Dielectric charging mechanisms in RF-MEMS capacitive switches

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***Abstract* — In this paper we present for the first time the simultaneous action of dipolar and space charge polarization charging mechanisms in the dielectric film of capacitive RF MEMS switches. These mechanisms charge the film surface with opposite charges. At room temperature the dominant mechanism is the space charge polarization while at higher temperatures the dipolar polarization prevails. In Si_3N_4 the transition occurs at about 380K where the average charging is minimized, an information that can be used to engineer the dielectric properties so that the transition occurs at room temperature.**

I. Introduction

Capacitive RF MEMS switches are one of the most promising applications in microelectromechanical systems (MEMS), but their commercialization is currently hindered by reliability problems. The most important problem is the charging of the dielectric, causing erratic device behavior [1–4]. Presently, the available models assume that the dielectric charging arises from charges distributed throughout the dielectric material [4], the presence of charges at the dielectric interface [5] and the injection of charges form the suspended bridge during ON-state [6]. So far the dielectric charging process has been investigated by recording the transient current in permanently ON switches [7-10], the transient response of the ON capacitance [11, 12] and the correlation of Poole-Frenkel current intensity to the shift of pull-out voltage [9]. These efforts, although constituted a major step towards the understanding of MEMS dielectric charging, were focused on the study of contribution of charge injection leaving out mechanisms that are related to the intrinsic polarization such as the intrinsic space charge polarization and the dipole orientation [13]. The effect of temperature on the dielectric charging has been investigated in MIM capacitors with SiO_2 dielectric [7, 9] and in MEMS switches with Si_3N_4 dielectric [11, 12]. Finally, a process arising from contact-less charging and related to the dielectric intrinsic polarization processes has been reported recently [14, 15]. Taking all these into account it becomes clear that the simultaneous study of all charging mechanisms, of extrinsic and intrinsic origin, is of paramount importance.

The aim of the present work is to demonstrate that when a RF-MEMS switch is in the ON state both the extrinsic and intrinsic charging processes occur. Moreover, that temperature plays a key issue role on the manifestation of each mechanism, so that at low temperatures the dielectric charging arises from the charge injection while at high temperatures the dominant mechanism is the dipolar polarization.

II. BASIC Theory

On the time scale of interest to RF-MEMS capacitive switches response (i.e. greater than 1μsec) an electric field can interact with the dielectric film in two primary ways. These are the reorientation of defects having an electric dipole moment, such as complex defects, and the translational motion of charge carriers, which usually involve simple defects such as vacancies, ionic interstitials and defect electronic species. These processes give rise to the dipolar (P_D) and the intrinsic space charge (P_{SC-i}) polarization mechanisms, respectively. Moreover, when the dielectric is in contact with conducting electrodes charges are injected through the trap assisted tunneling and/or the Poole-Frenkel effect [16] giving rise to extrinsic space charge polarization (P_{SC-e}) whose polarity is opposite with respect to the other two cases. In RF-MEMS capacitive switches during ON state all polarization mechanisms occur simultaneously and the macroscopic polarization is given by

$$P_{tot} = P_D + P_{SC-i} - P_{SC-e} \qquad (1)$$

Now, from elementary physics it is known that the electric displacement, D, defined as the total charge density on the electrodes, will be given by $D = \varepsilon_0 E + P$, where E is the applied field and P the dielectric material polarization. The resulting polarization P may be further divided into two parts according to the time constant response [17]:

a) An almost instantaneous polarization (P∞) due to the displacement of the electrons with respect to the nuclei. The time constant of the process is about 10-16 sec and defines the high frequency dielectric constant that is related to the refractive index.

b) A delayed time dependent polarization P'(t), starting from zero at t=0, due to the orientation of dipoles and the distribution of free charges in the dielectric, the dipolar and space charge polarization respectively. Moreover the growth of these polarization components may be described in the form of $P_j(t) = P_{j0} \cdot \left[1 - f_j(t)\right]$. The index j refers to each polarization mechanisms and $f_j(t)$ are exponential decay functions of the form $\exp\left[-\left(\frac{t}{\tau}\right)^{\beta}\right]$, where β=1 in the ideal case of Debye relaxation and β<1 for the stretched exponential relaxation law, in the case of materials that possess a degree of disorder.

Under the application of an electric field the time dependent component of polarization will be given by

$$\Delta P(t) = P_{SC-e} \cdot f_{SC-e}(t) - \left[P_D \cdot f_D(t) + P_{SC-i} \cdot f_{SC-i}(t)\right] \qquad (2)$$

The degradation of capacitive RF-MEMS switches depends on the actuation time. In the ON-state the suspended electrode lands on the dielectric surface and the device capacitance must not increase further. In spite of this, due to elastic deformation of the suspended electrode the capacitance continues to increase with the bias increase. So, if the applied bias is maintained constant, the capacitance variation with time will allow the observation of the contribution of the different polarization mechanisms.

