \mu\text{m}$  and  $0.01 \mu\text{m}$ , respectively.

With regards to assigning values for the conductivity in the silicon oxide, use is made of the fact that the conduction mechanism in  $\text{SiO}_2$  is predominantly of the Fowler-Nordheim type,

$$J = K_1 E^2 \exp(-K_2/E) \quad (7)$$

where  $K_1$  and  $K_2$  are constants given by,

$$K_1 = \frac{q^3 m_o}{16\pi^2 \hbar \phi m^*} \quad K_2 = \frac{4(2m^*)^{1/2} \phi^{3/2}}{3\hbar q} \quad (8)$$

CHARGING or DOWN-STATE							
No.	Voltage(V)	$\epsilon_a$	$\epsilon_b$	$\epsilon_c$	$\sigma_a$	$\sigma_b$	$\sigma_c$
1	30	2.3	4.0	3.8	0.98e-13	1.8e-13	1.8e-13
2	40	2.5	4.0	3.8	4.00e-13	7.0e-13	7.0e-13
3	50	2.6	4.0	3.8	9.78e-13	15.0e-13	15.0e-13
DISCHARGING or UP-STATE							
No.	Voltage(V)	$\epsilon_a$	$\epsilon_b$	$\epsilon_c$	$\sigma_a$	$\sigma_b$	$\sigma_c$
1	30	1.0	4.0	3.8	0.0	0.9e-13	0.9e-13
2	40	1.0	4.0	3.8	0.0	3.5e-13	3.5e-13
3	50	1.0	4.0	3.8	0.0	7.5e-13	7.5e-13

TABLE I  
PARAMETERS FOR DIFFERENT VOLTAGES

In this equation,  $q$  is the electronic charge,  $\hbar$  is the Planck's constant,  $m_o$  is the electron mass,  $m^*$  is the effective electron mass, and  $\phi$  is the barrier potential. Thus, interpreting (7) in terms of Ohm's law with an electric field-dependent conductivity, yields the following expression for the conductivity in the dielectric

$$\sigma_b = K_1 E \exp(-K_2/E) \quad (9)$$

This expression clearly shows the exponential dependence of  $\sigma_b$  on the electric field,  $E$ , and, hence, on the voltage  $V$ . The exact fit for bulk conductivities  $\sigma_b$  (Table I) has been obtained using equations (7)-(9), for barrier height 3.12 eV, 3.78 eV and 4.32 eV for 30 V, 40 V and 50 V, respectively. Bulk conductivities for layers 'b' and 'c' during discharging (or UP state) are taken as average of their values during charging, whereas for the top layer 'a' it is taken as zero (air gap).

Depicted in Fig. 3 is the evolution of the charge densities at the top and bottom dielectric interfaces for a stress voltages of 30 V, 40 V and 50 V. Note that the voltage is applied as a step input at  $t = 0$ , is kept at that value for 300s and then is set to zero for rest of the time. Also shown is the temporal evolution of the resulting actuation voltage shift.

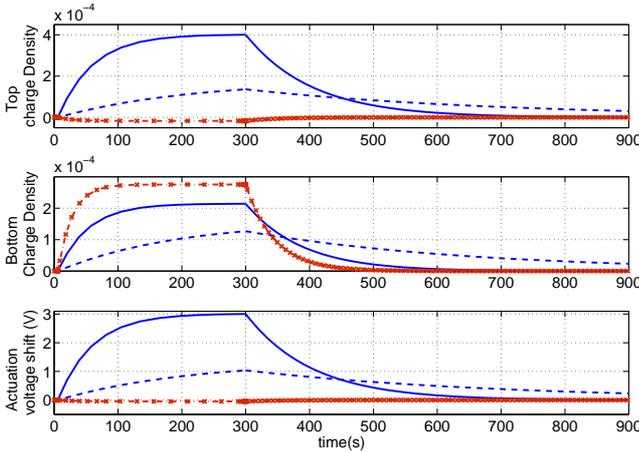


Fig. 3. Charge densities and actuation voltage shift as a function of control voltage : 30 V (blue solid line), 40 V (blue dash line) and 50 V (red line)

Our results are in good agreement with the experimental results reported in [8]. For the case of 30 V and 40 V, positive

charges accumulate at both the bottom and the top interface. For the case of 50 V, a negative charge accumulates at the top interface and a positive charge at the bottom (Fig. 3), consistent with the findings in [8]. Also, the charge at the top interface has greater influence on the actuation voltage shift. Further, the exponential voltage dependence of charge accumulation is evident from the plot.

As already mentioned in the introduction, the parameters chosen for the description of the proposed three-layer model have been motivated by the desire to provide means for incorporating in the model several of the physical effects that govern dielectric charging. For example, it will be demonstrated in the following section that the variation of the permittivity of the top contact layer with voltage can be related to the surface roughness on the dielectric surface. The same also holds for the thickness of the layers. Furthermore, as demonstrated through the example in this section, allowing the bulk conductivity to be voltage dependent provides for incorporating in the model the appropriate conduction mechanism for the insulating material under consideration.

#### IV. IMPACT OF SURFACE ROUGHNESS

Surface roughness plays an important role in the quality of electrical contact between the metal electrode and the dielectric. More specifically, it dictates the effective (actual) contact area at the metal-dielectric interface [9]. In what follows, we employ the Greenwood-Williamsom (GW) model [10] used in [9] to model the rough contact between the top electrode and the dielectric.

