The Discharge Current Through the Dielectric Film in MEMS Capacitive Switches

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Abstract. A new method to determine the bulk discharge current in the dielectric film of MEMS capacitive switches is presented. The method is based on the elementary theory of the discharge process in dielectric materials and the physical model of MEMS capacitive switches with non uniform trapped charge and air gap distributions. The shift of the bias for the minimum of the pull-up capacitance allows the calculation of current densities in the order of picoAmpere per unit area. Assessment of switches with silicon nitride dielectric film shows that the discharge current transient obeys the stretched exponential law. Finally the proposed method is applied to assess the discharge of electrical stressed devices.

Key words: MEMS capacitive switch, dielectric charging, lifetime, reliability.

1. Introduction

Capacitive RF MEMS switches although are very promising components for radio frequency applications their commercialization is still hindered by reliability problems. The key issue problem in these electrostatically actuated devices is the dielectric charging because it causes erratic device behavior and limits the device lifetime [1–3]. So far the dielectric charging of MEMS switches has been investigated by recording the shift of pull-in and pull-out voltages as a function of electrical stress conditions [1], [4-7] or the shift of the bias for the pull-up capacitance minimum [8]. In order to obtain a better understanding of the charging processes the electrical properties of the dielectric films have been investigated with the aid of MIM capacitors [9-11], which although cannot simulate the charging through roughness and asperities can provide the same information when the decay of top electrode potential is monitored [12]. Finally, the assessment of both MIMs and MEMS [13] revealed that the shift of bias for minimum capacitance is thermally activated.

Recently the Kelvin Probe Force Microscopy (KPFM) method [14-16] has been employed to investigate the dielectric charging. This method allowed the monitoring of surface charge dissipation when injection occurs through a single asperity, simulated by AFM tip, or over a large area when charging occurs through the contacting armature. The method also allowed the determination of the influence of ambient on the discharge process [15, 16].

The lifetime of a MEMS capacitive switch is determined by the rates of injected charges during the pull-down state and the collected, by the bottom electrode, charges during the pull-up state. The charge decay rate, which is related to the current paths in the bulk of dielectric film, has been attempted to be determined by monitoring the discharge current in MIM capacitors. As shown in [17], in MIM capacitors the discharge current in the external circuit measured with thermally stimulated depolarization current (TSDC) method and in earlier papers with the discharge current transients (DCT) method [11] arises from collection of charges located in the vicinity of the injecting electrodes. Taking into account the recovery time of a charged MEMS capacitive switch we are easily led to the conclusion that the discharge current of a MIM capacitor measured in external circuit is several orders of magnitude larger than the current through the bulk material. Here it must be pointed out that recently has been attempted to measure the discharge current in MEMS capacitive switches [18]. In this experiment the duration of the current transient was limited to about 150 sec thus providing little information on those parameters that determine the switch lifetime.

The aim of the present work is to demonstrate a new method that allows the determination of the discharge current in MEMS capacitive switches. Transients with duration in excess of 103 sec have been monitored and current densities of the order of pico Ampere per unit area or even less have been calculated. The method takes into account the model of a real MEMS switch with non uniform trapped charge and air gap distributions [19]. The rate of the shift of bias for minimum pull-up capacitance and the dielectric film thickness allow the calculation of the discharge current. The discharge current, determined by mechanisms such as hopping, percolation etc, which are expected in an amorphous and disordered dielectric, provides valuable information that can be used for further optimization and/or engineering of the dielectric material.

2. Theoretical Background

The dielectric charging/polarization in an insulating film arises from charges, injected through surface roughness and asperities, and/or redistributed throughout the dielectric material, the orientation of dipoles and presence of charges at the dielectric interface [21]. In the case of a MEMS capacitor the depolarization process will induce a discharge current density transient through the dielectric film that is given by:

$$.J_{dis}(t) = -\frac{d}{dt}\psi(t) \tag{1}$$

where ψ(t) is the surface charge density.

