Assessment of dielectric charging in electrostatically driven MEMS devices: A comparison of available characterization techniques

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A B S T R A C T
The present work investigates the results of different characterization methods for the dielectric charging phenomenon applicable to metal–insulator–metal (MIM) capacitors and electrostatically actuated micro-electro-mechanical-systems (MEMS). The discharge current transients (DCT), thermally stimulated depolarization current (TSDC) and Kelvin probe force microscopy (KPFM) assessment methods have been applied to either MIM capacitors or electrostatic capacitive MEMS switches or both. For the first time, the KPFM methodology has been used to create a link between the results obtained from the DCT and TSDC techniques applicable for MIM and the results from MEMS switches. The comparison shows that the application of KPFM method to MIM and MEMS leads to the same results on the electrical properties of the dielectric material. This provides a novel powerful tool for the assessment of dielectric charging for MEMS switches using MIM capacitors which have much simpler layer structure. On the other hand the TSDC method reveals a continuous distribution of relaxation time constants, which supports the dependence of relaxation time constant calculated for MEMS on the duration of the observation time window.

1. Introduction
The increasing demand for more functional and flexible, yet lightweight and low-power-consumption wireless systems, has generated the need for a technology that can dramatically reduce manufacturing cost, size, and weight, and improve performance. Since MEMS technology enables batch fabrication of miniature mechanical transducers integrated with complementary metal-oxide semiconductor (CMOS) circuits, MEMS for radio frequency applications (RF-MEMS) provides an opportunity to meet these requirements. The term “RF-MEMS” encompasses several distinct types of devices, including RF switches, resonators, varactors and tunable inductors. Compared to conventional RF components, RF-MEMS offer significant benefits, including lower power consumption, lower insertion loss, lower cost and smaller form factor. Due to ease of fabrication and integration issues, electrostatically actuated MEMS devices are of high interest. However, such devices suffer from reliability issues related to dielectric charging. This phenomenon is found to be more pronounced in the case of electrostatic capacitive MEMS switches and currently results in hindering the commercialization of these devices [1].

The charging/polarization of a dielectric material arises from dipolar and space charge polarizations that often coexist and the electric field and polarization must then be considered as averaged over the thickness of the sample [2,3]. This implies that the resulting charge displacement and microscopic dipoles orientation will give rise to a macroscopic dipole moment, which after removing the stressing voltage will decay and lead to discharge current transients (DCT) [4–6] or thermally stimulated depolarization currents (TSDC) [7] measured in external circuit of metal–insulator–metal (MIM) capacitors. In capacitive MEMS switches although the charging process is similar to the one in MIM capacitors the relaxation differs significantly since the injected charges are collected only through the bottom electrode when the applied voltage is removed and the suspended electrode is in the pull-up state. In MEMS the dielectric charging has been monitored through the shift of pull-down and pull-up voltages [8,9] as well as voltage at which the pull-up capacitance becomes minimum [1]. Recently, Kelvin probe force microscopy (KPFM) has proved to constitute an efficient method to simulate charging through asperities [10–14] and assess the discharge process in MEMS dielectric by monitoring the film surface potential [13,15].

In spite of these efforts there has been no correlation between the abovementioned assessment methods. Thus, the methods associated to MIM capacitors have been considered as efficient tools to assess the bulk properties of the dielectric film, which pro-
vide limited information and therefore being not appropriate to simulate MEMS. The aim of the present work is to reveal the common features and main differences between these assessment methods. In order to succeed this, the decay of surface potential of both MEMS insulating film and MIM capacitor top electrode were monitored and compared. Moreover, KPFM surface potential evolution with time was compared with the decay of DCT and TSDC spectra of MIM capacitors. To our knowledge, this is the first time to introduce a characterization methodology for the dielectric charging phenomenon based on KPFM for MIM capacitors.

The paper is organized as follows. First the theoretical background for the abovementioned assessment methods is presented. This is followed by the experimental details for each applied method. Finally, the results for each method as well as the correlation between the results obtained from different techniques are presented and discussed.

