

# Dielectric Charging and Thermally Activated Processes in MEMS Capacitive Switches

George Papaioannou<sup>1</sup>, Negar Tavasolian<sup>2</sup>, Charles Goldsmith<sup>3</sup>, John Papapolymerou<sup>2</sup>

<sup>1</sup>National Kapodistrian University of Athens, Athens 15784, Greece

<sup>2</sup>Georgia Institute of Technology, Atlanta, GA, 30332, USA

<sup>3</sup>Memtronics Corp., Plano, TX 75075, USA

<sup>1</sup>gpapaioan@phys.uoa.gr

<sup>2</sup>negar1@gatech.edu

<sup>2</sup>papapol@ece.gatech.edu

<sup>3</sup>cgoldsmith@memtronics.com

**Abstract**— The paper investigates dielectric charging effects for capacitive RF MEMS switches with SiO<sub>2</sub> as the dielectric material. Two different actuation schemes are implemented in order to incorporate and better understand the charging history over time. Experimental results indicate that regardless of the actuation scheme the charging is thermally in principle, and that the activation energy decreases as the voltage sweep rate increases.

## I. INTRODUCTION

Capacitive RF MEMS switches are promising components for terrestrial and space applications but their commercialization is still hindered by reliability problems. A key issue problem is the dielectric charging because it causes erratic device behavior and limits the device lifetime [1–3]. Presently, it is well understood that the dielectric charging arises from charges distributed throughout the dielectric material [4], the presence of charges at the dielectric interface or distribution of inverse polarity charges at the dielectric surface and the injection of charges from the suspended bridge during ON-state through asperities at the dielectric and contacting electrode surface roughness.

So far the lifetime of MEMS switches, hence the process of dielectric charging, has been investigated by recording the shift of pull-in and pull-out voltages as a function of electrical stress conditions [1], [5]. Since this methodology offers little information on the physics of failure mechanisms, complementary assessment methods, such as the transient current in permanently ON-state switches and MIM capacitors [6], [7], the transient response of the ON capacitance in MEMS switches [8] and the employment of both MIM and MEMS capacitors [4], [9], [10] were introduced. These allowed the determination of charging and discharging current time constants, the observation of the contribution of different charging mechanisms and the determination of the dependence of time constants magnitude on the dielectric deposition method and dielectric film structure [11] as well as the determination of the activation energy of thermally activated charging mechanisms [8], [9].

The elementary theory of dielectric materials states that the increase of temperature accelerates the thermally activated

polarization–depolarization (charging–discharging) processes [12]. This effect is particularly exploited in the field of in MOS technology and precisely for the investigation of temperature effect on hot carrier stress [13], [14]. In MEMS the dielectric film is much thicker than the MOSFET gate oxide that excludes charging due to Fowler-Nordheim effect etc [15]. Moreover, the armature contact is not perfect due to surface roughness and asperities. The necessity to take into account these effects led to the development of a more realistic model, which explained the shift of the actuation characteristics and the deformation of the C-V curves without assuming any trapping/detrapping [16].

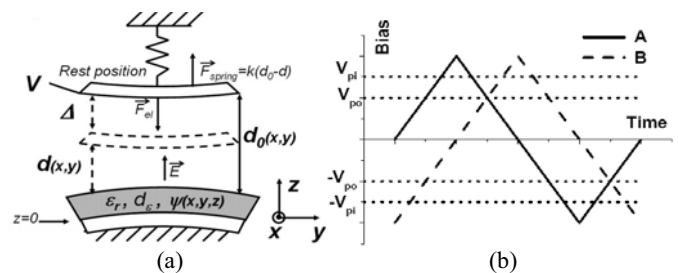


Fig.1 (a) Model of a capacitive switch with non uniform trapped charge and air gap distributions [16] and (b) employed actuation schemes.

