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Physics of Charging in Dielectrics and Reliability of Capacitive RF-MEMS Switches

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1. Introduction

The dielectric charging constitutes a major problem that still inhibits the commercial application of RF MEMS capacitive switches. The effect arises from the presence of the dielectric film (Fig.1a), which limits the displacement of the suspended electrode and determines the device pull-down state capacitance. Macroscopically, the dielectric charging is manifested through the shift (Fig.1b) (Rebeiz 2003, Wibbeler et al. 1998, Melle et al. 2003, Yuan et al. 2004) or/and narrowing (Czarnecki et al. 2006, Olszewski et al. 2008) of the pull-in and pull-out voltages window thus leading to stiction hence the device failure. The first qualitative characterization of dielectric charging within capacitive membrane switches and the impact of high actuation voltage upon switch lifetime was presented by C. Goldsmith et al. (Goldsmith et al. 2001) who reported that the dependence of number of cycles to failure on the peak actuation voltage follows an exponential relationship. Particularly it was reported that the lifetime improves by an order of a decade for every 5 to 7 V decrease in applied voltage. The lifetime in these devices is measured in number of cycles to failure although experimental results have shown that this tests do not constitute an accurate figure of merit and the time the device spends in the actuated position before it fails is a much better specification to judge device reliability (Van Spengen et al. 2003).

The aim to improve the reliability of capacitive switches led to the application of different characterization methods and structures such as the MIM (Metal-Insulator-Metal) capacitors that allowed to determine the charging and discharging times constants (Yuan et al. 2004, Lamhamdi 2008) as well as to monitor the various charging mechanisms (Papaioannou 2007a), since these devices marginally approximate the capacitive switches in the pull-down state. A method that approximates more precisely the charging process through asperities and surface roughness in MEMS and allows the monitoring of the discharging process is the Kelvin Probe Force Microscopy (Nonnenmacher 1991). This method has been recently employed for the investigation of the charging and discharging processes in capacitive switches (Herfst 2008, Belarni 2008).

The charging of the dielectric film occurs independently of the actuation scheme and the ambient atmosphere (Czarnecki et al. 2006). Up to now the effect has been attributed to the charge injection during the pull-down state (Wibbeler et al. 1998, Melle et al. 2003,

Olszewski 2008, Reid 2002, Papaioannou 2006a) and dipoles orientation (Papaioannou 2005, Papaioannou 2006b), which are present in the dielectric material.

In order to minimize and control the dielectric charging and obtain devices with high capacitance aspect ratio, several materials, such as SiO_2 (Yuan 2004), Si_3N_4 (Melle 2003, Papaioannou 2005), AlN (Lisec 2004, Papaioannou 2007b, Papandreou 2009), Al_2O_3 (Berland 2003, Blondy 2007), Ta_2O_5 (Lisec 2004, Rottenberg 2002), HfO_2 (Luo 2006, Tsaour 2005), have been used. The selection has been made taking into account the maturity of low temperature deposition method and the magnitude of dielectric constant. Although these materials exhibit excellent insulating properties little attention was paid on the fact that their lattice is formed by either covalent or ionic bonds, which affect significantly the dielectric polarization/charging. It is worth noticing that among these materials, the crystalline AlN exhibits piezoelectric properties, which seems to increase significantly the device lifetime (Lisec 2004, Papandreou 2009).

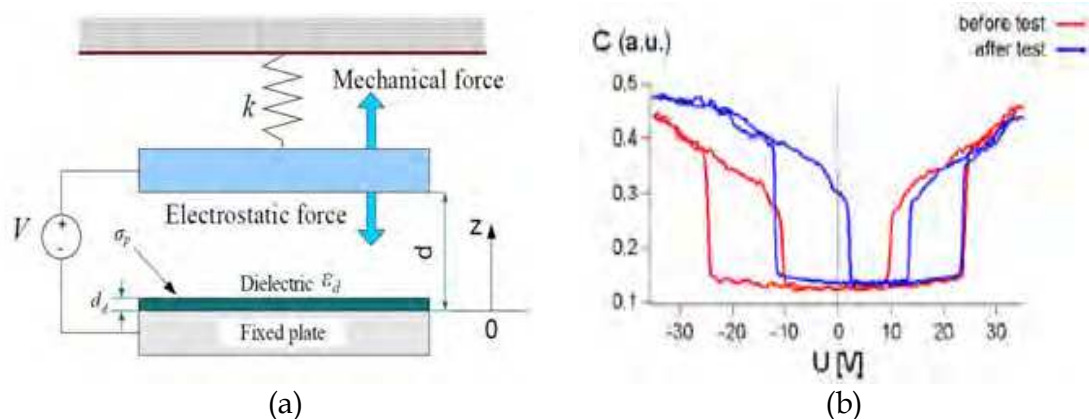


Fig. 1. (a) Simplified model of a capacitive switch based on the parallel plate model and (b) the shift of the capacitance-voltage characteristic after stress.

A key issue parameter that affects significantly the electrical properties of dielectrics and may prove to constitute a valuable tool for the determination of device lifetime is the device operating temperature. This is because temperature accelerates the charging (Papaioannou 2005, 2006, Daigler 2008) and discharging (Papaioannou 2007c) processes by providing enough energy to trapped charges to be released and to dipoles to overcome potential barriers and randomize their orientation. Finally, the presence or absence (Mardivirin 2009) of dielectric film as well as its expansion on the film on the insulating substrate (Czarnecki...) constitute a key issue parameter that influences the charging process.

The aim of the present chapter is to provide an overview and better understanding of the impact of various parameters such as the dielectric material properties, the operating temperature, etc on the physics of charging in dielectrics and reliability of capacitive RF-MEMS switches as well as to present the presently available assessment methods.

The basic polarization mechanisms in dielectrics will be presented in order to obtain a better insight on the effect of the ionic or covalent bonds of the dielectrics used in capacitive MEMS. The deviation from stoichiometry, due to low temperature deposition conditions, will be taken into account. Finally, the effect of temperature on the charging and discharging

processes will be discussed in order to draw conclusions on the possibility of identification and predict of charging mechanisms and their relation to the deposition conditions.

2. Dielectric polarization

2.1 Principles of dielectric polarization

When an electric field E is applied to an insulating material, the resulting polarization P may be divided into two parts according to the time constant of the response (Barsukov 2005):

i. An almost instantaneous polarization due to the displacement of the electrons with respect to the nuclei. This defines the high-frequency dielectric constant ε_∞ related to the refractive index.

$$\varepsilon_\infty - 1 = P_\infty / E\varepsilon_0 \quad (1)$$

The time constant of this process is about 10^{-16} s.

ii. A time-dependent polarization $\Delta P(t)$ arising from mechanisms such as the orientation of dipoles, the buildup of space charge etc in the presence of the electric field. It must be emphasized that the magnitude and sign of the time-dependent polarization is determined by the magnitude of the contributing mechanisms. If the field remains in place for an infinitely long time, the resulting total polarization P_S defines the static dielectric constant ε_S :

$$\varepsilon_S - 1 = P_S / E\varepsilon_0 \quad (2)$$

Thus the static polarization will be determined by the sum of the instantaneous and time dependent polarizations:

$$P_S = P_\infty + \Delta P(t) \quad (3)$$

The simplest assumption that allows the understanding of the response of such a system is that $\Delta P(t)$ is governed by first-order kinetics, that is, a single-relaxation time τ , such that

$$\tau \frac{\Delta P(t)}{dt} = P_S - P(t) \quad (4)$$

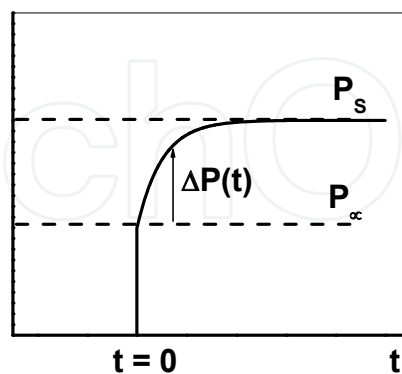


Fig. 2. Time dependence of the polarization P after the application of an electric field

This means that the rate at which P approaches P_S is proportional to the difference between them. Referring to Figure 2, on application of a unit step voltage and solving for $P(t)$, we obtain

$$P(t) = P_{\infty} \left[1 - (P_S - P_{\infty}) \exp\left(-\frac{t}{\tau}\right) \right] \quad (5)$$

For most of the systems investigated, the experimental results cannot be generally described by such equation only. For this reason, it is necessary to use empirical relations that formally take into account the distribution of the relaxation times. A general form that approximates such cases is contained in the Kohlrausch-Williams-Watts (KWW) relaxation function (Kliem 2005):

$$\Delta P(t) = (P_S - P_{\infty}) \cdot \exp\left[-\left(\frac{t}{\tau}\right)^{\beta}\right] \quad (6)$$

where τ is the characteristic time constant and β the stretched factor. The KWW dielectric relaxational polarization has been found either in the time or in the frequency domain in many materials containing some degree of disorder. The list of materials is far away from being complete. Also in magnetic materials such relaxations are present. The fact that so many classes of materials exhibit the KWW behavior led to the supposition that there might be a universal law behind the experimental findings (Homann 1994). Since the observed relaxations can be distributed over more than 11 to 12 decades, the physical property causing the relaxations should be distributed in such a broad range, too. An early solution was given by H. Fröhlich (Fröhlich 1949) who reduced the broad distribution of relaxation times τ to a relatively small distribution of activation energies E_A assuming thermally activated processes with

$$\tau = \tau_0 \cdot \exp\left(\frac{E_A}{kT}\right) \quad (7)$$

The linear superposition of such processes can result in the KWW relaxations. With $kT = 0.026$ eV at room temperature we find for $0.2 \text{ eV} \leq E_A \leq 1 \text{ eV}$ a distribution of τ over more than 13 decades.