As already mentioned, during actuation charges will be injected through asperities [8]. The injected charges will initially decrease the local polarization and depending on the amount of injected charge the sign of local polarization may change. Therefore, the dielectric surface will contain charges of opposite polarity [6], the injected ones through bridge asperities and the dipole bound ones. Taking into account these, we are led to the conclusion that the capacitance transient component will be proportional to the time dependent polarization [12]

$$\Delta C(t) \approx \Delta P(t) \qquad (3)$$

Now it becomes obvious that the shape and polarity of ΔC(t) will reveal both the dominating polarization/charging mechanism and dependence of the charging mechanism on temperature.

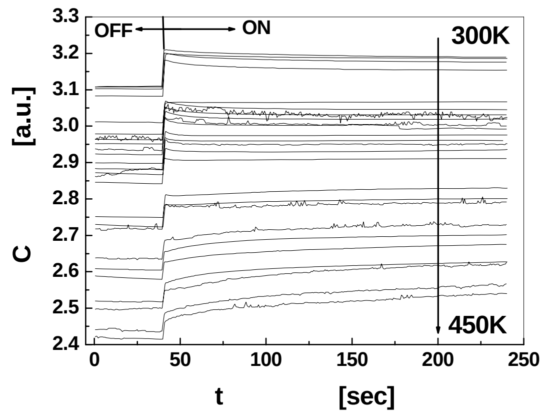

Fig. 2. Temperature dependence of switch-ON capacitance transients

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 (ρ>2KΩ.cm). A 2500 A 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 a 1sec time step. During measurements, the switch 'bridge' bias was varied from 0V to 20V, negative or positive. Finally the capacitance transients were recorded in the temperature range of 300K to 450K at a step of 5K.

IV. RESULTS AND DISCUSSION

As shown in Fig.2 the switch-ON capacitance transient has the form of overshoot at low temperatures. As the temperature increases the transients are gradually turning to solely undershoot, which is the dominant mechanism at high temperatures. Here it must be pointed out that the turning point from overshoot to undershoot occurs in the temperature range of 360K to 400K. This region is the same with one at which the bias levels for the minimum capacitance of the ascending and descending C-V characteristics coincide [11]. In this transition regime the behavior can be easily fitted with two stretched exponential relaxation adopting the grouping proposed in Eq. 2. The fitting results for low, intermediate and high temperatures are shown in Fig.3a-c.

