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A MIM CAPACITOR STUDY OF DIELECTRIC CHARGING FOR RF MEMS CAPACITIVE SWITCHES

Loukas Michalas, Matroni Koutsoureli, Eleni Papandreou,
Anestis Gantis, George Papaioannou

Solid State Section, Physics Department, National Kapodistrian University of Athens,
Panepistimiopolis Zografos, Athens 15784, Greece

Abstract. *MIM capacitors are considered equally important devices for the assessment of dielectric charging in RF MEMS capacitive switches. Beside the obvious similarities between the down state condition of RF MEMS and MIM capacitors there are also some important differences. The paper aims to introduce a novel approach to the study of dielectric charging in MEMS with the aid of MIM capacitors by combining experimental results obtained by the application of DC, Charging Transient and Kelvin Probe techniques. The strengths and weaknesses are discussed in conjunction with experimental results obtained on* SiN_x *based MIM capacitors and MEMS capacitive switches fabricated under the same conditions.*

Key words: *RF MEMS, MIM, Dielectric Charging, Reliability*

1. INTRODUCTION

Micro electro mechanical system (MEMS) capacitive switches have received important research attention over the last two decades mainly due to their potential implementation on RF applications such as filters and antennas [1]. However, although they offer several advantages over their conventional semiconductor counterparts, such as lower power consumption and high linearity, their commercialization is still hindered by reliability issues mainly related to dielectric charging.

Regarding the dielectric charging, three major modes are acknowledged as responsible up to date. Two of them are usually referred as contactless charging and arise by either redistribution of internal charges and/or dipoles orientation [2-4], or by injection of electrons emitted by asperities at the bottom of the metal bridge due to field emission [5,6]. Such effects occur in the non contact areas that are formed between the dielectric film and the bridge in the down state condition due to surface roughness but also in the up state before the device actuation. The third and most well studied charging mode occurs

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Corresponding author: Loukas Michalas
Solid State Section, Physics Department, National Kapodistrian University of Athens, Panepistimiopolis Zografos, Athens 15784, Greece
(e-mail: lmichal@phys.uoa.gr)

with the bridge in the down state and therefore is referred as contacted charging. In this case charges are injected from the metal electrodes under the presence of an electric field in the range of MV/cm. The commonly used dielectric, low temperature deposited SiN_x, contains a large amount of electrically active defects and may store these injected charges for times longer than 10^4 sec [7]. The stored charges are responsible for several undesirable effects such as shift of C-V characteristics, narrowing of pull-in/out windows, degradation of the ratio C_{down}/C_{up} and finally lead to device failure due to bridge stiction [8,9].

Contact mode dielectric charging has been assessed with a variety of experimental techniques and by several research groups world wide over the last years [10]. Beyond the studies directly applicable on RF MEMS switches, equally important research takes place on Metal Insulator Metal (MIM) capacitors. The dielectric charging in MIM capacitors has been investigated with the aid of Charge/Discharge current transients (CCT/DCT) [11], by Thermally Stimulated Depolarization/Polarization Currents (TSDC/TSPC) [12,13] and by Kelvin Probe Force Microscopy (KPFM) [14]. In addition, combinations of the above techniques have been also implemented in order to clarify the importance of MIM structure [15] and of the dielectric film deposition condition on the characteristics of dielectric charging [16-18].

Indeed the study of MIM capacitors has advantages since it resembles the ideal down state condition of MEMS switches from the macroscopic point of view and also it is quite easier to fabricate such a structure without moveable parts. However, it should be always taken into consideration that beside some obvious similarities the two devices also have some important differences. Therefore the results obtained from MIM are not straightforwardly transferred to MEMS and the up to date the knowledge obtained from the study of MIM capacitor only constitutes the physical background to the understanding of MEMS results.

The present paper introduces a novel approach to the study of dielectric charging in MEMS with the aid of MIM capacitors by combining experimental results obtained by the application of DC, Charging Transient and Kelvin Probe (KP) techniques. The study extends our previously published work in [19] and adds some knowledge on how information obtained when well accepted characterization techniques applied on MIM capacitors may be transferred to the study, understanding and/or prediction of dielectric charging of MEMS. The experiments were performed on SiN_x based MIM capacitors and MEMS capacitive switches fabricated under the same conditions.