2.2 Polarization/Charging mechanisms

The time dependent polarization of a solid dielectric submitted to an external electric field occurs through a number of mechanisms involving microscopic or macroscopic charge displacement. As already mentioned, according to the time scale of polarization build up we can divide the polarization mechanisms in two categories, the instantaneous and the delayed time dependent polarization. The time dependent polarization mechanisms (van Turnhout 1987, Vandershueren 1979, Barsoukov 2005, Kao 2004), which are responsible for the "dielectric charging" effects are characterized by a time constants that may be as low as 10-12 sec or as large as years, so that no relaxation is observed under the conditions of observation. These mechanisms are called slow and may occur through a number of processes involving either microscopic or macroscopic charge displacement. The slow polarization mechanisms, a summary of which is presented in Fig.3, are:

The **dipolar** or **orientational polarization** occurs in materials containing permanent molecular or ionic dipoles. In this mechanism depending on the frictional resistance of the medium, the time required for this process can vary between picoseconds to even years. The dipolar polarization of inorganic crystals may be caused by structural properties of the crystal lattice or it may be due to lattice imperfection or doping, for example in impurity

vacancy dipole systems. The structural interpretation of the dielectric processes occurring in many polar materials is usually approached by assuming impaired motions or limited jumps of permanent electric dipoles. In molecular compounds for example, relaxation can be considered as arising from hindered rotation of the molecule as a whole, of small units of the molecule or some flexible group around its bond to the main chain, while in ionic crystals, it can be mainly associated with ionic jumps between neighboring sites (ion-vacancy pairs). From conventional dielectric measurements it is known that materials obeying the classical Debye treatment with a single relaxation time are rather rare.

The **space charge** or **translational polarization** is observed in materials containing intrinsic free charges such as ions or electrons or both. The space charge polarization arises from macroscopic charge transfer towards the electrodes that may act as total or partial barriers. Moreover, the charging of space-charge electrets may be achieved by injecting (depositing) charge carriers. Other methods consist in the generation of carriers within the dielectric by light, radiation or heat and simultaneous charge separation by a field. The space charge polarization causes the material to be spatially not neutral (fig.3) hence is a much more complex phenomenon than the dipolar polarization.

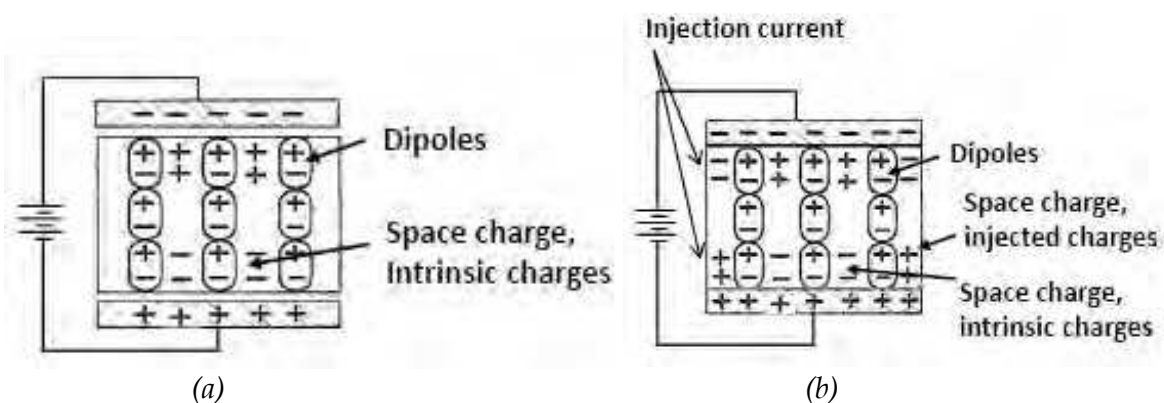


Fig. 3. Summary of polarization mechanisms under (a) non contacting and (b) contacting charging

The **interfacial polarization**, which sometimes is referred as Maxwell-Wagner-Sillars (MWS) polarization, is characteristic of systems with heterogeneous structure. It results from the formation of charged layers at the interfaces due to unequal conduction currents within the various phases. In structurally heterogeneous materials, such as complicated mixtures or semi-crystalline products, it can be expected that field-induced ionic polarization will obey more closely an interfacial model of the Maxwell-Wagner-Sillars type than a space-charge model of the barrier type. There the action of an electric field can achieve a migration charge by (a) bulk transport of charge carriers within the higher conductivity phase and (b) surface migration of charge carriers. As a consequence surfaces, grain boundaries, interphase boundaries (including the surface of precipitates) may charge. Charges "blocked" at the interface between two phases with different conductivity give a contribution to the net polarization of the body exposed to the electric field.

In most of the theoretical treatments, the polarized material is assumed to be free of charge carriers, so that the internal field and the dipolar polarization can be considered as space independent. In practice, however, dipolar and space charge polarizations often coexist and the electric field and polarization must then be considered as averaged over the thickness of

the sample. Finally, the simultaneous displacement of free charges and dipoles during the polarization process may lead to a particular situation where the internal electric field is nearly zero, so that no preferred orientation of dipoles occurs.

3. Dielectric materials for RF-MEMS capacitive switches

As already mentioned the dielectric materials used in MEMS capacitive switches are as SiO_2 , Si_3N_4 , AlN , Al_2O_3 , Ta_2O_5 and HfO_2 . The charging mechanisms in each dielectric will depend on the material structure and for this reason each one will be discussed separately.

So far the dielectric charging has been intensively investigated in SiO_2 and Si_3N_4 . Regarding the other materials i.e. Ta_2O_5 , HfO_2 and AlN there is little information on their impact on the reliability of MEMS devices. In the case of Ta_2O_5 (Rottenberg 2002) and HfO_2 (Luo 2006, Tsaur 2005), although the materials are attractive due to their large dielectric constant, the knowledge on the charging processes is still limited and arises from the study of MIM and MIS capacitors, the latter for MOSFET gate applications. Both materials exhibit ionic conduction and in the case of Ta_2O_5 it has been shown that under high electric field space charge arises due to formation of anodic-cathodic vacancy pair, (Frenkel pair dissociation) (Duenas 2000). Moreover, isothermal current transients in chemical vapor deposited material revealed that protons are incorporated in the structure and the current transient arises from proton displacement (Allers 2003). For HfO_2 it has been shown that hole trapping produces stable charge (Afanas'ev 2004). The trapped charge density was found to be strongly sensitive on the deposition methods and the work-function of the gate electrodes. In thin layers ($\leq 10\text{nm}$) it was shown that charge trapping follows a logarithmic dependence on time (Puzzilli 2007). On the other hand the de-trapping rate was found to depend on the film thickness, with a power law behavior as a function of time.