In order to calculate the switch discharge current transient, the present work device model adopts both the model proposed in [19]. For this we consider the setup in Fig. 1 that includes a fixed nonflat metal plate of area A which is covered with a dielectric layer of uniform thickness d_ε, dielectric constant ε_r, and volume charge density, $\rho(x, y, z)$. Above it a rigid but nonflat movable metal plate is fastened with a linear spring k to a fixed wall above the dielectric layer at a rest position $d_0(x, y)$.

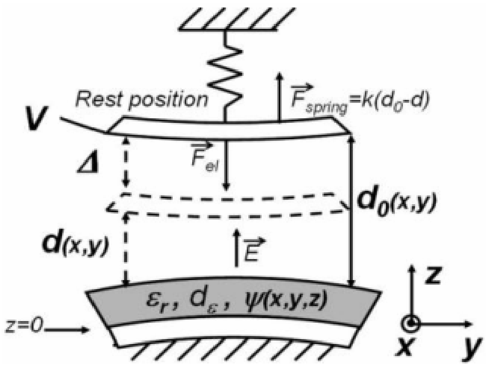

Fig. 1. Model of a capacitive switch with non uniform trapped charge and air gap distributions [12].

A dc bias source of amplitude V is applied to the two plates. Following the procedure analyzed in [19] we find that the electrostatic force F_{el} can be written in a compact form of

$$F_{el}(\Delta) = \frac{A}{2\varepsilon_0}\left[\left(V\mu_\alpha - \mu_\beta\right)^2 + V^2\sigma_\alpha^2 + \sigma_\beta^2 - 2V\operatorname{cov}_{(\alpha,\beta)}\right] \tag{2}$$

where μ, σ_2, and cov denote the mean, variance, and covariance, respectively, of the α(x, y, Δ) and charge β(x, y, Δ) distributions:

$$\alpha(\alpha, y, \Delta) = \frac{\varepsilon_0}{\left[d_0(x, y) - \Delta\right] - \frac{d_\varepsilon}{\varepsilon_r}} \tag{3}$$

which is the distribution of capacitance per unite area and

$$\beta(x, y, \Delta) = \frac{d_\varepsilon}{\varepsilon_r\,\varepsilon_0}\cdot\psi_{eq}(x, y)\cdot\alpha(x, y) \tag{4}$$

the distribution of charge density induced at armature area and $\psi_{eq}(x,y)$ and Δ are the equivalent surface charge distribution and the displacement from equilibrium respectively. At equilibrium positions the system is determined by equating the electrostatic and spring forces that reduce to

$$\frac{2\varepsilon_0 k \Delta}{A} = \left(V\mu_\alpha - \mu_\beta\right)^2 + V^2 \sigma_\beta^2 - 2V \operatorname{cov}_{(\alpha,\beta)} \tag{5}$$

Depending on the adopted device model the above equations can lead to different level complexity approaching in an improved manner the behavior of real MEMS switch. In the general case of distributed equivalent charge [$\psi(x, y, z)$], and air gap [$d_0(x, y)$, (2) cannot be simplified. The bias at which the capacitance in the up state attains minimum (V_m), for which the electrostatic force becomes minimum independently of the charge and air gap distributions is given by

$$V_m = \frac{\mu_\alpha \mu_\beta \operatorname{cov}_{(\alpha,\beta)}}{\mu_\alpha^2 + \sigma_\alpha^2} \tag{6}$$

which can be further written as:

$$V_m = \frac{1}{1 + \left(\sigma_\alpha / \mu_\alpha\right)^2} \cdot \left(\frac{\mu_\beta}{\mu_\alpha} + \frac{\operatorname{cov}_{(\alpha,\beta)}}{\mu_\alpha^2}\right) \tag{7}$$