2. EXPERIMENTAL

Both MIM capacitors and MEMS capacitive switches that have been investigated in the present work have been fabricated under the same conditions in order to have identical dielectric materials that allow the extraction of comparative conclusions. Standard lithography process on high resistivity silicon wafer has been used. The dielectric film is 250 nm thick SiN_x deposited at 300°C with the PECVD technique. The same metal electrodes (Au/Ti/Au) were used in both cases while in the case of MEMS the 2 μm thick bridge is suspended about 2μm above the dielectric material

The DC and transient current measurements were recorded with the aid of a Keithley K6517A electrometer that provided the applied bias and measured the current flow through the device. The capacitance voltage characteristics of MEMS switches were monitored with a Boonton 72B capacitance meter. All measurements were performed in a vacuum cryostat after 2 hours annealing at $140^{o}C$ to remove humidity. Current voltage characteristics, the charging current transient technique and Kelvin Probe technique for the assessment of dielectric were charging applied on MIM capacitors while the charging and discharging effects in RF MEMS capacitive switches were assessed by monitoring the shift of the bias for minimum up state capacitance. The latter technique is the equivalent Kelvin Probe for MEMS and is based on the principle that the bias at which the capacitance attains its minimum is the one corresponding to the minimum electrostatic force independently of the charge uniformity and air gap distribution as well as bridge deformation [8,20].

3. RESULTS AND DISCUSSION

The charging and discharging processes in MEMS capacitive switches can be expressed briefly as following. During the device actuation (down state), charges are injected from the metal bridge under the presence of an electric field, usually in the range of MV/cm. When the bridge pulls-up, these stored charges are collected only through the bottom electrode. This process occurs under the presence of a low intrinsic field, in the range of a few KV/cm, generated by the injected charges. Therefore, in order to asses the issue of dielectric charging, it is essential to bear in mind that the charging process is a high field process while the discharging one is a low field process that occurs only through the bottom electrode.

3.1. Conduction mechanism

A study of the DC characteristics in MIM capacitors could provide information on the corresponding conduction mechanism under high and low field, thus during charging and discharging process respectively.

During the charging process charges are injected from the metal bridge into the insulating film with trap assisted tunneling (TAT). These injected charges are redistributed under the presence of the high field. A commonly observed high field process in dielectric films is Poole Frenkel conductivity [21,22]. In this case the current density (*J*) as a function of the applied field (E) is expressed as

$$J \approx AE \exp\left[-\frac{\Phi_B - B\sqrt{E}}{kT}\right] \tag{1}$$

Where A,B are constants and Φ_B is the energy barrier for process associated to the defects characteristics and k is the Boltzmann constant.

The straight line obtained for the high field regime in Poole-Frenkel plot presented in Fig. 1 is a signature for the mechanism confirming that the conduction mechanism responsible for the charge redistribution during charging is Poole Frenkel. For the applied fields intensities below 500 kV/cm which correspond to the data out of the fitting curve, the Poole Frenkel mechanism is no longer valid to describe the conductivity of the films.

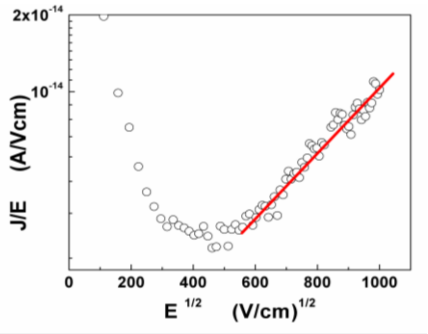

Fig. 1 Poole Frenkel signature plot for high field conductivity

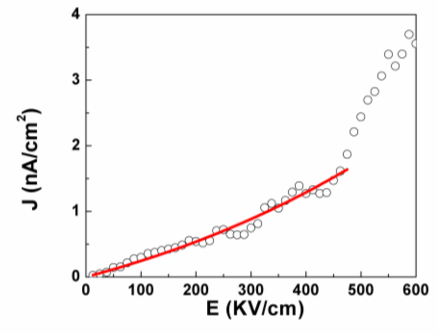

Fig. 2 Non linear fitting with Eq.2 on low field experimental data confirms hopping conductivity as corresponding mechanism

Therefore, a different mechanism is expected to dominate in the low field regime that provide information on the conduction mechanism for the applied fields below 500 kV/cm, thus during the discharging process.