2. Theoretical background

2.1. MIM discharge current transients

The dielectric charging in MIM capacitors has been often investigated through two methods, DCT and TSDC. Both methods are based on the application of electric field for a long time so that to produce saturation of dipole orientation and trapping of injected charges. This is followed by measuring the transient discharging currents in the external circuit.

2.1.1. Discharge current transient (DCT)

The discharge current primarily takes place through tunneling towards the injecting electrodes and further through transport/diffusion. The latter gives rise to two currents with opposite direction, towards the injecting electrodes and through the film that diminish the measured current in the external circuit. Moreover, because no external field is applied during discharge, the process is more complex since it may arise from dipole–dipole interactions, anisotropy of the internal field in which the dipoles are reoriented, the random walking of sequentially trapping and emission of the charges diffusing towards the contacts, etc. [2,3]. The discharge current transient when arises from trapped charges, i.e. holes, or dipole reorientation is given by

\[ I_{ds}(t) = \frac{dP(t)}{dt} = \frac{P(t)}{\tau} \]

where \( P(t) \) is the buildup of polarization during a time \( t \) after the application of an electric field and \( \tau \) the process time constant. In both cases, the polarization and depolarization, the current flowing through the external circuit consists of several components including the polarization or depolarization current, the absorption current and, in the case of polarization, the dielectric conduction current [5,6].

The distribution of time constants around discrete activation energies and across the energy domain [2,3], a behavior that has been reported for amorphous SiN as [7], imposes the approximation of the polarization/charging decay with the stretched exponential law which is very successful in describing the behavior of a wide variety of disordered systems. Thus the resulting DCT current decay can be approximated by [6]:

\[ J_{ds}(t) = \sigma_0 \cdot \frac{\beta \cdot \left( \frac{t}{\tau} \right)^{\beta - 1}}{\tau} \cdot \exp \left[-\left( \frac{t}{\tau} \right)^{\beta} \right] \]

where \( \sigma_0 \) the measured charge in the external circuit, \( \beta (0 \leq \beta \leq 1) \) is the stretch factor, and \( \tau \) is the process time constant.

A key issue parameter for the determination of MEMS capacitive switches lifetime is the process time constant \( \tau \) and the density of charging centers. Up to now the determination of \( \tau \) has been based on fitting a multi exponential decay function [4] or a modified stretched exponential law (Eq. (2)). The distribution of the density of charging centers versus the relaxation time has been obtained by plotting the charge per unit voltage, calculated from the discharge current, \( t \cdot I_{ds}(t)/V \), versus time and assuming Debye relaxations [16].

The discharging current of MIM structures can be considered of constituting a method to determine the presence and distribution of traps in the band gap of insulators. Here it must be pointed out that the DCT method in a disordered material is limited by the time window of observation that does not allow the identification of process time constants \( \tau \) much larger than that window.

2.1.2. Thermally stimulated depolarization current (TSDC)

The thermally stimulated depolarization current (TSDC) technique is used as an efficient tool for the investigation of dipolar and DC relaxation phenomena observed by heating a variety of materials over a wide temperature range after polarization by an electrostatic field at a polarization temperature \( (T_p) \). The observed phenomena occur due to the orientation sensitivity of bond dipoles and charges (electrons and ions) to the external electrostatic field.

