

Dielectric Discharging processes in RF-MEMS Capacitive Switches

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Abstract — The discharging processes in silicon nitride dielectric film of RF-MEMS capacitive switches are investigated for the first time. The study includes the dependence of discharging as a function of temperature that allows the detection of thermally activated mechanisms. The discharging time constants were found to depend only on temperature and not on the actuation bias polarity.

Keywords: Dielectric polarization, microelectromechanical devices, reliability, surface charging

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 [1–4]. Presently, the available models assume that the dielectric charging arises from charges distributed throughout the dielectric material [3,4], the presence of charges at the dielectric interface [4] or distribution of inverse polarity charges at the dielectric surface [5] and the injection of charges from the suspended bridge during ON-state through dielectric material and/or bridge asperities [6].

So far the process of dielectric charging has been investigated by recording the transient current in permanently ON-state switches and MIM capacitors. This allowed the determination of charging and discharging current time constants [7, 8], identify the contribution of dipolar polarization and determine the dependence of time constant magnitude on the dielectric deposition method [7]. In the case of MEMS capacitors, the transient response of the ON capacitance was used to determine the activation energy of space charge polarization charging process [9, 10] while the

employment of MIM and MEMS capacitors allowed the direct correlation of Poole-Frenkel injection current intensity to the shift of pull-in and pull-out voltages [6]. A successful step towards the correlation of dielectric charging to material quality was recently achieved [11] by correlating the shift of bias for capacitance minimum of the capacitance-voltage characteristic with the charging due to material dipolar polarization. On the other hand the extension of MEMS capacitive switch lifetime was investigated through a thorough analysis of charging and discharging processes in MIM capacitors [12]. In spite of all these investigations there are still several unanswered issues among which the one of primary importance is the dielectric discharging process. This is because the in a MEMS switch the discharge occurs when the switch bridge is no more in contact with the dielectric. This obviously means that the discharge has to take place through the dielectric through a redistribution of dipoles' orientation and the diffusion and drift of injected charges under the presence of local electric fields.

Therefore, the discharging processes in real MEMS switches constitute a quite complex and difficult to be identified. The aim of the present work is to present for the first time the presence of thermally activated mechanisms in the discharge process of MEMS capacitive switches. The investigation is based on the fact that temperature plays a key issue role on the dipole and free charge redistribution. Parameters such as the process time constant and activation energy are determined for opposite bias charging polarities. The importance of the determination of these parameters lays on the fact that the thermally activated mechanisms are easily traced and can be related the material quality.

II. THEORY

Upon the application of an electric field, the dielectric film of a MEMS capacitive switch is polarized. The polarization occurs through several mechanisms involving microscopic and/or macroscopic charge displacement. The most significant mechanisms are the almost instantaneous polarization (P_∞), which arises from the displacement of the electrons with

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respect to the nuclei, dipolar polarization (P_D) and the space charge polarization, the later arising from intrinsic charge displacement (the intrinsic space charge polarization, P_{SC-i}) and charge injection (the extrinsic space charge polarization, P_{SC-e}). The total time dependent polarization will be given by

$$P = P_\infty + (P_D + P_{SC-i} - P_{SC-e}) \quad (1)$$

which time constant may vary from milliseconds to years.

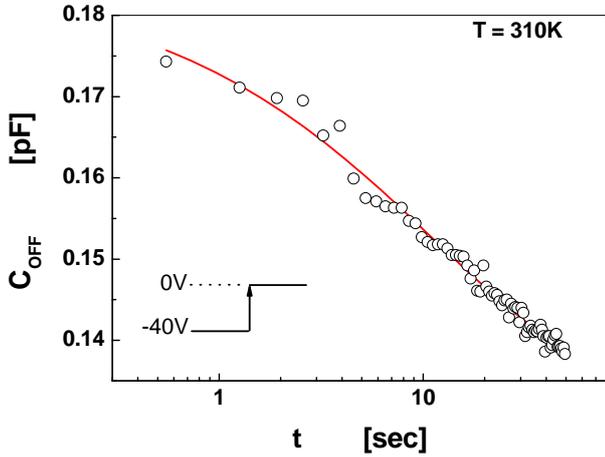


Fig.1 Switch-OFF transient of a MEMS switch at 310K

In order to proceed, we adopt a simple model where the bulk and surface charges are replaced by the macroscopic dipole moment per unit volume P [10]. Now, when a voltage V is applied across the capacitor electrodes the resulting electric field will polarize the insulating film and the charged bridge electrode will be attracted by the rigid electrode. The applied voltage can be calculated from $V = -\int_0^{z-d} \vec{E} \cdot d\vec{l}$, where z is the distance between the electrodes when no bias is applied and d bridge displacement under bias. Since the electric displacement is constant in the space between capacitor electrodes, the sheet charge σ_1 at the surface of the suspended bridge will be given by:

$$\sigma_1 = \frac{\epsilon_0 V + z_1 P}{z - d} \quad (2)$$

where the symbols have the usual meaning [10, 13].