The aims of the present work is to investigate the dielectric charging in MEMS capacitive switches taking into account the implication caused by surface roughness. By monitoring the temperature evolution of capacitance-voltage characteristic we obtain a better understanding on the charging induced in a single C-V cycle as well as the presence of thermally activated mechanisms. The investigation is based on the fact that temperature plays a key issue role on the injected charge redistribution. Parameters such as the dependence of charging time constant and its dependence on activation energy are determined. The importance of the determination of these parameters lays on the fact that the thermally activated mechanisms are easily traced and can be directly related to the material deposition parameters.

## II. THE MODEL

The present work device model adopts both the one and the formulation proposed by X. Rottenberg et al in [16]. For this we consider the setup in Fig. 1a that includes a fixed nonflat metal plate of area  $A$  is covered with a dielectric layer of uniform thickness  $d_\epsilon$ , dielectric constant  $\epsilon_r$ , and volume charge density  $\psi(x, y, z)$ . Above it a rigid but nonflat movable metal plate is fastened with a linear spring  $k$  to a fixed wall above the dielectric layer at a rest position  $d_0(x, y)$ . A dc bias source of amplitude  $V$  is applied to the two plates. Following the procedure analyzed in [16] we find that the electrostatic force  $F_{el}$  can be written in a compact form of

$$F_{el}(\Delta) = \frac{A}{2\epsilon_0} \left[ (V\mu_\alpha - \mu_\beta)^2 + V^2\sigma_\alpha^2 + \sigma_\beta^2 - 2V \text{cov}_{(\alpha,\beta)} \right] \quad (1)$$

where  $\mu$ ,  $\sigma^2$ , and  $\text{cov}$  denote the mean, variance, and covariance, respectively, of the  $\alpha(x, y, \Delta)$  and charge  $\beta(x, y, \Delta)$  distributions:

$$\alpha(x, y, \Delta) = \frac{\epsilon_0}{(d_0(x, y) - \Delta) - \frac{d_\epsilon}{\epsilon_r}} \quad (2)$$

which is the distribution of capacitance per unite area and

$$\beta(x, y, \Delta) = \frac{d_\epsilon}{\epsilon_r \epsilon_0} \cdot \psi_{eq}(x, y) \cdot \alpha(x, y) \quad (3)$$

the distribution of charge density induced at armature area and  $\psi_{eq}(x, y)$  and  $\Delta$  are the equivalent surface charge distribution and the displacement from equilibrium respectively. At equilibrium positions the system is determined by equating the electrostatic and spring forces that reduce to

$$\frac{2\epsilon_0 k \Delta}{A} = (V\mu_\alpha - \mu_\beta)^2 + V^2\sigma_\alpha^2 + \sigma_\beta^2 - 2V \text{cov}_{(\alpha,\beta)} \quad (4)$$

Depending on the adopted device model the above equations can lead to different level complexity approaching in an improved manner the behavior of real MEMS switch. In the general case of distributed equivalent charge  $[\psi(x, y, z)]$  and air gap  $[d_0(x, y)]$ , (1) cannot be simplified. Then (4) can be transformed to get some insight in the profile of the actuation characteristic. By isolating  $V$  the equilibrium positions are described by (5)

$$V = \frac{\mu_\alpha \mu_\beta + \text{cov}_{(\alpha,\beta)}}{\mu_\alpha^2 + \sigma_\alpha^2} \pm \sqrt{\frac{\mu_\alpha \mu_\beta + \text{cov}_{(\alpha,\beta)}}{\mu_\alpha^2 + \sigma_\alpha^2} + \frac{2\epsilon_0 k \Delta}{A} - (\mu_\beta^2 + \sigma_\beta^2)} \quad (5)$$

Equation (5) can be used to demonstrate numerically the evolution of C-V characteristic under different geometrical and charge distribution conditions. In the present case we need to provide concrete results related to dielectric material properties. For this reason we introduce in (5) experimental

data that will lead to a more simple and applicable form. The experimental data that can be exploited from a C-V characteristic are the pull-in ( $V_{pi}$ ) and pull-out ( $V_{po}$ ) voltages as well as the bias at which the capacitance, in the up state attains minimum ( $V_m$ ). For the later the electrostatic force becomes minimized independently of the charge and air gap distributions. From (1) we obtain

$$V_m = \frac{\mu_\alpha \mu_\beta + \text{cov}_{(\alpha,\beta)}}{\mu_\alpha^2 + \sigma_\alpha^2} \quad (6)$$