During temperature scan, the current density produced by the progressive decrease in polarization in the course of a TSDC experiment, where time and temperature are simultaneously varied, is approximated by [3]:

\[ J_0(T) \approx \frac{P_s(T)}{\tau_0} \cdot \exp \left( \frac{-E}{kT} \right) \cdot \exp \left( \frac{1}{\gamma \tau_0} \cdot \frac{kT^2}{E} \cdot \exp \left( \frac{E}{kT} \right) \right) \]

where \( \tau_0^{-1} \) is attempt escape frequency related to lattice, \( P_s \) is the steady state polarization, \( E \) the activation energy of the contributing polarization mechanism, \( \gamma \) the heating rate and

\[ \tau(T) = \tau_0 \cdot \exp \left( \frac{E}{kT} \right) \]

the thermally activated relaxation time for each contributing mechanism with a corresponding activation energy \( E \) and \( \tau_0 \). The electric charge \( Q \) produced during the depolarization (heating) stage in a TSDC experiment reduced to the sample-electrode surface area can be estimated by the integration over the TSDC spectrum (from \( T_0 \) to \( T_f \)):

\[ Q = \gamma^{-1} \int_{T_0}^{T_f} I(T) \cdot dt \]

which is proportional to the dielectric film polarization.

2.2. Kelvin probe force microscopy (KPFM)

KPFM presently constitutes an efficient approach for the study of dielectric charging in MEMS insulating films. The unique advantages of this technique are twofold. First, charge injection through the AFM tip simulates charging through asperities [10–14] which take place in MEMS switch. Second the discharging process in a microscopic scale in a charged MEMS dielectric can be assessed by monitoring the film surface potential decay [13,15]. This decay has been investigated by adopting the stretched exponential relaxation [10–14]

\[ U_s(t) = U_0 \cdot \exp \left[ -\left( \frac{t}{\tau} \right)^{\beta} \right] \]

The operating principle of the KPFM method is to set off the electrostatic force between the tip and the sample surface by applying a feedback potential to the AFM tip. This electrostatic force has three spectral components at DC, \( \omega \) and \( 2\omega \) where \( \omega \) is...
the mechanical resonance frequency of the cantilever. The cantilever responds only to forces at or very close from its resonance frequency \( F_0 \), which is given by [17]

\[
F_0 = -\frac{dC}{dz} (\Delta \Phi - \Delta V_{DC}) V_{AC}
\]  

(7)

where \( z \) is the tip-sample separation, \( C \) is the capacitance between the tip and the sample surface, \( \Delta \Phi \) is the work function differences between the tip and the sample materials, \( \Delta V_{DC} \) is the DC component of the voltage difference between the tip and the sample (includes the applied DC voltage from the KPFM feedback loop and the surface charge effects), and \( V_{AC} \) is the amplitude of the sinusoidal signal applied to drive the AFM tip at its mechanical resonance frequency, \( \omega \). Thus, the main goal of the KPFM feedback loop is to adjust the potential of the tip until the term \( \Delta \Phi - \Delta V_{DC} \) becomes 0, at which point the cantilever oscillation amplitude should be zero \( (F_0 = 0) \). The measured tip potential is therefore used to generate a map of the sample surface potential.

In spite that charge injection through the AFM tip has been proved to be an efficient method to simulate charging through asperities, this technique suffers from various drawbacks. First, the AFM tip could simulate only a single asperity where in MEMS switch charge injection takes place through thousands or might be millions of asperities at the same time due to the roughness of both the dielectric film and the switch bridge. Additionally, when the dielectric surface is charge injected with the AFM tip, the sample surface becomes inhomogeneous with variations in surface potential between the charged and non-charged positions. Since the capacitance between the tip and the sample and its derivative depend on the tip shape, the tip-sample separation and the position of the tip over various regions on the sample surface, the measured KPFM potential is averaged over all existing potentials on the surface, with the capacitance derivatives being the weighting factors [18,19]. Therefore, the measured KPFM potential in this case does not reflect accurately the real induced surface potential. For a homogeneous sample (a sample with an equal surface potential like metal) the KPFM measured surface potential is independent of the mentioned AFM tip related issues and therefore could provide a closer surface potential from the real one. Finally, since the scanned surface potential depends on the scanned surface topography, additional techniques might be required in order to eliminate the impact of charge injection using the AFM tip on the measured dielectric surface topography [20].