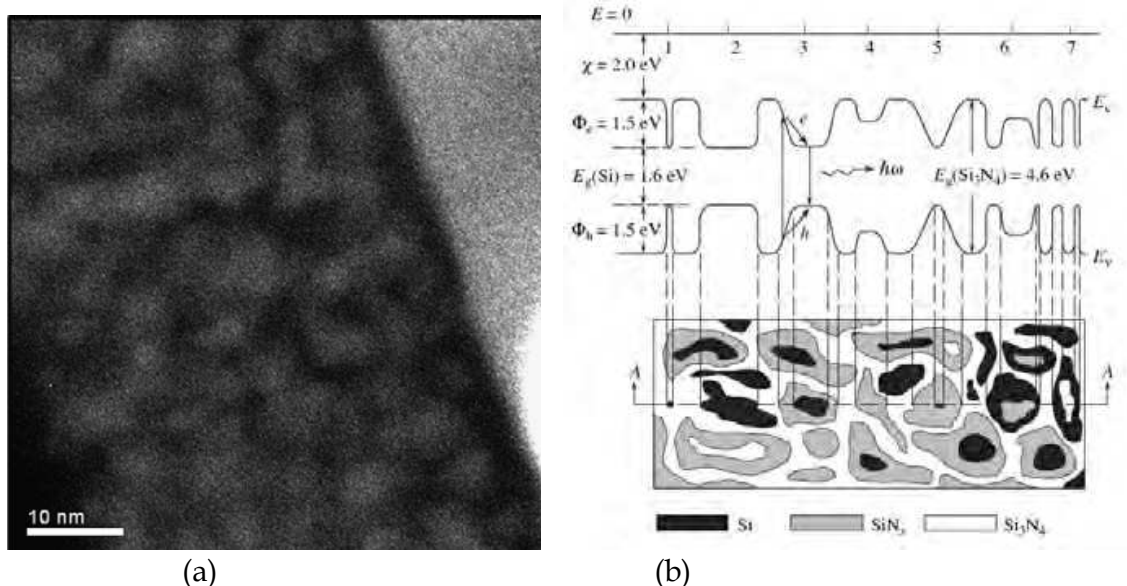


Fig. 4. (a) Cross-sectional energy-filtered TEM image of Si-ncs embedded in SiN_x layers deposited with a gas flow that corresponded to 21% Si excess (Carrada 1998) and (b) representation of material non-homogeneity and band gap fluctuation (Gritsenko 2004)

α -Al₂O₃ is a wide-gap insulator with a direct energy gap of about 8.3 eV (Fang 2007). The O-Al bonds in the compound exhibit highly ionic nature and theoretical calculations have shown that the valence band is well separated into two parts, with the lower part consisting of O 2s states and the upper part being dominated by O 2p states. The lower part of the conduction band is in general believed to be dominated by Al 3s states. Regarding the electrical properties and charging behavior the dc behavior of alumina has been little investigated. The experimental I(t) curves have shown that the 'quasi' steady-state current is reached for time ranging from 10⁴ to 10⁵ s (Talbi 2007). The transient current was reported to consist of two parts, the first one that arises mainly from the polarization of dipoles in the dielectric which dominate at short time, whereas the second part was found to correspond to the carriers transport mechanism. Moreover the conduction mechanism in the high field regime was reported to obey the space charge limited current law. The conduction mechanism high temperatures has been found to be dominated by carriers emitted from deep traps while the low temperatures one by carriers emitted from discrete shallow traps or transport in the band tails (Li 2006, Papandreou 2008). Here it must be pointed out that the characteristics of the charge traps introduced during deposition depend strongly on the deposition conditions (Papandreou 2008).

Aluminum nitride (AlN) piezoelectric thin film is very popular in RF micro-machined resonators and filters MEMS devices. The advantages arise from its high resistivity and piezoelectric coefficient, which is the largest among nitrides as well as the possibility to be deposited at temperatures as low as 500°C and patterned using conventional photolithographic techniques. AlN generally exhibits smaller piezoelectric and dielectric constant and differs from PZT materials in that it is polar rather than ferroelectric. Theoretical results have indicated that nitride semiconductors possess a large spontaneous polarization (Papandreou 2008), associated with which are electrostatic charge densities analogous to those produced by piezoelectric polarization fields. In wurtzite structure the polar axis is parallel to the c-direction of the crystal lattice that may give rise to a macroscopic spontaneous polarization, which can reach values up to 0.1 C/m². This macroscopic lattice polarization is equivalent to two dimensional fixed lattice charge densities with values between 10¹³ and 10¹⁴ e/cm² located at the two surfaces of a sample (Bernadini 1997). Finally, in inhomogeneous alloy layers, variations in composition are expected to create non-vanishing and spatially varying spontaneous and piezoelectric polarization fields and associated charge densities that can significantly influence the material properties. Thus in contrast to the single crystalline material, the sputtered one exhibit near-zero, positive or even negative piezoelectric response indicating a change in crystalline orientation, grain size, concentration of defects or even a complete reversal of dipole orientation (Bernadini 1997, Zorrodo 2001). Recently, AlN has been introduced in MEMS switches (Ruffenr 1999) and reliability tests have proved that under low pull-in bias or certain polarity the device degradation may be extremely low. Assessment of MIM capacitors with crystalline AlN dielectric has indicated that this behavior has to be attributed to the presence of a spontaneous polarization arising from dislocations that may induce a surface charge of the order of $c \times 10^{-7} \text{ C cm}^{-2}$, which is much smaller than the theoretically predicted spontaneous polarization (Papandreou 2009).

The SiO₂ and Si₃N₄ are the most important dielectrics used in modern silicon-based electronic devices. In spite of the five decades of intensive investigation, the gained knowledge has not be effectively applied in MEMS capacitive switches. The reasons behind

this deficiency lie on the fact that in MEMS capacitive switches technology the dielectric film is deposited on rough metal surfaces at low temperatures ($\leq 300^\circ\text{C}$). Thus the film surface morphology is affected by the substrate and the low temperature leads to significant deviation of stoichiometry. The latter allows us to describe silicon oxide and nitride as SiO_x and SiN_x with $x < 2$ and $x < 1.33$ respectively. The low temperature deposition gives rise to formation of silicon nanoclusters and/or nanocrystals in both materials due to the fact that Si excess is high and the phase separation mechanism is not nucleation and growth as in the case of low Si excess, but spinodal decomposition (Carrada 2008). Fig.3a shows clearly the percolation of nanocrystal after 1 min annealing at 1000°C under Ar ambient. A simplified schematic diagram illustrating the two-dimensional structure of SiN_x (Gritsenko 2004) shows in Fig.3b (bottom) the regions of silicon phase, stoichiometric silicon nitride, and subnitrides and (top) the corresponding energy band profile. Similar is the behavior of SiO_x (Ikona 2004, Yoshida 2002).

Material	Ionic	Dipolar	Space charge	Dielectric constant
SiO_2	-	(✓)	✓	3-4.5
Si_3N_4	-	(✓)	✓	6-7.5
Al_2O_3	✓	✓	✓	8-9
AlN	✓	✓	✓	10-12
HfO_2	✓	✓	✓	11-12
Ta_2O_5	✓	✓	✓	~100

Table 1. Dielectric films for MEMS capacitive switches and charging mechanisms (✓) due to deviation from stoichiometry

Although these materials consist of covalent bonds, in substoichiometric silicon oxide the E'_δ defect gives rise to the formation of dipoles by trapping holes (Fleetwood 2003). Although these dipoles were observed after gamma ray irradiation, their presence in the SiO_x used in MEMS capacitive switches cannot be overruled. Moreover, the presence of such structures cannot be rejected in SiN_x .

Taking all these into account we can conclude that the charging mechanisms taking place in insulating films used in MEMS capacitive switches can be summarized in Table 1. So, in all cases the space charge polarization due to presence of free charges or injected charges as well as the dipolar polarization constitutes the major charging mechanisms. The presence of nanoclusters or nanocrystals is expected to give rise to a random distribution of dipolar polarization and in the same time is expected to give rise to interfacial polarization; a fact that needs to be experimentally demonstrated.

Presently, due to above analyzed effects, there is still no clear information on the charging of thin dielectric films used in MEMS capacitive switches. The electrical properties of these dielectrics obviously depend strongly on the deposition methods and conditions. Due to the absence of standardization of deposition methodology, the study of dielectric charging, employing MEMS and MIM devices, still leads to no concrete results. A key issue parameter, towards the solution of this problem, seems to be the dielectric film temperature since it accelerates the charging and discharging processes by providing enough energy to

trapped charges to be released and to dipoles to overcome potential barriers and randomize their orientation. The effect of temperature will be analyzed in the following.

4. Assessment of dielectric charging

The dielectric charging is a complex effect, which cannot be monitored through simple test method hence requires various techniques involving specific experimental setups. The charging can be monitored using bare dielectric material or Metal-Insulator-Metal (MIM) capacitor or MEMS capacitive switch. As it will be understood from the following analysis each method provides partial information.

4.1 Kelvin Probe Force Microscopy (KPFM)

The Kelvin probe force microscopy (KPFM), also known as surface potential microscopy, is a noncontact variant of atomic force microscopy (AFM) that was invented in 1991 (Nonnenmacher 1991). The KPFM is a scanned probe method where the potential offset between a probe tip and a surface can be measured using the same principle as a macroscopic Kelvin probe.