Fig. 2 presents a fitting of eq. 2 on the experimental data. In the low field regime charge transport arise by hopping described by Eq.2, where α is a constant related to material microstructure.

$$J \approx \mathrm{E}\exp[aE] \qquad (2)$$

3.2. The charging process

The charging process was investigated in both MIM capacitors and MEMS capacitive switches in order to extract comparative information. In case of MIM capacitors the charging process was investigated with the aid of charging current transient technique (CCT). The density of charge injected and stored into the dielectric film upon the application of a specific applied field as a function of charging time is estimated by monitoring the current decay. The total measured current through the device is the sum of the dielectric relaxation current and the steady state leakage current of the dielectric film

$$J_{Total}(t) = J_{relax}(t) + J_{leak} \qquad (3)$$

A typical charging transient $\Delta J(t) = J_{total}(t) - J_{leak}$, is presented in Fig. 3.

The stored charge is then calculated by the following integral.

$$\sigma = \int_o^t \Delta J(t)dt \qquad (4)$$

By varying the upper integration limit it is possible to calculate the stored charge in the dielectric film as a function of stressing time for a specific applied field. In case of 1MV/cm, which corresponds to the same condition applied to MEMS switches, the stored charge is presented in Fig. 4.

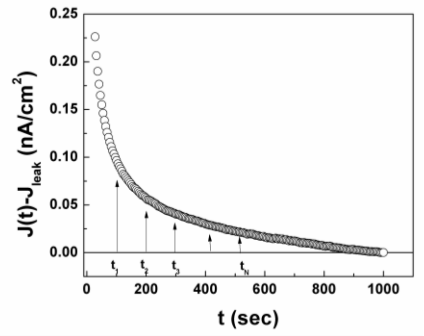

Fig. 3 Charging transient. The t_i denotes the different integration times for eq. 4

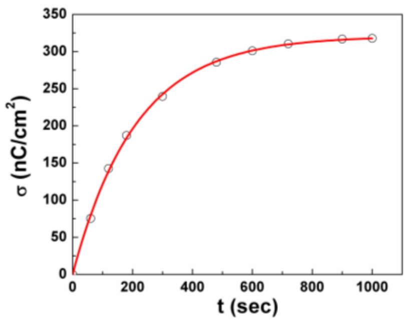

Fig. 4 Charge storage in MIM capacitors as a function on charging time under applied field of 1MV/cm

In MEMS capacitive switches the stored charge after a successive contacting stress is calculated by monitoring the shift in the bias for minimum up state capacitance (Fig. 5) [23,24] as presented in details in [20]. The stored charge (σ) is then calculated as

$$\sigma = \frac{\varepsilon_r \varepsilon_0}{d} \Delta V_{\min} \qquad (5)$$

where d is the dielectric film thickness and ε_0 and ε_r the vacuum and material relative dielectric permittivity and $\Delta V_{\min}$ is

$$\Delta V_{\min} = V_{\min}(t) - V_{\min}(0) \qquad (6)$$

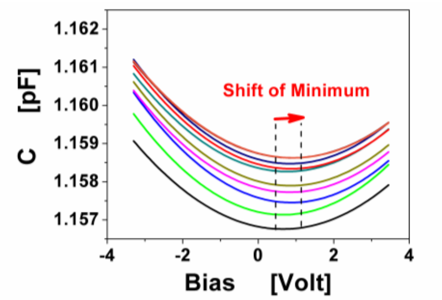

Fig. 5 Up state C-V curves recorded in MEMS switches after each successive stress step. The arrow indicates the shift direction and the increase of time.

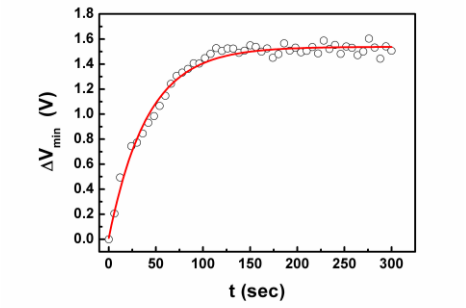

Fig. 6 MEMS up state C-V minimum shift versus charging time. The shift is proportional to the stored charge

In our case the stored charge at the surface of the dielectric film after 5 minutes stress under a field of 1 MV/cm has been calculated to be 30 nC/cm^2.

Comparing the results obtained by the Charge Current Transient (CCT) in MIM and Kelvin Probe technique for MEMS and taking also into consideration similar reports [11-

19], it is concluded that it is quite important to take into consideration that charging in MIM capacitors occurs through a perfect contact under uniform electric field and without air gaps that are always present in MEMS due to surface roughness. Therefore even the application of the same field leads to important differences in the charge storage in the two devices. The charge stored in MEMS under the application of 1 MV/cm for 5 min was calculated to be 30 nC/cm^2, while in MIM it exceeds 200 nC/cm^2.