Due to the mentioned drawbacks, other assessment techniques based on KPFM method have been investigated in this work. In the first approach (KPFM–MEMS), KPFM is applied for a charged dielectric in a capacitive MEMS switch while in the second technique (KPFM–MIM), KPFM is applied for a charged dielectric film in a MIM capacitor.

### 3. Experimental approach

The dielectric materials used in this work are PECVD SiN\(_x\) films with 500 nm thickness and were deposited using the high frequency deposition mode as presented in [14]. The investigated test structures for our experiments include circular MIM capacitors of 500 \( \mu \)m diameter and electrostatic MEMS capacitive switches, both employing the same SiN\(_x\) film.

Four different characterization methods have been investigated which are DCT, TSDC, KPFM–MEMS and KPFM–MIM. For the DCT method, an electric filed is applied to MIM capacitor for a specific time followed by measuring the discharge current transients [6]. Keithley 4200 Semiconductor Characterization System has been used to record the discharge current. In the case of TSDC technique, the discharge current of MIM capacitor is measured under simultaneous temperature scan using Keithley 6487 picoampere-meter in the range of 200–450 K [7]. Additionally, KPFM methodology has been used to measure the surface potential decay of charged SiN\(_x\) films implemented in both MEMS switch (KPFM–MEMS) and MIM capacitor (KPFM–MIM). The KPFM experiment has been performed using a commercial AFM (NanoScope\textsuperscript{\textregistered} Illa MultiMode\textsuperscript{TM} with Extender\textsuperscript{TM} Electronics Module, Digital Instruments) along with the SCM-PIT conductive tips. For all investigated techniques, the same stress conditions have been applied for charging the SiN\(_x\) film, which are 10 V for 15 min. Also, the decay of both surface potential or discharge current transients has been monitored for a fixed observation time window which is 20,000 s.

#### 3.1. KPFM for MEMS dielectric film (KPFM–MEMS)

In KPFM–MEMS technique, the surface potential of charged SiN\(_x\) film implemented as the dielectric layer in capacitive MEMS switch is monitored with time. This unique technique allows a microscopic monitoring of the induced surface potential which results from charge injection through many asperities at the same time. A capacitive MEMS switch with lateral actuation electrodes has been used in this study [21] where the electrostatic actuators located far from the transmission line as shown in Fig. 1. This switch topology allows charging the SiN\(_x\) film with a smaller stress voltage than the actual pull-in voltage of the electrostatic actuators.

First the switch is actuated through the lateral electrodes at approximately 35 V and the bridge is pulled down towards the dielectric layer. This is followed by applying a 10 V stress voltage for 15 min to the bridge while the transmission line is grounded in order to charge the SiN\(_x\) film over the transmission line (see Fig. 1). The bridge is then mechanically destroyed and removed in order to make the SiN\(_x\) surface naked and hence ready for the KPFM surface potential measurements. The whole area of the charged dielectric surface is scanned first (100 \( \mu \)m \( \times \) 100 \( \mu \)m) in order to localize the hot spots with the maximum induced potential [15]. Then, a smaller area (5 \( \mu \)m \( \times \) 5 \( \mu \)m) which exists within one of these hot spots has been scanned with time. During surface potential measurements the transmission line is connected to the AFM chuck which is grounded. This action is of extreme importance in order to provide a path for the injected charges in the SiN\(_x\) film to be released as occurs in real MEMS switch during the ‘UP’ state. Finally the KPFM–MEMS measurements have been performed in a controlled environment AFM chamber with a very small relative humidity (RH \( \approx 0.02\% \))