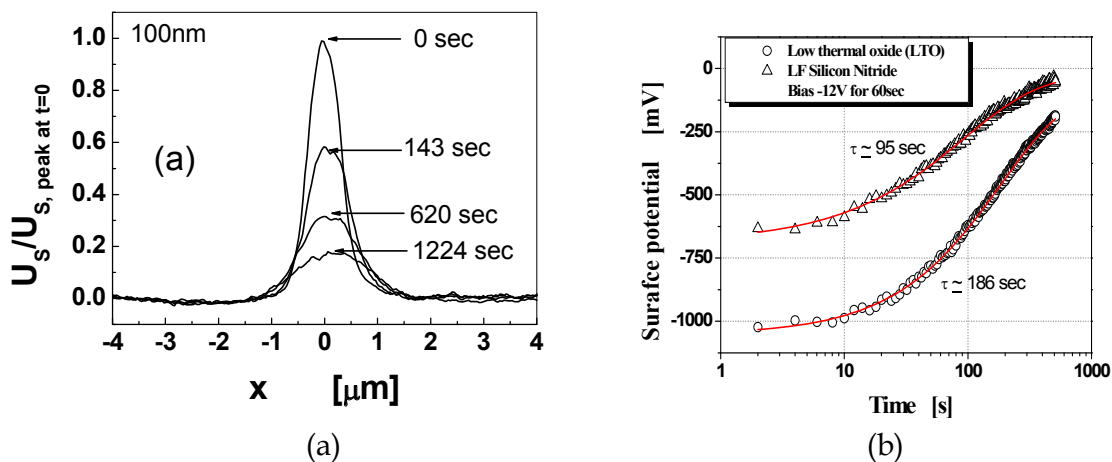


Fig. 5. (a) Dielectric film surface potential distribution vs time (Zaghloul 2008) and (b) peak charge decay (Belarni 2008).

Among the various characterization methods of dielectric charging in MEMS capacitive switches the KPFM method plays a significant role since it allows the simulation of the charging through the dielectric film and suspended electrode roughness and asperities. Presently, the Kelvin probe force microscopy is employed to provide qualitative information on dielectric free surface discharging process. The charges are injected into the dielectric with the probe conductive tip in proximity or contact to the dielectric surface. Then the tip is used to scan the charged area. In these experiments, an important result not yet fully related to switches performance, is the evolution of the deposited charges which showed that the charges are not spreading on the surface (fig.5a) (Zaghloul 2008).

The decay of the amount of charge has been attributed to the penetration and trapping into the bulk of the dielectric. The potential relaxation was reported to be exponential (fig.5b). On the other hand the surface potential induced by charges injected with the Kelvin probe tip was found to decay following the stretched exponential law. Finally, the decay time constant was reported to depend on the dielectric material and practically not affected by the tip potential (Belarni 2008).

4.2 Metal-Insulator-Metal (MIM) capacitors

The MIM capacitors, although do not substitute MEMS switches in the pull-down state, have been proved to be a valuable test structure for assessing the electrical properties of dielectric materials. The dielectric charging in MIM capacitors has been investigated through two experimental methods, the Discharge Current Transients (DCT) and the Thermally Stimulated Depolarization Currents (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. Finally, the DCT method is better exploited if the transients are recorded at different temperatures while the TSDC method requires the current recording during the temperature sweep (Vandershueren 1979).

4.2.1 Discharge Current Transient method

The DCT method is based on the measurement of charging and discharging currents of a MIM capacitor. The discharge current transient when arises from trapped charges i.e. holes, or dipole reorientation is given respectively by

$$j = \frac{dP(t)}{dt} = -\frac{P(t)}{\tau} \quad (8)$$

were P_t is the macroscopic polarization and τ the polarization emission or relaxation time, depending on the model. Here it must be pointed out that the dielectric charging and discharging currents in principle are not equal due to the presence of external electric field during charging and the internal one during discharging (fig.6). For this reason the charging current may be masked by high leakage currents.

The DCT characterization method has been extensively applied for assessment of dielectric charging in silicon dioxide (Yuan 2005) and silicon nitride (Exarchos 2005, Lamhamdi 2008, Zaghoul 2009) films. In all cases the experimental results revealed that both charging and discharging transients are multi exponential with temperature independent time constants. On the other hand in silicon nitride the DCT method revealed the presence of thermally activated mechanisms. The decay was fitted using the stretched exponential law and the Arrhenius plot of relaxation time, Eq. 8, allowed the calculation of activation energy EA and estimation of relaxation time at room temperature ($\tau_{300K} \approx 6 \cdot 10^3$ sec) (Exarchos 2005).

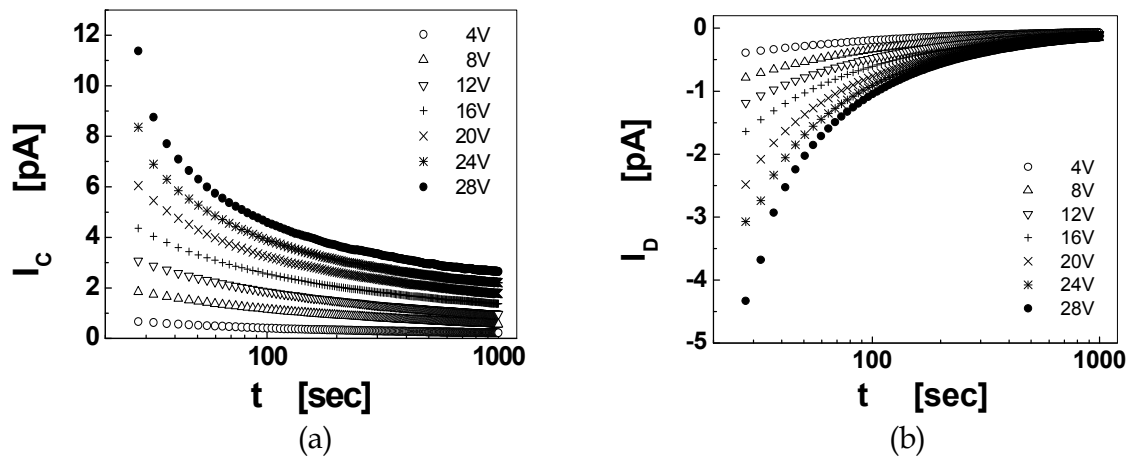


Fig. 6. Dependence of (a) charging and (b) discharging current transient on charging bias (Lamhamdi 2008)

4.2.2 Thermally Stimulated Depolarization Current method

In order to obtain a better insight on the TSDC method it is essential to take into account that in insulators, the time and temperature dependence of polarization and depolarization processes are determined by

- in the case of dipolar polarization the competition, between the orienting action of the electric field and the randomizing action of thermal motion and
- in the case of space charge polarization the processes are far more complex because several mechanisms can be involved simultaneously

The thermally stimulated depolarization current (Vandershueren 1979, Turnhout 1987) is given by:

$$j(T) \approx \frac{P_s(T_p)}{\tau_0} \cdot \exp\left(-\frac{E_A}{kT}\right) \cdot \exp\left[-\frac{1}{\gamma\tau_0} \cdot \frac{kT^2}{E_A} \exp\left(-\frac{E_A}{kT}\right)\right] \quad (9)$$

where γ is the heating rate, being kept constant during temperature scan.

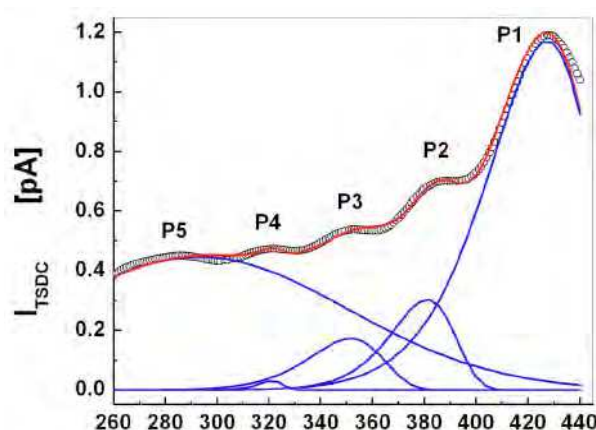


Fig. 7. Temperature dependence of TSD current of a SiN_x MIM capacitor and its analysis (Papaioannou 2007a).

The dependence of TSD current on temperature is presented in Fig.6 and analyzed by fitting Eq.9 to the experimental data. Each contribution (P1-P5) arises from a specific charging mechanism for which the activation energy E_A and τ_0 can be determined. The values of activation energy and τ_0 constitute basic parameters since they allow the calculation of relaxation times at room temperature for each contributing mechanism. Another important parameter is the range of magnitudes of relaxation times because in amorphous dielectric films the relaxation times are distributed over several decades. The difficulty of the determination of such a distribution has been minimized with the aid of Fröhlich model (Fröhlich 1949) that allowed the reduction of relaxation times to a relatively small distribution of activation energies. This model allows the extraction of the dependence of room temperature relaxation time on activation energy assuming that τ_0 is known. A simple example of the importance of this model on the prediction of MEMS reliability is plot of the dependence of room temperature relaxation time, normalized to its value at 450K (fig.8a). Since τ_0 is not known for the sake of simplicity the relaxation time has been assumed to be $\tau_{450K} = 1$. The validity of the relaxation time exponential dependence on activation energy has been confirmed through thermally stimulated depolarization current assessment of SiN_x MIM capacitors, which dielectric film was deposited with high frequency (13.6 MHz) (HF), low frequency (380 KHz) (LF) and mixed frequency (13.6 MHz + 380 KHz) PECVD method and the top contacts were extended over areas with uniform or varying stress (Papandreou 2007) (fig.8b). The results presented by Papandreou et al (Papandreou 2007) revealed that the relaxation times are distributed around specific activation energies with values of 0.17eV, 0.35eV and 0.55eV. It is interesting to point out that the distributions seem to be independent on the film deposition methods as well as the presence of uniform or non uniform stress in the nitride films. Finally it is worth noticing that presently the available data are still limited and no general rules can be extracted on the dependence of these charging mechanisms on the material "quality".