3.3. The discharging process

When the actuation voltage is no longer applied in a MEMS switch the bridge returns to the up state position and the electric field is no longer applied across the dielectric film. This is the onset of the discharging process. The injected and stored charges are starting to move from the surface through the dielectric film to the bottom contact and collected there. This charge collection process which is the most essential one for the device lifetime occurs under a very low intrinsic field generated by the injected charges themselves.

In case of MIM capacitors there are two types of measurements associated to the discharging of the dielectric film. The first one is the Discharge Current Transient (DCT) technique which is actually the monitoring of the current arising by the collection of the injected charges by short-circuit of the capacitor. In this case the charges are collected by the injection electrode and not through the opposite one as in the case of MEMS. Therefore the DCT technique is not suitable to provide valuable information on the discharging process in MEMS. The discharging process in this case is much faster and it contains no information regarding the transport of charges across the dielectric film. However, the DCT technique is a powerful tool to assess the material properties themselves. Fig. 7 presents the discharge transient obtained from MIM capacitors charged up to 30 nC/cm^2. The time constant obtained in this case is only 300 sec.

Another approach for the assessment of the discharging process in MIM capacitors is by the application of Kelvin Probe (KP) method. This technique is based on the monitoring of the surface potential of a MIM capacitor without contact (Fig. 8), thus the discharging through the bottom electrode. Kelvin probe method resembles quite realistically the discharging process in RF MEMS. Indeed the results obtained after charging the MIM with the equivalent charge denote that this technique can be used to obtain information from MIM to MEMS. The time constant is in the same order of 10^4 sec, while in both cases the discharging obeys the stretched exponential relaxation.

It is worth to mention that similar studies based on Kelvin Probe Force Microscopy (KPFM) on metal free dielectric film surfaces have been already reported in the past [14]. However, there is a difference between the KPFM and KP method. The first assesses the surface potential by minimizing the electrostatic force on the system tip. The second by minimizes the current through a vibrating capacitor [25]. The presence of the MIM top electrode ensures uniform electric field arising from the charge at the surface of the dielectric film. In addition, the KPFM method has been used to assess the charge distribution of very small surfaces and the delay caused by sweeping the KPFM tip across the surface does not allow the real time measurement of the charge dissipation. Thus, although the KP method does not resemble the real MEMS discharge, it provides a more accurate determination of discharge process, normal to film surface, that is not affected by lateral charge diffusion as shown in [24]

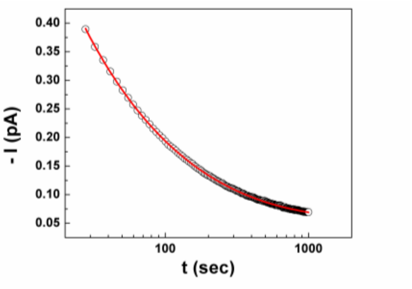

Fig. 7 Discharge current transient obtained in MIM capacitor charged up to 30nC/cm^2

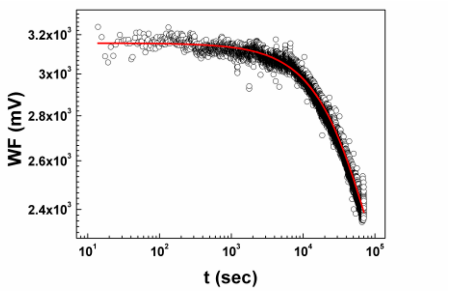

Fig. 8 The discharging process through the dielectric film as obtained in MIM capacitors charged up to 30nC/cm^2

Regarding the stretched exponential relaxation, the transient decay is expressed by the following equation

$$\Delta V = \Delta V_0 \exp\left[-\left(\frac{t}{\tau}\right)^{\beta}\right] \tag{7}$$

where τ is the time constant for the discharging process, usually referred as relaxation time, and β is the stretched factor ($0<\beta<1$), and is commonly observed in many systems with important degree of disorder like amorphous materials [26].

In MEMS switches the discharging process is quite accurately monitored by recording the position of the bias corresponding to the minimum up state capacitance (Fig. 9) [20]. In our case MEMS switches have been stressed under the applied field of 1 MV/cm for 5 min which as mentioned in the previous sections results in charge storage of 30nC/cm^2. The following discharging process is presented in Fig. 10.