#### 3.2. KPFM for MIM capacitors (KPFM–MIM)

For the KPFM–MIM experiment, MIM capacitor is electrically stressed first. Then, the surface potential of the top electrode, which reflects the potential of the SiN\(_x\) film, has been measured with time. Similar to the KPFM–MEMS technique, during surface potential measurement the bottom electrode of MIM capacitor is connected to the AFM chuck which is grounded.
There are many advantages for this proposed technique when compared with charge injection in single points with the AFM tip [10–14]. First, as the MIM top metal electrode is homogeneous (has equal surface potential), the KPFM surface potential is independent of tip-sample separation, tip shape and tip position over the sample surface. In addition, as the measured potential is an average value for a sample with equal surface potential, it represents a close value from the real surface potential of the charged dielectric. Finally, the impact of the charge injection step using the AFM tip on the dielectric surface topography is completely eliminated. The MIM capacitor can be stressed using any homemade flexible probes in order to avoid any scratch over the electrode surface. Besides, any area over the top electrode surface can be scanned. Therefore, this technique is considered to be simpler and more reliable.

4. Results and discussion

The surface potential decay measured through both KPFM-MEMS and KPFM-MIM techniques are shown in Figs. 2 and 3, respectively. As the charge injection in MEMS switches is not uniform due to roughness and topography of both the bridge and the dielectric film, the surface potential decay has been analyzed in two different positions over the SiN film surface within the scanned area (5 μm × 5 μm). The selected two positions are the ones with the minimum (position 1) and maximum (position 2) surface potential as highlighted in Fig. 2. On the contrary, the charge injection is uniform in case of MIM capacitor and the surface potential is the same all over the top metal electrode.

Comparing Figs. 2 and 3, it is obvious that the initial value of the measured surface potential for MEMS is smaller than the measured value in MIM (around 4.8 V for MEMS and 9.5 V for MIM). Basically, this was expected due to various reasons. As already mentioned, charge injection in MEMS is not uniform while it is uniform in MIM capacitor. Then, the time interval between the end of the dielectric stressing and the beginning of KPFM surface potential scan is much longer in KPFM–MEMS than in KPFM–MIM. For MEMS the bridge has to be carefully removed and then a surface potential scan for the whole dielectric area over the transmission line has been performed in order to localize the hot spots while in MIM the scanning process has been started directly after the end of dielectric stressing. Finally, the naked dielectric layer was exposed to the ambient (relative humidity = 30–40%) in case of MEMS during both dielectric stressing and the bridge removal while in case of MIM the dielectric layer was protected by the top electrode. According to [22], the surface potential decays very fast as the employed relative humidity increases.

Due to the complexity of involved discharging processes the most commonly used decay function for handling relaxation data is the stretched exponential function, exp[−(t/τ)β] and is used in this context. It is clear from both figures that the surface potential decay for both KPFM–MEMS and KPFM–MIM follow accurately the stretched exponential equation through the whole observation time window. Comparing the decay results obtained from both techniques (Figs. 2 and 3), it is obvious that the stretched exponential equation gives very close values for decay time constants τ and stretch factors β for both KPFM–MEMS and KPFM–MIM techniques, in spite of the mentioned differences. This finding indicates that the decay of MIM and MEMS surface potential arises from the charge collection by the bottom electrode through the same mechanisms. In consequence, MIM capacitors and MEMS can lead to the same results when assessed with the same method which is the KPFM in this work. This further recommends the application of the KPFM–MIM technique as a novel and powerful assessment methodology for the dielectric charging in MEMS.

The discharge current transient resulting from the DCT method is presented in Fig. 5. The results for two different fitting equations which are the stretched exponential equation and Debye law are shown in the figure. It is obvious that similar time constants for the DCT decay can be obtained using both equations. However, when using the Debye law the fitting fails to provide adequate information in the short time range while the stretched exponential law fits very well for both short and long time range. Moreover, the fitting although greatly improved when the number of contributing Debye mechanisms increases, does not lead to a concrete conclusion because a continuous distribution of defects is expected for an amorphous material such as SiN used in MEMS. On the contrary, based on the stretched exponential equation the application of the DCT method revealed that the discharge time constant increases with the charging electric field intensity [6].