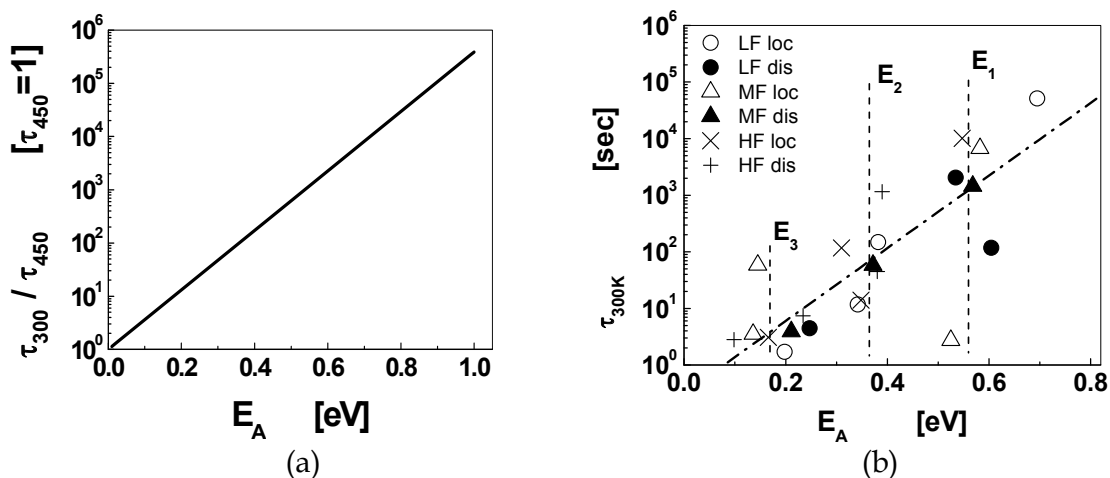


Fig. 8. (a) Dependence of room temperature relaxation time vs activation energy and (b) dependence of room temperature relaxation times on the corresponding polarization mechanism activation energy (Papandreou 2007)

4.3 MEMS capacitive switches

The assessment of dielectric charging in MEMS capacitive switches constitutes an issue which still has not been established. The basic assessment methods rely on the monitoring of the shift of bias for capacitance minimum, $V_{\min} = -\frac{z_d \langle \sigma \rangle}{\epsilon_r \epsilon_0}$ and the pull-down and pull-up

voltages. The shift of the bias for capacitance minimum is a quantity that accurately provides information on the dielectric charging and does not depend on the mechanical parameters of the metal bridge or cantilever. For this reason it has been widely used (Wibbeler 1998, Papaioannou 1996, Ruan 2008 etc) to assess the charging due to cycling and ESD stress at room as well as at elevated temperatures. On the other hand the charge calculated through this method is obtained under low electric field conditions while the performance of a capacitive switch is determined by the shift of pull-down and pull-up voltages which are directly related to the device performance and occur under high electric fields. This limits the importance of V_{\min} . Another method to assess the charging and discharging processes in MEMS are the pull-down and pull-up transients (Papaioannou 2005, Papaioannou 2007c). The presence of thermally activated mechanisms in dielectrics, requires the assessment of MEMS switches to be performed as a function of temperature in order to extract better information on the dielectric charging processes.

Due to the fact that these methods are routinely used for the assessment of MEMS reliability and the limited space, the values of each method will be revealed in the following paragraph.

5. Reliability of RF-MEMS capacitive switches

The reliability of MEMS capacitive switches is determined by a large number of factors. The aim of the present chapter is to present and discuss the failure mechanisms that are related to dielectric charging:

- Effect of contact roughness
- Effect of DC bias and temperature
- Influence of substrate on MEMS reliability
- Ambient effect on MEMS reliability
- MEMS reliability to ESD stress
- Reliability to RF signal power

5.1 Effect of contact roughness

The surface roughness has been recognized as a key issue performance and reliability problem in MEMS capacitive switches. The metal bridge and the dielectric film roughness constitute a technological limitation related to the deposition techniques, which does not allow the roughness better than a few tens of nanometers.

Regarding the device performance the surface roughness plays a critical role at the down position capacitance. Thus the capacitance ratio, which is given by:

$$\frac{C_{down}}{C_{up}} = \frac{\epsilon_r t_{air} + t_{diel}}{t_{diel}} \quad (10)$$

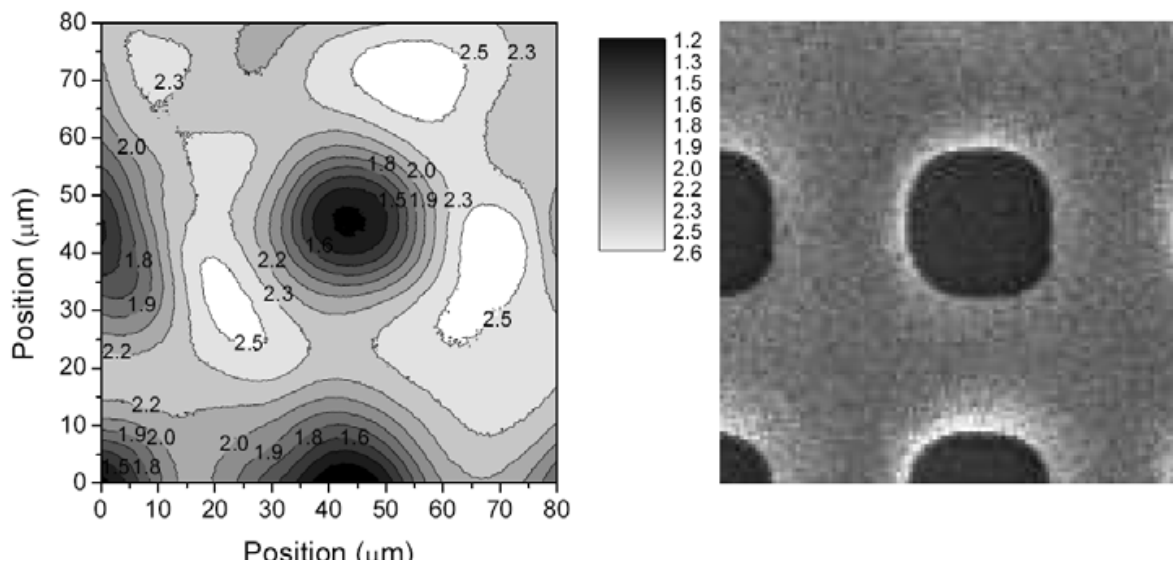


Fig. 9. Contour plot of the measured surface potential of a stressed device and the corresponding section of a SEM picture of the top electrode (Herfst 2008).

where the down state capacitance (C_{down}) must be as high as possible. In equation (11), t_{air} and t_{diel} are the thicknesses of the air and dielectric layers beneath the membrane. Due to the importance of the surface roughness on the device performance there has been an intensive effort on the modeling of the roughness using a statistical approach (Yu 2006) or AFM assessment of the bottom of switch membrane (Suy 2008). The results showed that at the up-state, the capacitance and the insertion loss increases with the RMS roughness and in the down-state, the capacitance and the isolation decreases. Moreover, it was revealed that the overall real contact area between the metal bridge and the dielectric layer surface is less than 1% of the apparent contact area, hence the down-state capacitance is mainly determined by the noncontact area between the metal bridge and the surface of the dielectric layer. The modeling suggested that the improvement of the device performance would require the RMS roughness to be kept below 10nm in order to achieve a normalized isolation of about 60% a parameter that increases with the applied hold-down voltage. Attempts to minimize this effect have been performed by adding a metal electrode, which would determine the down state capacitance, on the top of the dielectric film (Bartolucci 2008).

The surface roughness of the metal bridge and dielectric film affect directly the dielectric charging since charges are injected through the contacting areas. The effect of dielectric charging through surface roughness and asperities has been reported in several papers (Cabuz 1999, van Spengen 2002, Melle 2005, Sumant 2007, Papaioannou 2007d, Herfst 2008). Moreover charges are injected through micro gap discharge (Torres 1999, Slade 2002, Hourdakis 2006) in the proximity areas due to deviation from Paschen law and the charging is induced due to high electric field (Papaioannou 2006b) in areas where no one of the previous mechanisms can occur.