The GW model contains the following three parameters: a) the assumed constant radius of the spherical asperities,  $R$ ; b) the standard deviation of the asperity height,  $\sigma_s$  (assumed to be a Gaussian distribution); c) the asperity density,  $D_{SUM}$ . These parameters can be extracted from experimental measurements of moments of surface topography [10].

Let us consider the down-state of the switch (Figure 1). Based on the GW model, the actual contact area with respect to apparent contact area  $A_0$  is given by [10],

$$A^* = \frac{A_c}{A_0} = 0.064 (\alpha - 0.8968)^{1/2} * \int_{g'}^{\infty} \left( \frac{z - g'}{\sigma_s} \right) \phi(z) dz \quad (10)$$

where  $A_c$  is the real contact area and  $g'$  is the separation between the top electrode and the asperity-mean-height plane. As the top electrode approaches the dielectric layer,  $g'$  will decrease. The separation  $g'$  is related to the applied load. The load  $P$  on the switch is a combination of the electrostatic force of attraction and the restoring elastic force.

$$P = F_{elect} - F_{elast} \quad (11)$$

$$F_{elect} = \frac{1}{2} C^r \frac{V^2}{t_d} \quad F_{elast} = k(g - t_d - g'), \quad (12)$$

$C^r$  is the actual down state capacitance,  $k$  is the effective spring constant,  $t_d$  is the thickness of the dielectric layer and  $V$  is the applied voltage.

The actual down-state capacitance can be expressed as

$$C^r = C^1 + C^2 \quad (13)$$

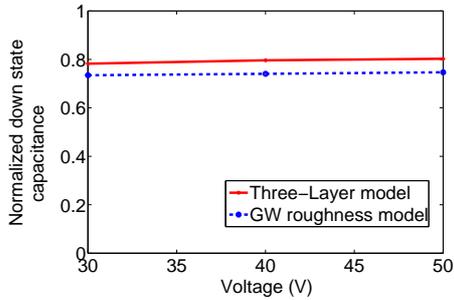


Fig. 4. Comparison of down state capacitance from GW roughness model and Three-Layer model

where  $C^1$ ,  $C^2$  are the capacitances corresponding to surface areas where the top electrode contacts and does not contact, respectively, the dielectric surface.  $C^2$  can be further split into two parts,  $C^{21}$  and  $C^{22}$ , which come from the air gap between the metal bridge and the Silicon Dioxide and the Silicon Dioxide itself, respectively, as illustrated in Fig. 1(b). Finally, the normalized down-state capacitance can be expressed as

$$C^* = \frac{C^r}{C^a} \quad (14)$$

Equations (10)-(14) form a set of non-linear equations in  $g'$ , which can be solved iteratively to obtain a value of  $g'$ , and hence  $C^*$  for different applied voltages. Note that a detailed set of equations can be found in [9],[10].

Next, we compute the voltage dependence of the normalized, down-state capacitance for the following set of roughness parameters  $\sigma_s = 6.8nm$ ,  $R = 18.23nm$ ,  $D_{SUM} = 509\mu m^{-2}$ , and material properties,  $E_{Al} = 70$  GPa,  $\mu_{Al} = 0.34$  and  $E_{SiO_2} = 75$  GPa,  $\mu_{SiO_2} = 0.20$  [11]. We also compute the voltage dependence of the normalized, down state capacitance from the series connection of the capacitances of the layers in the three-layer model developed in section II. This comparison is depicted in Fig. 4. The comparison demonstrates consistency between the two approaches. Furthermore, the thickness  $a$  of the top layer in the three-layer model is approximately  $6\sigma_s$ , thus encompassing more than 99 % of surface asperities.

Next, we plot the variation of permittivity and conductivity of top layer 'a' as a fraction of bulk properties 'b' in Fig. 5. These results clearly demonstrate a strong correlation between surface roughness and effective permittivity, conductivity and thickness of the top contact layer in the three-layer model.

## V. CONCLUDING REMARKS

In summary, we have presented a one-dimensional, electro-quasi-static model for the macroscopic, quantitative description of the process of dielectric charging in RF MEMS capacitive switches. The proposed model provides for a unifying framework for the incorporation of the various physical attributes and processes known to impact dielectric charging. More specifically, the model allows for the specific conduction mechanism in the dielectric to be taken into account in the model. In addition, it provides for the impact of the imperfect contact at the metal-dielectric interface, which is due to surface

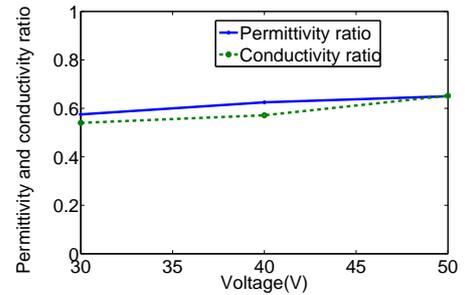


Fig. 5. Voltage variation of permittivity and conductivity of top layer as a fraction of bulk properties

roughness, to be incorporated in the model. The proposed model relies on experimental input for the definition of several of the parameters used. More specifically, these parameters can be extracted through experiments involving surface roughness characterization and capacitance and conductivity measurements as a function of applied voltage.

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