A close comparison of the decay data obtained from the KPFM based methods (Figs. 2 and 3) and DCT (Fig. 5) reveals that the DCT method provides always smaller decay time constants with respect to the KPFM based techniques. This difference obviously arises from the charge collection mechanisms, the collection by the injecting electrode in DCT and the opposite electrodes in the KPFM based methods. Thus, in MEMS switches, so does in the KPFM–MIM and KPFM–MEMS, the discharge occurs through currents crossing the dielectric film. This discharge current is expected to be much smaller than the one measured in DCT method.

Fig. 2. Surface potential decay for two different positions over a charged SiN film implemented in MEMS switch measured using the KPFM–MEMS technique.

Fig. 3. Surface potential decay measured over the top electrode of a charged MIM capacitor using the KPFM–MIM technique.
Decay time constants versus the duration of the observation time window for the KPFM–MEMS, KPFM–MIM and DCT methods. 

Because of the successive trapping and emission of charges and the charge percolation due to potential fluctuation caused by inhomogeneities in the non-stoichiometric material, i.e. in PECVD SiN,[24] or SiO2,[25] films implemented in MIM capacitor. For KPFM–MEMS, it is obvious from the figure that the decay time constant increases as the observation time window increases. As the time constants for KPFM–MEMS and KPFM–MIM are found to be very close (Figs. 2 and 3), a similar trend for the relaxation time constant versus the observation time window is also expected for KPFM–MEMS technique. On the other side, from our DCT experiments the continuous increase of TSDC current with increasing temperature exhibiting thermal activation, I(T) ∝ exp(−E_a/kT), where E_a is related to the fractional dimension, has been attributed to power-law relaxation and attributed to a fractal distribution of charge trapping centers. The continuous spectrum is observed because the current in the power-law regime is determined by the peak maxima of the Debye sub processes that become active in a certain temperature window.[28,29] Finally, it is evident from Fig. 6 that the TSDC spectrum shows the envelope of the measured current peaks.

TSDC method provides indirectly information on dipoles and trapping centers relaxation time constants. The linear temperature ramp in TSDC allows the scan of both a very wide range of time constants through Eq. (4) and simultaneously a scan of dielectric film band gap through Eq. (3). For SiN, material, it has been reported that charging arises from continuous distribution of time constants around specific activation energies [7]. Taking this into account, we are led to the conclusion that the TSDC spectrum in Fig. 6 arises from a continuous distribution of time constants too. This is supported by the data presented for both KPFM–MEMS and DCT where the calculated time constant is found to increase with the observation time window (see Fig. 4). Finally the electric charge Q produced during the depolarization stage can be calculated through Eq. (5) (see inset of Fig. 4). This makes TSDC method a complementary tool for both the DCT and TSDC method.

5. Conclusion

The charging of dielectric films used in MEMS capacitive switches has been assessed with the aid of the DCT and TSDC methods in MIM capacitors and the KPFM technique in MEMS switches and for the first time in MIM. The theoretical background on each method has been presented and used to highlight the potential and limitations of each method on drawing conclusions on the charging relaxation. The application of KPFM method in MIM capacitors leads to decay time constants similar to the ones obtained from direct charge injection in MEMS insulating films. In consequence, MIM capacitors and MEMS can lead to the same
results when assessed with the same method which is the KPFM in this work. This clearly suggests the application of KPFM method in MIM capacitors as a powerful tool for the evaluation of dielectric charging in MEMS. The new proposed method is based on a very simple device structure, MIM capacitor, which requires few fabrication steps comparing to MEMS devices and hence results in saving cost and time.

Due to processes involved on the collection of injected charges, which is the collection by the injecting electrodes, the DCT method reveals always shorter relaxation times. In contrast in KPFM method the injected charges are always collected by the opposite electrodes and due to successive charge trapping and emission as well as percolation the process relaxation time is always larger. In both methods due to the complexity of involved mechanisms the calculated time constants depend on the time window of experiment. Finally the TSDC method could be considered as a complementary technique to the above analyzed ones since it allows the evaluation of time constant dispersion over a wide range of values simultaneously with the distribution of centers in the material energy gap.

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