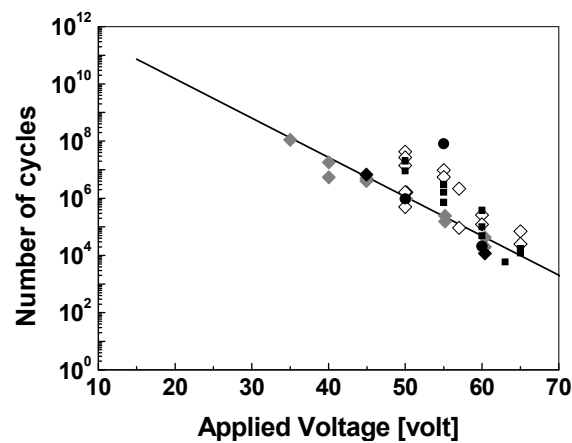
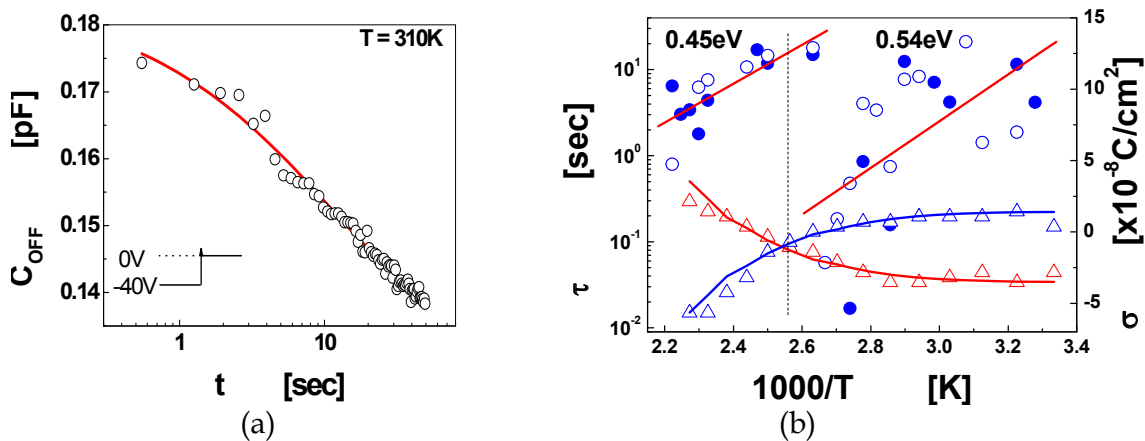


Fig. 10. MEMS lifetime dependence on actuation voltage


 Fig. 11. (a) pull-up transient and (b) simultaneous drawing of Arrhenius plot and shift of V_{\min} (Papaioannou 2007c).

These charging mechanisms in addition to the non planar dielectric film and bridge surfaces lead to a charge distribution that determines the switch behavior (Rottenberg 2008). This non uniform charge distribution has been monitored through measurements of surface potential on a capacitive switch dielectric with the aid of KPFM (fig.9) (Herfst 2008). Here it must be pointed out that the discharge data of Fig.10 allowed the determination of diffusion coefficient of electrons in SiN which was found to be of the order of $10^{-10}\text{cm}^2/\text{sec}$ (Herfst 2008).

5.2 Effect of DC bias and temperature

The first qualitative characterization of dielectric charging within capacitive membrane switches and the impact of high actuation voltage upon switch lifetime were presented by C. C. Goldsmith et al. (Goldsmith 2001). The results of evaluation of switch lifetime as a function of pull-down voltage, for all data reported in (Goldsmith 2001) are shown in Fig.10. The dependence of number of cycles on the peak actuation voltage was found to follow an

exponential relationship, which deviates from Poole-Frenkel injection current relation, as C. Goldsmith et al. pointed out and plotted with a dashed line and which has been normalized at applied voltage of 15 volt. A result of technological significance was the significant improvement in lifetime as voltage decreased. Particularly it was found that the lifetime improves on the order of a decade for every 5 to 7 V decrease in applied voltage. These results definitely provided a continuing impetus to design devices of reduced switch pull-down voltage and produce wafer lots with tight pull-down voltage distributions.

Presently it is well known that the commonly quoted number of cycles to failure does not constitute a good measure of the reliability of switches suffering from charging. W.M. van Spengen et al. (van Spengen 2003) have shown that number of cycles to failure is severely affected by the actuation frequency and duty cycle. Further they have shown that since the failure is purely due to charging, the contact time (down position gives rise to charge injection) is equal for all actuation schemes.

Previously has been analyzed the effect of temperature on the charging effects in dielectrics. In the case of MEMS switches, the pull-up transient is affected by the persisting electrostatic force due to dielectric charging. Thus the fast mechanical response is followed by a slow transient which corresponds to the dielectric film discharging process. The discharge transient was experimentally found to follow the stretched exponential relaxation law $\Delta C(t) = \Delta C_0 \exp\left[-\left(\frac{t}{\tau}\right)^\beta\right]$ (Papaioannou 2007c) (fig.12a). The recording of pull-up transient

as a function of temperature allows us to draw the Arrhenius plot and determine the discharging process activation energy. The transient itself provides information only on the activation energy of discharging mechanism. The nature of the dominant charging mechanism i.e. dipolar or space charge polarizations, the latter arising from charge injection or intrinsic free charges, can be only obtained from the shift of the bias at minimum of capacitance-voltage characteristic, $V_{\min} = -\frac{z_d \langle \sigma \rangle}{\epsilon_r \epsilon_0}$, where $\langle \sigma \rangle$ is the average value of

equivalent surface charge, z_d the dielectric film thickness and ϵ_0 the vacuum dielectric constant. Drawing both the Arrhenius and shift of V_{\min} with temperature in the same figure allows us to determine the activation energy and charge origin of each contributing charging mechanism (fig.12b). Moreover, it is possible to determine the origin of the charging mechanisms, i.e if they emerge from charge injection or charge induction. Finally, the detection of thermally presence of thermally activated mechanisms may lead us to the prediction of the lifetime of capacitive switches.

5.3 Influence of substrate on MEMS reliability

The presence of two different types of charges, which are responsible for the dielectric charging, has been confirmed by experiments using either positive or negative actuation voltage (Czarnecki 2008). The conclusion was drawn from the behavior of pull-in and pull-out windows immediately after stress as well as after 1 min after stress (fig.12)

Here it must be pointed out that these results confirm the predictions of [9.39] and are supported from previous publications (Papaioannou 2005) and (Papaioannou 2007a) as well as recent ones (Olszewski 2008) where the existence of two types of charges, which contribute to dielectric charging, has been reported.

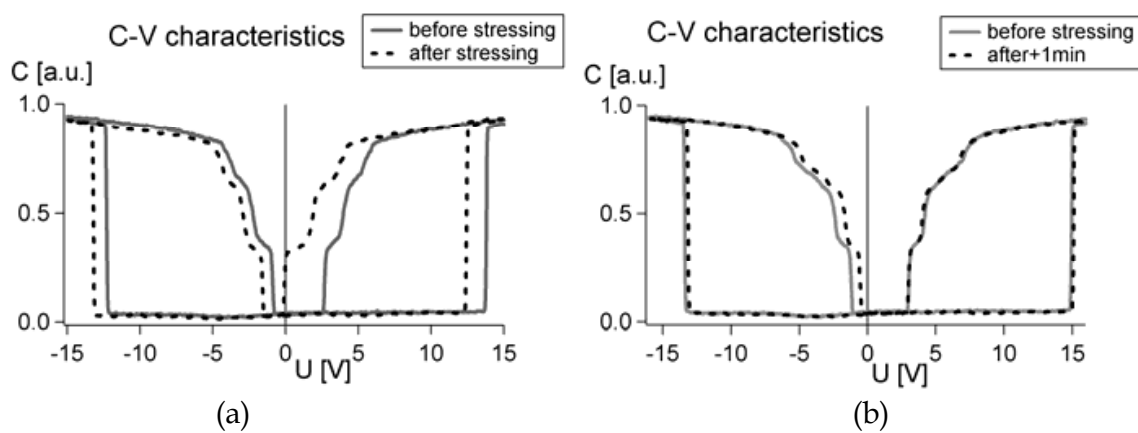


Fig. 12. C-V characteristics measured (a) before and immediately after stressing with positive voltage where a negative shift is visible and (b) before and 1 minute after end of stressing with positive voltage where positive shift is visible (Czarnecki 2008).

The nowadays available information clearly proves the presence of two types of charges, which is responsible for the shift of capacitance-voltage characteristic. The presence of opposite polarity carriers is responsible for the shift C-V characteristic in voltage and capacitance domain, a behavior has been predicted (Rottenberg 2007) and shown experimentally (Papaioannou 2005, Czarnecki 2008). Moreover, the charging, when occurs with the switch in the down state, arises from the Poole-Frenkel transient current component, which gives rise to time and electric field dependent dielectric charging (Melle 2005). Here it must be emphasized that the presence of two types of charges needs further investigation since the homocharge, due to charge injection is well understood. The origin of heterocharge, which is opposite polarity charges, at the dielectric free surface needs further investigation since it is not clear whether they arise from dipole orientation or rear interface charge injection. Finally, the non symmetrical shift of pull-in and pull-out windows needs further investigation since the attribution to mobile charges cannot explain adequately the effect. This issue is highly important since the position of positive and negative charge centroids determine the magnitude and orientation dielectric polarization which in turn will directly affect the capacitance-voltage characteristic through shift of pull-in and pull-out voltages as well as the shift of capacitance minimum.