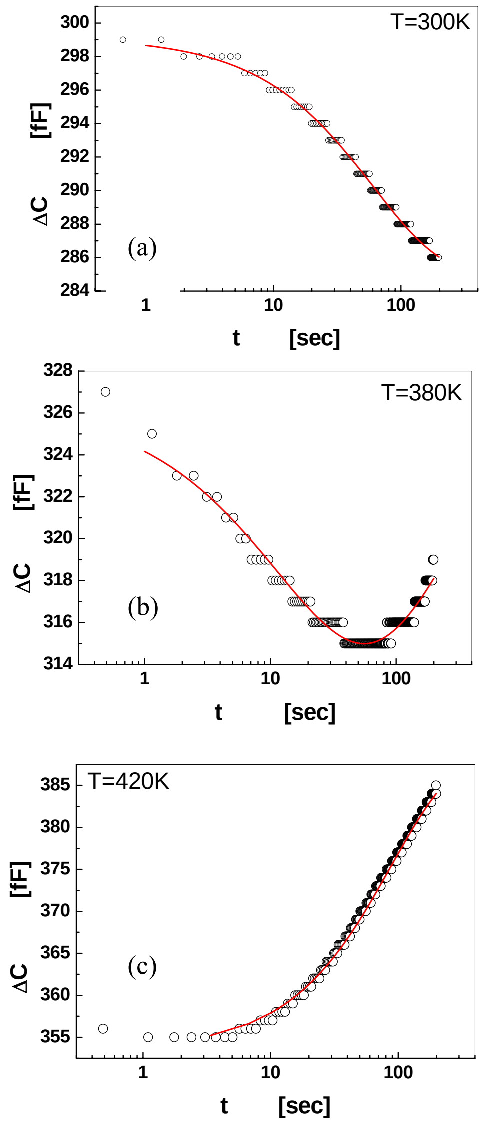

Fig. 3(a-c). Switch-ON transients and fitting results

This behavior clearly shows that the basic competing mechanisms are the space charge polarization and the dipolar polarization. If we assume that the free carrier concentration in SiNx is very low we can, for the sake of simplicity, ignore the intrinsic space charge polarization. In any case the conclusions are not affected by the validity or not of this assumption since the redistributed free charge is compensated by the injected, through Poole-Frenkel mechanism, ones [8]. So, according to the experimental results, at room temperature the dominant mechanism is the extrinsic space charge polarization, as revealed by the shape and polarity of capacitance transient response. This is supported from experiments performed through current transient measurements in MIM capacitors with different dielectric materials [8-10]. At higher temperatures the Poole-Frenkel injection current is expected to increase by several orders of magnitude, the latter depending on the activation energy of the involved traps. The increase of injection current is expected to lead to a homogenization of injected and intrinsic charge distribution resulting to a decrease of the space charge polarization, thus leaving the key role to the dipolar polarization. This occurs if the concentration of available dipoles is large enough so that to not be screened by the injected carriers. Presently there is no available information on the concentration and distribution on traps and dipoles in the dielectrics used in MEMS; the conclusions will relay on the fitting results of the temperature dependence of the capacitance transients magnitude (ΔC_0) vs temperature, shown in Fig.4. The overlapping area, around 380K, was obtained by fitting a double stretched exponential low. Finally, the positive transient amplitude corresponds to overshoot and the negative to undershoot. The calculated capacitance transients for both mechanisms are presented in Fig.4. There the magnitude of the space charge polarization appears to be smaller than the dipolar one. The temperature dependence of ΔC_0 shows a slow decrease rate for the space charge polarization and a sharp increase for the dipolar polarization. These results, although contradictory on a first approach, do not disagree with the experimental results in MIM capacitors if we bear in mind that in MEMS the charging is local since it occurs through asperities and not through the whole dielectric area like in MIM capacitors. Moreover, in the temperature range of 380K the average value of the resulting capacitance transient is minimal. This effect may be possibly exploited for a charge-less operation of a capacitive switch as shown from the data of the present work and the temperature shift of the corresponding bias for the minimum capacitance of C-V characteristic [11]. Here it must be pointed out that this effect needs further investigation taking into account the surface roughness which affects significantly the area of injected charge. In spite of these, this effect can be used for further improvement of the device lifetime.

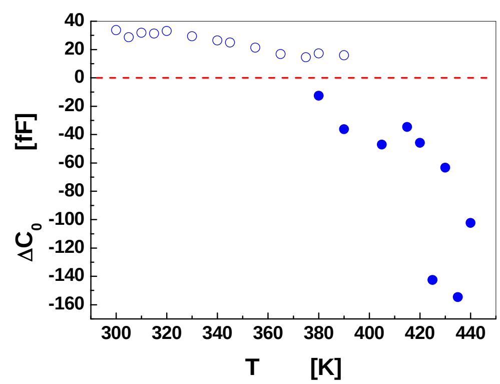

Fig. 4. Temperature dependence of capacitance transient magnitude

Finally the relaxation time of the stretched exponential law was found to be thermally activated for all temperatures, given by $\tau(T) = \tau_0 \exp\left(\frac{E_A}{kT}\right)$. The Arrhenius plot allows the determination of activation energy E_A and the relaxation time at infinite temperature, which represents the inverse of escape frequency of charges from traps and dipoles from the oriented state. of activation energies.

V. Conclusion

In conclusion, this paper demonstrates the simultaneous action of different charging mechanism in RF-MEMS capacitive switches. The mechanisms involved are the dipolar and space charge polarization. The analysis of experimental data confirms that at room temperature the extrinsic space charge polarization is the dominant charging mechanism, while at higher temperatures the dominant mechanism is the dipolar polarization. The transition temperature lays close to 380K where both mechanisms are present and the average polarization/charging is minimized. This effect obviously has to be further investigated in connection with the dielectric engineering in order to decrease the transition temperature to ranges of commercial application for MEMS switches with increased lifetime and reliability.

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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] X. Yuan, S. Cherepko, J. Hwang, C. I. Goldsmith, C. Nordquist and C. Dyck, "Initial Observation and Analysis of Dielectric-Charging Effects on RF MEMS Capacitive Switches", IEEE MTT-S Int. Microwave Symp. Digest 2004, pp.1943-6

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

[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, pp. 514-521, 2004

[6] 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

[7] X. Yuan, J. C. M. Hwang, D. Forehand and C. L. Goldsmith, "Modeling and Characterization of Dielectric-Charging Effects in RF MEMS Capacitive Switches", IEEE MTT-S Int. Microwave Symp. Digest 2005, pp.

[8] 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, "Failure Predictive Model of Capacitive RF-MEMS", Microelectronics Reliability, vol. 45, pp.1770-5

[9] 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

[10] 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

[11] 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)

[12] 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

[13] 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

[14] P. Czarnecki, X. Rottenberg, R. Puers, I. De Wolf, "Effect of Gas Pressure on the Lifetime of Capacitive RF MEMS Switches", MEMS-2006, 19th International Conference on Micro Electro Mechanical Systems, 2006, pp.890-3

[15] G. J. Papaioannou, G. Wang, D. Bessas and J. Papapolymerou, "On the Polarization Mechanisms of RF MEMS Capacitive Switches", 1st EuMIC Conference, Manchester, 2006, pp.513-516