According to this the shift of the bias for capacitance minimum consists of two components, the one arising from the net surface charge and the other from the covariance of the capacitance and charge distribution. Since the covariance depends on the magnitude of the capacitance and charge variances, the contribution of $\operatorname{cov}_{(\alpha,\beta)}$ can be mitigated by properly choosing a switch where $\left(\sigma_\alpha / \mu_\alpha \ll 1\right)$ the discharge current density, will be given by:

$$J_{disch}(t) = -\frac{d\overline{\psi_{eq}(t)}}{dt} = -\frac{\varepsilon_r \varepsilon_0}{d_\varepsilon} \cdot \frac{dV_m(t)}{dt} \tag{8}$$

where is the mean value of equivalent surface charge density.

Here it must be pointed out that (8) describes the average net charge discharge current density. Therefore in a switch where the net charge is zero Eq. 8 will lead to a zero current and only the nanoscale assessment with KPFM method can be used to obtain information on the surface potential decay only and not on the discharge current in the bulk dielectric.

3. Experimental

The switches utilized in the present work were fabricated with a standard photolithographic process on high resistivity silicon wafers on top of which SiO_2 film was deposited. The dielectric film is PECVD Si_3N_4 deposited at 300°C. Switches with 250 nm dielectric were fabricated. The membrane is an evaporated titanium-gold seed layer electroplated to a thickness of 2μm. Under no applied force, the membrane is normally suspended about 2.5μm above the dielectric. The sacrificial layer was removed with resist stripper and the switches were dried using a critical point dryer. The active area of the switches was about 2.5×10^{-5} cm^2.

The pull-up capacitance voltage (C-V) characteristics were monitored with a Boonton 72B capacitance meter while sweeping the voltage in 50 mV. The pull-in voltage was 25V and each switch was stressed at 30V and 40V before assessment. In all cases the discharge process was monitored for 14000 sec. The bias for pull-up state capacitance minimum was determined by fitting a parabola to the experimental data. This allowed also the determination of the magnitude of the capacitance minimum. Finally, in the present work for the sake of simplicity it was assumed that the capacitance variance is very small so that to satisfy the conditions to apply Eq.8. A switch complying to this condition can be selected with the aid of *i.e.* an optical profilometer or can be properly designed.

4. Results and Discussion

Figure 2 shows the evolution of the capacitance-voltage characteristic in the pull-up state of a switch stressed at 30 Volt for 5 min. In all devices and for all stress conditions the bias for capacitance minimum (V_m) was found to decrease with time and simultaneously the capacitance minimum (C_m) to decrease too. Since the stress was unipolar, the increase of capacitance minimum after stress can be attributed to non uniform charging [14] and creep.

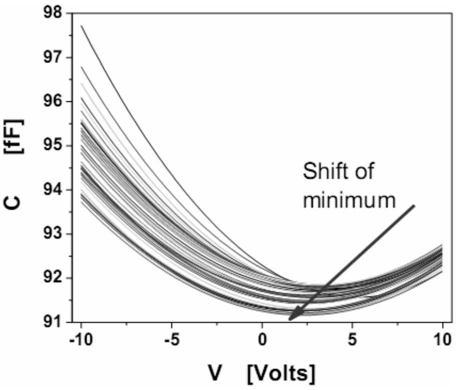

Fig. 2. Evolution of pull-up state capacitance-voltage characteristic of a switch stressed for 5 min at 30V.

Here it must be emphasized that Eq. 8 can be applied, even in the presence of non uniform charge distribution, as long as the capacitance variance is low, as assumed for the sake of simplicity in the present work.

The transient of bias for capacitance minimum, for a switch subjected to stress at 30V for 5 min, is presented in Fig. 3. The variation of V_m with time clearly reveals the presence of a very long time discharge mechanism with a characteristic time much larger than the time window of observation (14000 sec) used in the present experiment. This is the reason the value of V_m still remains large beyond 10 sec (fig. 3). Furthermore, taking into account that the dielectric film is amorphous silicon nitride we expect that the decay of the charge, which may arise from dipole orientation and space charge polarization, will obey the stretched exponential law.