5.4 Ambient effect on MEMS reliability

The dependence of switches lifetime on the environmental gas and the gas pressure have been recently investigated (Blondy 2007, Czarnecki 2008). Although it is well understood that gasses interact with the dielectric free surface the mechanism that affects the charge storage, hence the dielectric charging, is still not understood. (fig.14)

In order to monitor the charging and discharging process the shift of V_{PI} was measured when the switch was left in the down for 10min and the discharge when was left in the up

state. Humidity was removed by storing the device in high vacuum. In nitrogen ambient the charging/discharging time constants were found to be very similar. Moreover the charge trapping was found to cause the pull-voltage to drop by 7 Volts, when +50 Volts is applied for 10 minutes. When the same experiment performed in open air with typical humidity at 50%, with the devices left for 2 hours the shift of pull-in voltage was found to be completely different (fig.14). Finally, the investigation was performed assuming two charging mechanisms, the surface and bulk charging ones. According to this model when the devices was stressed in air the different behavior was attributed to change from bulk charging in the first minutes to surface charging, the latter being characterized by large time constants and degraded reliability. Finally, it is worth noticing that the effect of humidity on dielectric charging is an issue which has recently attracted attention (Peng 2009).

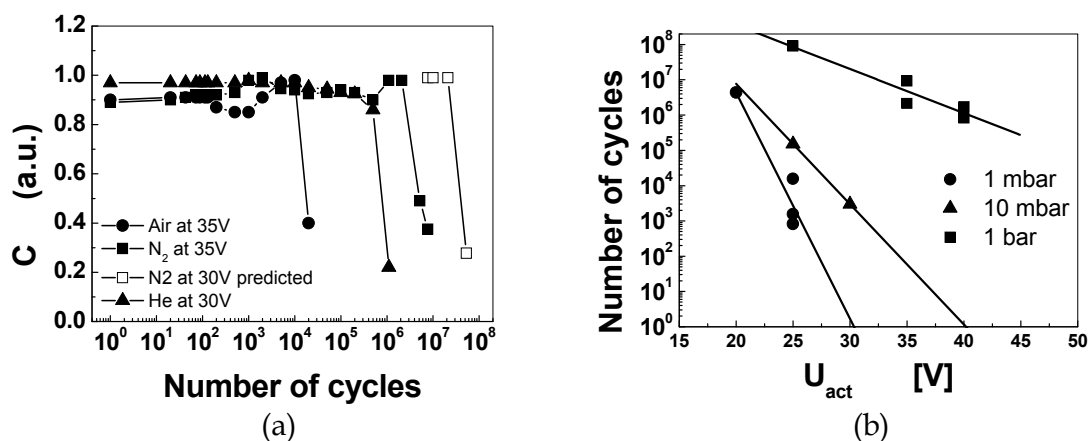


Fig. 13. Effect of (a) gas ambient and (b) gas pressure on MEMS reliability (reproduced from [9.50]).

5.5 MEMS reliability to ESD stress

Electrostatic discharge (ESD) occurs when a device is improperly handled. A human body routinely develops an electric potential in excess of 1000V. Upon contacting an electronic device the discharge will create a large potential difference across the device. In MEMS electrostatic discharge and electrical overstress (EOS) damage has been identified as a new failure mode. This failure mode has not been previously recognized or addressed primarily due to the mechanical nature and functionality of these systems, as well as the physical failure signature that resembles stiction. Because RF-MEMS devices function by electrostatic actuation they are susceptible to ESD or EOS damage as well as to catastrophic failure.

Recently, ESD has started generating interest among researchers as a possible cause of failure in MEMS devices. ESD as a threat to the reliability of MEMS devices was first reported in 2000 by Walraven et al. (Walraven 2000). Reliability issues in RF MEMS switches have been reported by Tazzoli et al. (Tazzoli 2006) and Ruan et al. (Ruan 2007, 2008, 2009a, 2009b, 2009c). The robustness of MEMS capacitive switches has been assessed with Transmission Line Pulsing (TLP) (Tazzoli 2006, Ruan 2007, 2008, 2009b, 2009c) and Human Body Model (HBM) (Ruan 2009a, 2009c) setups. Due to different shape of ESD pulses the When stressing with TLP setup, from the device's mechanical point of view, the pulse is a very short (100ns) and the resulting electric field cannot induce a displacement of the membrane (switching time ≈ 10 -20 μ s) (Ruan 2009b). Varying the applied pulse amplitude,

ranging from 10V to 400V, J. Ruan et al (Ruan 2007, Ruan 2009b) determined the failure signature. Three different stress regions were reported (fig.14); an area where the device is still functional after the stress and two failures areas, namely soft failures area and hard failures area. The functional zone indicates the highest TLP magnitude that the component can withstand and that will not affect its behavior. Then, soft failures occur for a voltage around 350V.

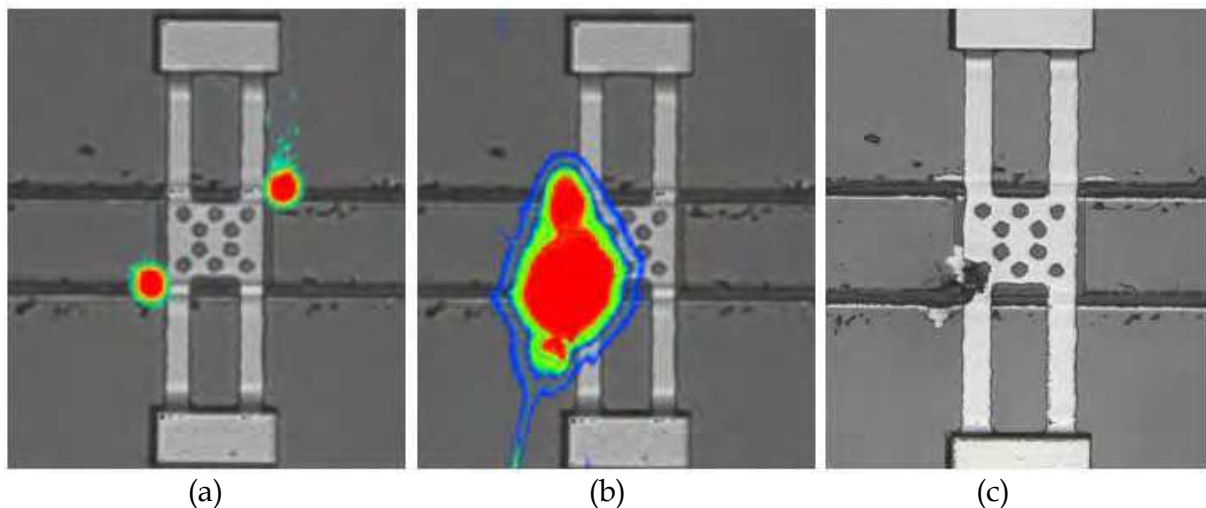


Fig. 14. Photo emission microscopy pictures, a) in soft failures area, b) in hard failures area and c) visible damages (after stresses) (Ruan 2009b)

In this case electric arc occurs across the air gap and can be captured using a photo emission microscopy (fig 14a). This threshold corresponds to the field emission induced breakdown level of the modified Paschen's curve. Above this threshold, hard failures happened (fig 14b) and the consequences are catastrophic (fig 14c). In the hard failures region damages were caused to the insulator layer and also to the metallic electrodes.

These three regimes can be also detected by monitoring the TLP current (fig.15a). The TLP pulses do not induce any significant current through the system up to the threshold of field emission. Above this a sharp current increase is observed and in the hard failure region the slope of the ESD current increases gradually with the pulse amplitude. It is worth noticing that in the soft failure regime the high electric field induces dielectric charging, which can be monitored through the shift of the voltage that corresponds to the minimum of capacitance. The dependence of the shift was reported to vary in all cases as a logarithmic function of the number of positive TLP pulses (Ruan 2008). Moreover, the TLP stress was found to cause narrowing of both the pull-down and the pull-up windows (Tazzoli 2006).