Bellow pull-in the capacitance of a RF-MEMS switch is determined by the balance between the electrostatic and mechanical force. Moreover, when the switch is driven to OFF-state by removing the bias ($V=0$) across the waveguide and suspended electrode, the capacitance will be determined by the remaining polarization which gives rise to a parasitic voltage, termed V_p in [2]. Then the OFF capacitance will be determined by the electrostatic force that in turn will depend on the non uniform distribution of charge, which is the dielectric polarization, [4]:

$$F_{el} = \frac{z_1^2}{2\epsilon_0(z-d)^2} \cdot \int P^2 \cdot da \quad (3)$$

According to this if we apply a step voltage from ON-state to zero the pull in force will not vanish but will be proportional to $\int P^2 \cdot da$ and decrease monotonously with time since both the space charge and dipolar polarization will decay with time. In the case of an unstressed device the variation of OFF capacitance with time can be approximated by:

$$\Delta C(t) \approx \frac{Az_1^2}{2z^4} \cdot \int P^2(t) \cdot da \quad (4)$$

which clearly indicated that the capacitance will vary with time like the dielectric polarization. An excellent style manual for science writers is [7].

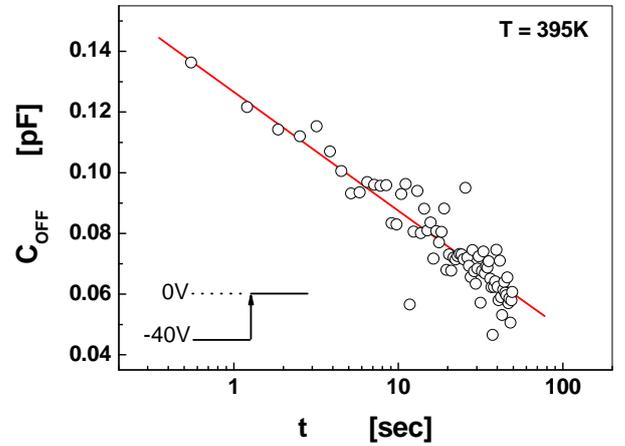


Fig.2 Switch-OFF transient of a MEMS switch at 395K

III. EXPERIMENTAL ANALYSIS

The capacitance of air-bridge type RF MEMS switches was monitored with a Boonton 72B capacitance bridge. The switches were fabricated with a standard photolithographic process on high resistivity silicon wafers ($\rho > 2 \text{K}\Omega \cdot \text{cm}$). A 2500 Å thick layer of Si₃N₄ was deposited with the PECVD technique. The sacrificial layer was removed with resist stripper and the switches were dried using a critical point drier. On each run, the capacitance transient was measured at approximately 1sec time step. For each measurement the switch 'bridge' bias was varied from negative or positive 40V to 0V. In order to avoid excess charging the ON bias was applied for 5sec and a different capacitor with approximately similar capacitance voltage characteristics was used. Finally the switch-OFF capacitance transients were recorded in the temperature range of 300K to 450K at a step of 5K with a resolution of 1fF.

IV. RESULTS AND DISCUSSION

Figure 1 show the switch-OFF capacitance transient response at 325K, when bias step of -40V to 0V was applied.