The discharging process is found to obey the stretched exponential relaxation mechanism with a time constant in the range of 10^4 sec.

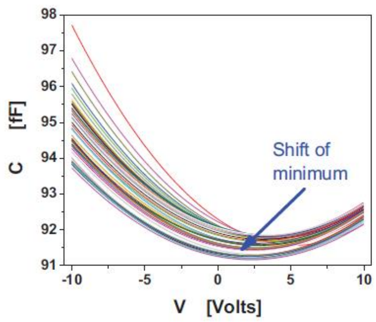

Fig. 9 Up state C-V curves recorded in MEMS switches during discharging process. The minimum gradually returns to the initial position denoting film discharging. The arrow indicates the shift direction and the increase of time.

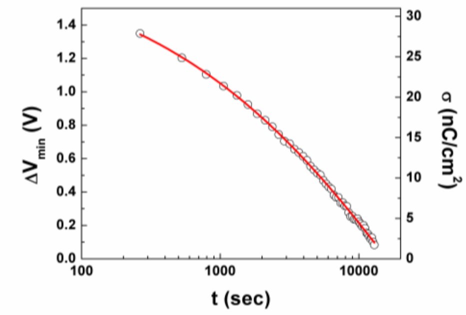

Fig. 10 Position of the minimum as a function of the discharging time. Monitoring of the discharging process in MEMS

3.4. Discussion

The analysis presented in the above sections confirms that the study of the electrical properties of MIM capacitor provides valuable information on the study of dielectric charging for RF MEMS. The analysis of the DC characteristics reveals the responsible mechanism for the charging and discharging processes. In addition, taking into consideration the results extracted in both devices after charging up to the equivalent stored charge (table 1), we may conclude that the main drawback of using a MIM capacitor for the study of MEMS arise by the differences in the top metal/dielectric contact.

Table 1 Summary of the results for the discharge in MEMS and MIM

250nm SiN	MIM	MEMS
stored charge (nC/cm^2)	30	30
Top surface potential relaxation	stretched exp.	stretched exp.
relaxation time (sec)	5 x10^4	3 x 10^4
Exponent β	0.9	0.4

The table summarizes the results for the discharge relaxation time (τ) and the stretched factor (β) obtained by fitting procedure with the stretched exponential relaxation law on experimental data obtained in MIM capacitors and MEMS switches.

The absence of air gaps in case of MIM capacitors results in a uniform distribution of injected charges. Therefore, even if the same charge density is injected, the resulting internal field is different in the two cases. In MEMS, the internal field is expected to be strongly non uniform resulting in locally enhanced densities. These fluctuations are responsible for the slight differences extracted from the discharging process.

The uniform internal field that is formed in the case of MIM results in slower discharging while the non uniformity in case of MEMS is also expressed by the reduced values of the stretched exponential exponent β. In this point it is worth to point out that the stretched exponential relaxation although appearing to be a fitting tool without significant physical meaning, arises from the superposition of many single exponentials relaxation processes and is multiscale in contrast to Debye relaxation [27]. Therefore, in the case of amorphous dielectric films for MEMS application, the stretched factor β is used as an indicator of the complexity of the charge collection process [28] and is mainly determined by the charge distribution formed at the film surface by the charging process [14]. Therefore, the study of MIM may provide the expected magnitude in the discharging time constant for MEMS, however different shapes on the discharging curves and mainly in curve's tails for long times should always been expected. In addition, the charging study in MIM cannot predict any effect arising by the non uniform charge injection such as the narrowing of pull-in/out window [8,9].

4. CONCLUSIONS

The paper presents an approach for the assessment of dielectric charging in RF MEMS capacitive switches with the aid of MIM capacitors. The study involved the DC analysis, charging current transients (CCT) and Kelvin Probe. The strengths and weaknesses of each technique are discussed. The DC study of MIM provided valuable information on the responsible mechanisms for the charging and discharging processes while the Kelvin Probe technique provided a quite realistic estimation of the discharging time. On the other hand, the perfect MIM contact leads to enhanced and uniform charge injection, thus the effects related to the non uniform charging arising mainly by the surface roughness of the dielectric film cannot be predicted. Therefore, minor differences in the case of MEMS discharging process should not be considered as unexpected results. Conclusively, it is presented that the appropriate use of MIM capacitor constitutes a useful and important tool on the study of dielectric charging in RF MEMS.

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