According to this (5) may significantly simplified to

$$V = V_m \pm \sqrt{V_m + \frac{\frac{2\epsilon_0 k \Delta}{A} - (\mu_\beta^2 + \sigma_\beta^2)}{\mu_\alpha^2 + \sigma_\alpha^2}} \quad (7)$$

Here we must emphasize that (7) still cannot lead to analytical solutions of pull-in and pull-out voltages. In order to minimize this problem and obtain a better understanding on the charging mechanisms we can take for granted that we measure the pull-in voltages very close to, but below, instability point. We apply the same for pull-out voltage. At such a close proximity to the instability point Eq.7 can be used to provide information on the temperature dependence of mean and variance values of the charge distribution at the dielectric surface. It is important to notice that during C-V measurement  $V_m$  will correspond to the last encountered capacitance minimum since it bears the charging history during down state and discharging during up state depending on the characteristic sweep speed.

## III. EXPERIMENTAL ANALYSIS

The switches measured here are bridge-type capacitive switches fabricated at MEMtronics Corporation [17]. The switches are fabricated on a pyrex glass substrate. The dielectric material used is a 280 nm thick  $\text{SiO}_2$  layer ( $\epsilon_r = 5.5$ ) sputtered on a chromium/gold bottom electrode. The top membrane is a thin layer of Aluminum alloy (about 0.3  $\mu\text{m}$  thick) which is attached to the DC and RF grounds. A top view of the switch geometry is shown below.

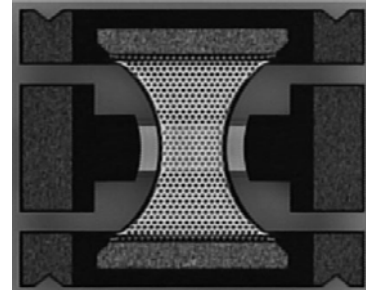


Fig. 2. Top view of the shunt MEMS capacitive switch [18]

The membrane is suspended about 2.2  $\mu\text{m}$  above the dielectric in the unactuated position. An applied voltage of about 36 V to the bottom electrode causes the membrane to collapse and contact the dielectric layer. This forms a 120  $\mu\text{m}$  x 80  $\mu\text{m}$  capacitor which shunts the RF signal to ground.

The capacitance-voltage characteristics were obtained following the actuation schemes presented in Fig.1b. The choice of the actuation schemes will be analysed below. In

order to control the charging time during each pull-in state we varied the sweep voltage speed. Three values were chosen, 57mV/sec, 114mV/sec and 228mV/sec. Finally, the C-V characteristic was recorded in the temperature range of 300K to 373K.

#### IV. RESULTS AND DISCUSSION

The choice of the actuation scheme was based on performing two loops where the history of electrical stress before reaching the first and second pull-in voltages was different. In the case of scheme A (fig.1b) the first pull in is attained without previous charging while the second one is affected by the unipolar charging during positive actuation. In the case of scheme B (fig.1b) the first pull in is attained after charging during negative actuation while the second one is affected by the discharging and the simultaneous charging during positive actuation.