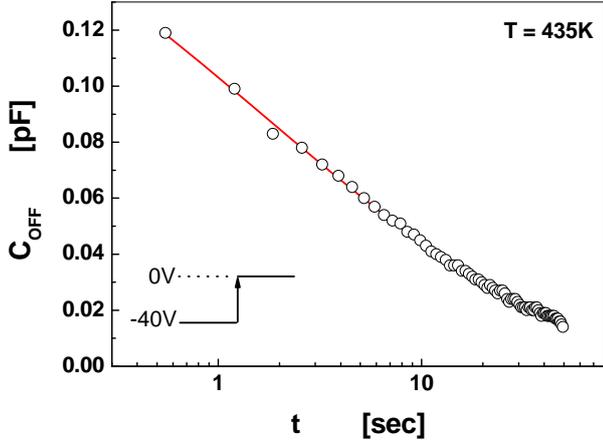


Fig.3 Switch-OFF transient of a MEMS switch at 435K

The transient decay was found to be non exponential. Due to the complexity of the process, that is the dipole reorientation and the injected charge reorientation and recombination under the presence of a time dependent electric field, the relaxation cannot obey a multi-exponential decay. A continuous distribution of decay times would represent better this process which is better approximated by the stretched exponential relaxation law. According to this the capacitance decay may be written as:

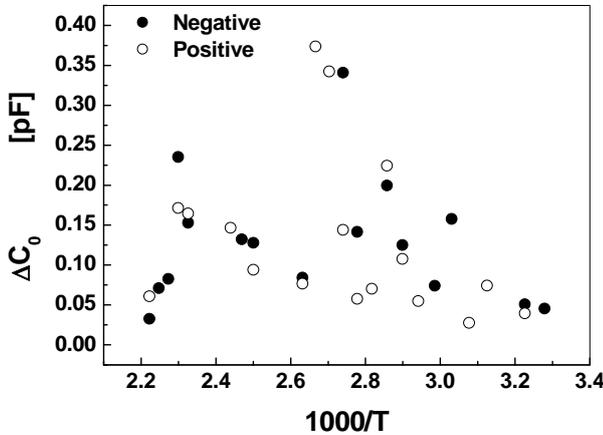


Fig.4 Dependence of capacitance transient amplitude on temperature for bridge (o) positive bias and (•) negative bias charging.

$$\Delta C(t) = \Delta C_0 \cdot \exp\left[-\left(\frac{t}{\tau}\right)^\beta\right] \quad (5)$$

where ΔC_0 is the transient amplitude, τ the process time constant and β the stretch factor ($0 < \beta \leq 1$), which reveals the process degree of complexity.

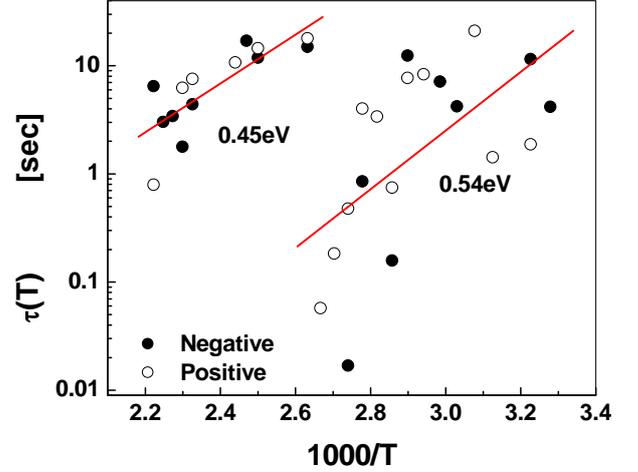


Fig.5 Arrhenius plot of process time and demonstration of processes grouping

In all experiments the transient decay were found to be non exponential. This is clearly shown in Figures 1 to 3. More specifically, at certain temperatures the decay was found to be rather logarithmic with time (fig.2) instead of stretched exponential, hence the values of τ and β were not determined at these temperatures. At these temperatures, a transition from one thermally activated mechanism to another was monitored. This transition, where a wide range of time constants are present, seems to be responsible for the logarithmic decay. Due to its significance on the MEMS switch lifetime this process is presently under further investigated.

The transient amplitude, which was determined from the fitting of (5) to the experimental data, is plotted in Fig.4. The fitting was performed for temperatures where the decay obeyed (5). Due to bridge thermal expansion the dependence of transient amplitude on temperature cannot be fully exploited. In spite of this a comparison between the negative and positive bridge polarity can be done. The data distribution in Fig.4 clearly shows that the bridge charging polarity does not affected significantly the transient. Here it must be pointed out that the discharge process in MEMS capacitive switches in the OFF-state is very different with the one investigated in MIM capacitors. In MIM capacitors the discharge currents are strongly affected by:

- i) the partial dissipation of excess charges by space independent intrinsic conductivity that passes unnoticed in the external circuit,
- ii) the incomplete release of the image charges induced at the electrodes due to their partial neutralization by the excess charges and
- iii) the dependence of the diffusion released current on the blocking character of the electrodes.