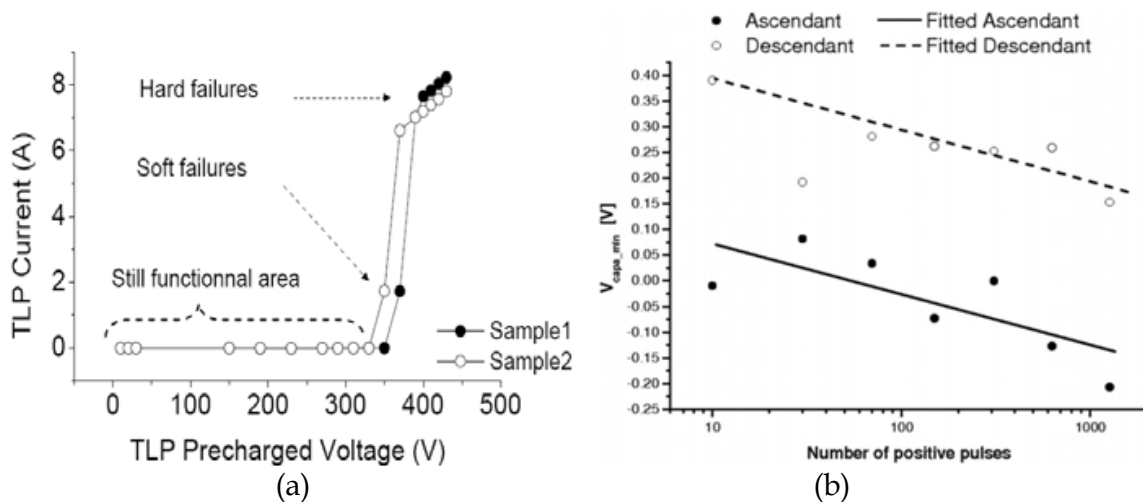


Fig. 15. (a) TLP Current-Voltage failure signature of RF-MEMS capacitive switches and (b) the shift in the voltage corresponding to the minimum of capacitance as a function of the number of positive TLP pulses (Ruan 2008, 2009b).

Finally, regarding the HBM stressing it must be noticed that a MEMS capacitive switch constitutes a capacitive and non conductive load. The duration of a HBM pulse is large enough to bring the switch in the down state and cause considerable charging, much larger than the TLP stress. For this reason, recently (Ruan 2009a) proposed an accelerated stress method based on an HBM setup.

5.6 Reliability to RF signal power

In real world transmit applications the RF power that may be applied to a switch can vary over a broad range of power levels. These power levels and their effects on RF MEMS devices have not been fully explored in order to define in what applications RF MEMS

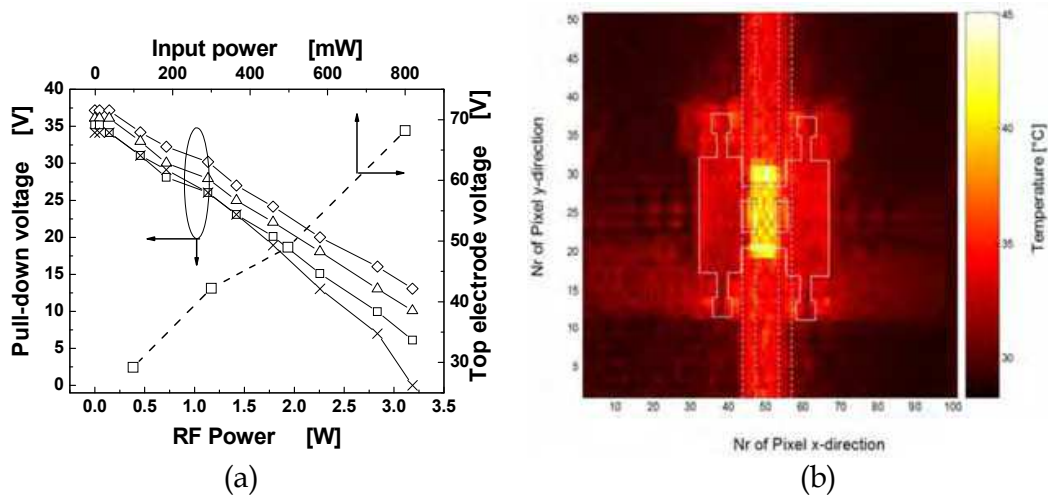


Fig. 16. (a) DC pull-down voltage vs RF power level (Pillans 2002) and measured pull-up voltage vs input power (Peroulis (2004) and (b) ON-state (membrane up) temperature map for the thermal steady-state in case $P_{in}=6W$ (Cocchetti 2005)

switches can be used effectively. RF power signals can cause self actuation in MEMS due to high electric fields and the electrostatic force that are developed across the switch gap.

B. Pillans et al. (Pillans 2002) reported (fig. 16a) a fairly linear relationship exists between the minimum DC pull-down voltage and the RF power level applied. This result has been found to be in disagreement with the expected square relationship between the power and voltage. In the same figure (fig.16a) we included the dependence of measured pull-up voltage on input power (Peroulis 2004). Under power driving the dissipation across various parts of a switch may vary significantly. The results for a capacitive MEMS switch have shown that for 6.3W of RF incident signal at 10GHz, the temperature rise reaches the 75.5°C in case of switch in OFF state, while remains below 28°C in the ON-State for the same input signal (Cocchetti 2005). Therefore, because of the linear proportionality between incident RF power and temperature, thermo-mechanical failures may be expected for the analysed device working in the OFF-State, and for input power above 10W. In this case, the hot spots temperatures are expected to reach temperatures above 120°C.

6. Conclusions

The present chapter attempts to provide a better insight on the dielectric charging and reliability of RF-MEMS capacitive switches. It has been shown that the dielectric material properties play a key issue role in the dielectric charging process. In ionic materials the ionic/dipolar polarization as well as the space charge polarization is the dominant charging mechanisms. In the case of the well established stoichiometric Si_3N_4 and SiO_2 dielectric materials the covalent bonds prevent the dipolar polarization. On the other hand, the low temperature deposition conditions, which are suitable for MEMS capacitive switches, lead to materials that are Si-rich and the significant deviation from stoichiometry gives rise to the formation of Si nanoclusters which allow the formation of defects that exhibit dipole properties, hence giving rise to dipolar polarization in addition to the space charge one.

Presently, the assessment of dielectric charging is mainly based on cycling the devices between the pull-down to pull-up states. Additional assessment is performed through Metal-Insulator-Metal capacitors but these devices can provide information only on the bulk electrical properties of the dielectric film. These devices cannot be considered similar to MEMS switches since they lack free surface which interacts with ambient and accumulate surface charges. Moreover, the top electrode is in excellent contact with the top surface a fact that is not encountered in MEMS switches. A reasonable equivalent to the contacting of bridge with the dielectric film is achieved with the aid of Kelvin Probe Force Microscope (KPFM) since the contacting and charge injecting tip can reasonably simulate the surface roughness and asperities of the metal bridge. This technique has been successfully used to simulate the decay of injected charges. Moreover, it allowed the recording of charge injected in a stressed switch. The results were excellent and the preliminary evaluation of the charge decay allowed the determination of the diffusion coefficient of charges in silicon nitride. Regarding the lateral diffusion, this is still an open issue since there are no concrete results supporting such an effect. For this reason the injected charges in capacitive switches are still considered to be directly collected by the rigid electrode.

Temperature dependence of dielectric charging constitutes a key issue assessment tool. This is because the observed relaxations in disordered materials such as the dielectrics used in MEMS can be distributed over more than 11 to 12 decades. This broad distribution, as

shown by H. Fröhlich model, can be reduced to a relatively small distribution of activation energies. According to this it is highly expected to monitor thermally activated relaxation mechanisms in MEMS devices. The knowledge of the activation energy of such mechanisms provides the means to acknowledge their presence associate them with defects introduced during deposition and monitor their influence on the device performance. Regarding the bulk dielectric material this can be succeeded with both the Discharge Current Transient (DCT) and Thermally Stimulated Depolarization Current (TSDC) methods. The first requires the transient recording at different temperatures while the second one requires the temperature scan. In the case of presence of thermally activated mechanisms both methods lead to same results requiring appropriate analysis of the experimental data. Regarding the TSDC the assessment of SiN MIM capacitors revealed the distribution of time constants, normalized to room temperature, which distribution is supported by the H. Fröhlich model. In the case of MEMS capacitive switches it has been demonstrated that the pull-up transient is reveals thermally activated mechanisms. These mechanisms have been correlated with data from TSDC measurements in MIM capacitors. Due to the fact that the mechanical performance in MEMS with metallic bridge is strongly affected by temperature, the only accurate method allows the determination of the temperature dependence of dielectric charging is the bias for capacitance minimum.

The reliability of MEMS switches is directly affected by a significant number of parameters. The failure mechanisms related to dielectric charging are the charging due to contact roughness, the DC bias and temperature, the influence of substrate, the device ambient, the ESD stress and the RF signal power. Although the nature of failure due to all these relies on dielectric charging there is still no direct connection between them. In spite of the charging and discharging acceleration observed when temperature is increased and the effect of the applied electric field intensity during when the devices is subjected to on catastrophic ESD stress and DC as well as RF power driving, there is still a significant gap of information, which would allow the unification of all these issues.

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