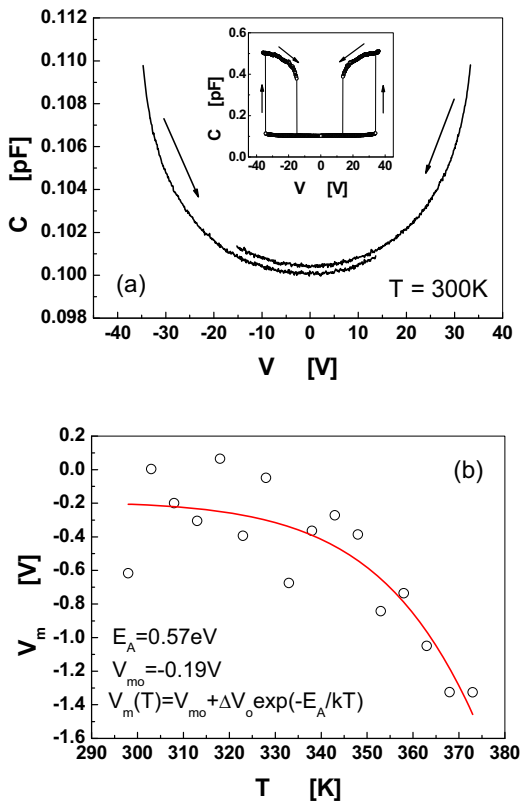


Fig.3 (a) Typical capacitance-voltage characteristic obtained under pull-up (the inset shows the full characteristic) and (b) temperature dependence of  $V_m$ .

A typical C-V characteristic of a MEMS switch obtained under pull-up condition at room temperature is plotted in Fig. 3a. The characteristic was obtained under scheme B in order to show the effect cumulative charging during successive pull-down states. The small shift of the capacitance at rest position by about 0.27fF (Fig.3a) indicates, according to (1) and (3), the presence of a relatively small amount of mean and variance values of equivalent charge at the dielectric surface. This charge almost vanishes at elevated temperatures. Meanwhile, the effect of a full cycle on  $V_m$ , was found to

cause a shift of  $\Delta V_m \cong -0.36V$ , which indicates also that  $\Delta(\mu_\alpha \mu_\beta + cov_{(\alpha,\beta)})$  is small with respect to pull-in and pull-out voltages, which are practically determined by the switch mechanical characteristics.

Finally, in order to further simplify and take advantage of (7) we plotted  $V_m$  vs temperature (fig.3b). The temperature dependence of  $V_m$  indicated the presence of a residual charge and a thermally activated induced charging, reported also in SiN switches [19], with activation energy of 0.56eV suggesting a slow charging process, per C-V cycle, due to large activation energy.

Taking all these into account and in order to overcome the nonexistent analytical solution of (7) and monitor the charging induced during a capacitance-voltage cycle we assume that the charge density variance at dielectric surface is low and define the sums  $\Sigma V_{pi} = V_{pi}^+ - V_{pi}^-$  and  $\Sigma V_{po} = V_{po}^+ - V_{po}^-$ . Due to  $V_m$  as well as charge density mean and variance small values, the sums are expected to be mainly affected by the charging history during the prior actuation, if any or the discharging and charging during proceeding up state or down state respectively, see Fig.3a.

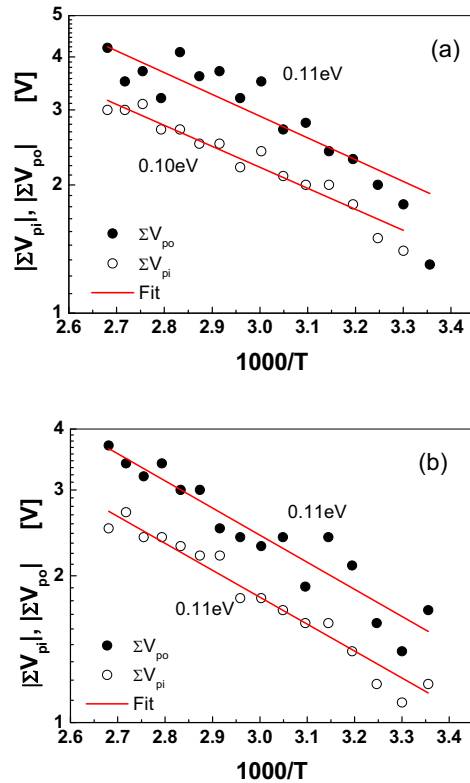


Fig.4 Arrhenius plots of the pull-in and pull-out voltage sums for (a) actuation scheme A and (b) actuation scheme B. Sweep rate for both is 57mV/sec.