In contrast, as already mentioned, in MEMS switches in the OFF-state the discharge takes place only through the dielectric.

Such a process in a MIM capacitor would give rise to discharge currents of opposite polarity, with respect to the discharge current of an ordinary capacitor [14].

In general the process time τ is thermally activated:

$$\tau(T) = \tau_0 \exp\left(\frac{E_A}{kT}\right) \quad (6)$$

The process time activation energy E_A is determined from the Arrhenius plot. As shown in Fig. 5 the temperature dependence of τ reveals that the process time constant does not depend on the polarity of the charging/polarization bias. Moreover, the Arrhenius plot reveals the presence of two thermally activated mechanisms with activation energies of 0.45eV at high temperatures and 0.54eV at lower temperatures. Here it must be pointed out that the higher activation energy at lower temperatures arises from large dispersion of time constant values. The present experiments cannot draw a concrete conclusion on the origin of the two revealed processes that is if they emerge from dipole randomization or charge redistribution. Indirect conclusions can be drawn if we assume that the charging and discharge process of the same origin show the same activation energies. In such a case we may draw some conclusions on the high temperature discharge process if we assume that it has the same origin with the charging one reported in [9]. Further, taking into account the conclusions of [11] we may attribute it to a randomization of dipole orientation. In any case the fact that these processes are thermally activated allows us to compare them with other experimental results on both MIM and MEMS capacitors. This allows us to overcome the difficulties that arise in the interpretation of MIM discharge currents, already mentioned above.

V. CONCLUSIONS

The discharge processes in the dielectric film of RF-MEMS capacitance switches has been investigated by monitoring the transient response of switch-OFF capacitance. The discharge process, due to its complexity, was found to obey the stretched exponential relaxation law. The Arrhenius plot of the process time constant reveals the presence of two thermally activated mechanisms that do not depend on the charging bias polarity. The activation energy of the high temperature one agrees with the activation energy of the thermally activated charging mechanism monitored in switches with the same dielectric material. The presence of the thermally activated mechanisms allows both their trace and comparison with the charging processes as well as the inclusion in lifetime modeling.

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)", *SensorsActuators*, vol. A 71, pp.74-80, 1998

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

[4] X. Rottenberg, B. Nauwelaers, W. De Raedt and H. A. C. Tilmans, "Distributed dielectric charging and its impact on RF MEMS devices", 12th GAAS Symposium, Amsterdam, 2004, pp.475-8

[5] X. Rottenberg, B. Nauwelaers, W. De Raedt and H. A. C. Tilmans, "Distributed dielectric charging and its impact on RF MEMS devices", 12th GAAS Symposium, Amsterdam, 2004, pp.475-8

[6] S. Melle, D. De Conto, L. Mazonq, D. Dubuc, B. Poussard, C. Bordas, K. Grenier, L. Bary, O. Vendier, J.L. Muraro, J.L. Cazaux, R. Plana, "Failure Predictive Model of Capacitive RF-MEMS", *Microelectronics Reliability*, vol. 45, pp.1770-5, 2005

[7] M.Lamhamdi, J.Guastavino, L.Boudou, Y.Segui, P.Pons, L. Bouscayrol and R. Plana, "Charging-Effects in RF Capacitive Switches Influence of insulating layers composition", *Microelectronics Reliability*, vol. 46, pp.1700-1704, 2006

[8] X. Yuan, Z. Peng, J. C. M. Hwang, D. Forehand and C. L. Goldsmith, "Temperature Acceleration of Dielectric Charging in RF MEMS Capacitive Switches", *IEEE MTT-S Int. Microwave Symp. Digest 2006*, pp. 47

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

[10] G. J. Papaioannou, M. Exarchos, V. Theonas, J. Psychias and G. Konstantinidis, D. Vasilache, A. Muller, and D. Neculoiu, "Effect of space charge polarization in radio frequency microelectromechanical system capacitive switch dielectric charging" *Appl. Physics Letters*, vol. 89, pp. 103512-4, 2006

[11] 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", *Applie Physics Letters* vol. 90, pp.233507-1 - 233507-4, 2007

[12] Z. Peng, X. Yuan, J. C. M. Hwang, D. Forehand and Charles L. Goldsmith, "Dielectric Charging of RF MEMS Capacitive Switches under Bipolar Control-Voltage Waveforms", *IEEE MTT-S Int. Microwave Symp. Digest 2007*

[13] 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, pp. 514-521, 2004

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