The sums were found to be thermally activated. The activation energies obtained from the Arrhenius plots in Fig.4a and b were found to be about 0.11eV for a sweep rate of 57mV/sec. Moreover, it is interesting to point out that for the same sweep rate same activation energies were obtained independently of capacitance-voltage cycle scheme.

Finally, the calculated activation energy was found to decrease with increasing the bias sweep rate (fig.5). This is expected because at higher sweep rates the device remains for a shorter time in the down state and faster the defects can respond faster. Nevertheless, due to the fact that the pull-in and pull-out windows are narrowing when the temperature increases, the dependence of the apparent activation energy on the sweep rate is still under investigation.

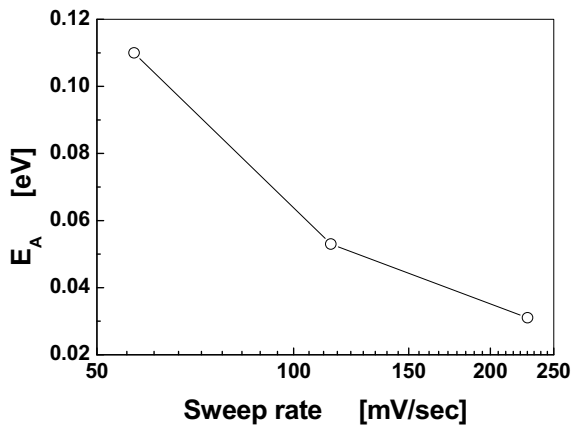


Fig.5 Dependence of activation energies on bias sweep rate.

#### V. CONCLUSIONS

The charging introduced during capacitance-voltage assessment has been investigated. The investigation adopted a general model of distributed equivalent charge and air gap. Two actuation schemes were employed for the study of dielectric charging in order to draw a better understanding on the sequence of preceding steps/processes. Taking into account the charging history, it was found regardless the actuation scheme the charging is thermally activated. The activation energies were found to decrease when the sweep rate increases. Although the investigation is still in progress it is important to stress that the calculated activation energies were found to be independent of the actuation scheme. According to this we can conclude that the experimental results indicate that for low charging levels in SiO<sub>2</sub> the dominant mechanism is the charge injection. Finally, it was shown that the general model of distributed charge and air gap can provide valuable information on the dielectric charging of MEMS switches.

#### ACKNOWLEDGMENT

The authors wish to acknowledge the support from the IMPACT Center for Advancement of MEMS/NEMS VLSI, funded by DARPA, through Grant No. HR0011-06-1-0046, under the DARPA N/MEMS Science & Technology Fundamentals Research Program

#### REFERENCES

[1] C L Goldsmith, J Ehmke, A Malczewski, B Pillans, S Eshelman, Z Yao, J Brank and M Eberly, "Lifetime Characterization of Capacitive

RF MEMS Switches", *IEEE MTT-S Int. Microwave Symp. Digest*, 2001, pp.227-230

[2] J Wibbeler, G Pfeifer and M Hietschold, "Parasitic charging of dielectric surfaces in capacitive microelectromechanical systems (MEMS), Sensors and Actuators", *Sensors Actuators*, vol. A 71, pp.74-80, 1998

[3] G. M. Rebeiz, "RF MEMS Theory, Design and Technology", Haboken, (New Jersey 2003), J. Wiley and Sons

[4] S. Melle, D. De Conto, L. Mazenq, D. Dubuc, B. Poussard, C. Bordas, K. Grenier, L. Bary, O. Vendier, J.L. Muraro, J.L. Cazaux, R. Plana, "Reliability Modeling of Capacitive RF MEMS, IEEE Tans. on Microwave Theory and Techniques", *Microelectronics Reliability*, vol. 45, No. 9-11, pp.1770-5, 2005

[5] W Merlijn van Spengen, Robert Puers, Robert Mertens and Ingrid de Wolf, "A comprehensive model to predict the charging and reliability of capacitive RF MEMS switches", *J. Micromech. Microeng.*, vol. 14, No., pp. 514-521, 2004

[6] M. Lamhamdi, P. Pons, U. Zaghoul, L. Boudou, F. Coccetti, J. Guastavino, Y. Segui, G. Papaioannou, R. Plana, "Voltage and temperature effect on dielectric charging for RF-MEMS capacitive switches reliability investigation", *Microelectronics Reliability*, vol. 48, No. 8-9, pp.1248-1252, 2008

[7] X. Yuan, J. C. M. Hwang, Da. Forehand and C. L. Goldsmith, "Modeling and Characterization of Dielectric-Charging Effects in RF MEMS Capacitive Switches", *International Microwave Symposium 2005*, pp 753-756

[8] G. Papaioannou, M. Exarchos, V. Theonas, G. Wang, and J. Papapolymerou, "Temperature Study of the Dielectric Polarization Effects of Capacitive RF MEMS Switches", *IEEE Trans. on Microwave Theory and Techniques*, vol. 53, pp 3467-3473, 2005

[9] G. Papaioannou, J. Papapolymerou, P. Pons and R. Plana, "Dielectric charging in radio frequency microelectromechanical system capacitive switches: A study of material properties and device performance", *Applied Physics Letters* vol. 90, pp 233507, 2007

[10] Z. Peng, X. Yuan, J. C. M. Hwang, D. I. Forehand and C. L. Goldsmith, "Dielectric Charging of RF MEMS Capacitive Switches under Bipolar Control-Voltage Waveforms", *International Microwave Symposium 2007*, pp 1817-1820

[11] E. Papandreou, M. Lamhamdi, C.M. Skoulikidou, P. Pons, G. Papaioannou and R. Plana, "Structure dependent charging process in RF MEMS capacitive switches", *Microelectronics Reliability* vol. 47, pp 1812-1817, 2007

[12] Vandershueren J and Casiot J in: Braunlich P (Ed.) *Topics in Applied Physics: "Thermally stimulated relaxation in solids"*, vol. 37, ch.4, pp 135-223, Springer-Verlag, Berlin, 1979

[13] N. D. Young, "The formation and annealing of hot-carrier-induced degradation in poly-Si TFT's, MOSFET's, and SOI devices, and similarities to state-creation in  $\alpha$ Si:H", *IEEE Trans. on Electron Devices* vol. 43, No.3, pp.450-456, 1996

[14] A. Acovic, G. La Rosa and Yuan-Chen Sun, "A review of hot-carrier degradation mechanisms in MOSFETs", *Microelectronics Reliability* vol. 36, No.7-8, pp. 845-869, 1996

[15] R. Ramprasad, "Phenomenological theory to model leakage currents in metal-insulator-metal capacitor systems", *phys. stat. sol. (b)* vol. 239, pp 59-70, 2003

[16] X. Rottenberg, I. De Wolf, B. K. J. C. Nauwelaers, W. De Raedt and H. A. C. Tilmans, "Analytical Model of the DC Actuation of Electrostatic MEMS Devices With Distributed Dielectric Charging and Nonplanar Electrodes", *J. of Microelectromechanical Systems*, vol. 16, No.5, pp 1243-1253, 2007

[17] [www.memtronics.com](http://www.memtronics.com)

[18] C.L. Goldsmith, and D.I. Forehand, "Temperature Variation of Actuation Voltage in Capacitive MEMS Switches", *IEEE Microwave and Wireless Components Letters*, vol 15, Oct. 2005, pp 718 - 720

[19] R. Daigler, G. Papaioannou, E. Papandreou and J. Papapolymerou, "Effect of Dielectric Film Thickness on Dielectric Charging of RF MEMS Capacitive Switches", *International Microwave Symposium 2008*, pp 1275-1278