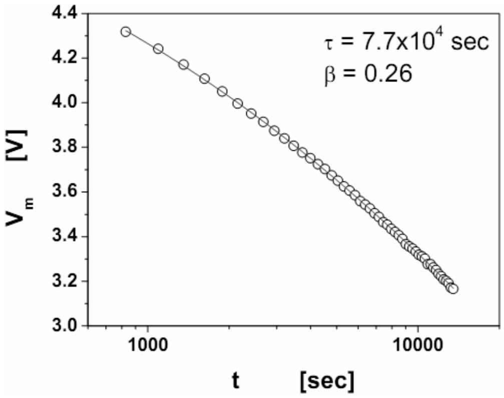

Fig. 3. Bias for capacitance minimum (V_m) transient for a switch stressed for 5 min at 30V.

The fitting revealed a time constant of 7.7×10^4 sec and a value for stretch factor of 0.26, indicating a long discharge time and a complex process.

$$V_m(t)=V_0\cdot\exp\left[-\left(\frac{t}{\tau}\right)^{\beta}\right] \tag{9}$$

The discharge current transient, calculated form (8) by derivation of (9), is presented in Fig. 4. According to this the discharge current will be given by:

$$J_{disch}(t)=\overline{\psi_0}\cdot\frac{\beta}{\tau}\cdot\left(\frac{t}{\tau}\right)^{\beta-1}\cdot\exp\left[-\left(\frac{t}{\tau}\right)^{\beta}\right] \tag{10}$$

where $\overline{\psi_0}=\frac{\varepsilon_r\,\varepsilon_0}{d_\varepsilon}\cdot V_0$

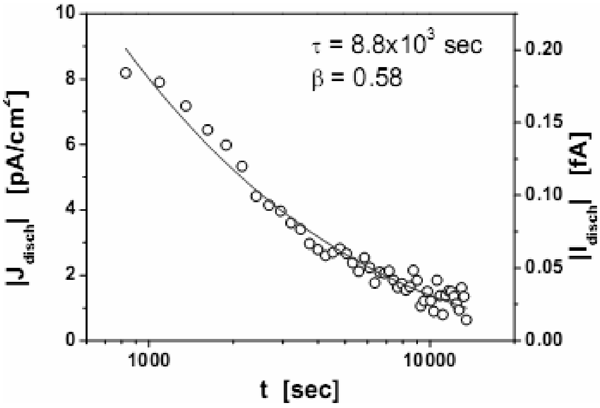

Fig. 4. Calculated discharge current transient for a switch stressed for 5 min at 30V.

The fact that both decays obey the stretched exponential law is not surprising because the same behavior has been observed in the discharge current transient of MIM capacitors and dielectric films assessed with KPFM methods [12]. A close examination of the discharge current reveals the time constant is shorter and the stretch factor larger than the ones determined from V_m decay. The differences must be attributed to the fact that V_m is determined from the contribution from all present charging mechanisms, several of which persisting beyond the time window of the present experiment (see Fig. 3). On the other hand the discharge current is practically determined by the mechanism which dominates the discharge process in the time window of the experiment. Obviously the use of longer time window of observation will provide more information.

The increase of stress conditions, bias of 40 Volt for 15 min, affects both the discharge current and the decay characteristic time constant due to larger amount of injected charge and different occupancy of trapping centres. The decrease of stretch factor with the electric field intensity increasing has been also observed in the discharge current transients in MIM capacitors [15, 20].

5. Conclusion

A new method to calculate the long term discharge current in the bulk of the dielectric film of RF MEMS capacitive switches is presented for first time. The applied method takes into account the constrains of a real MEMS switch with non uniform trapped charge and air gap distributions. The rate of the shift of bias for minimum capacitance in the pull-up state and the dielectric film thickness are used to determine the discharge current. The discharge current has been found to lie in the range of pico Amperes per unit area, a much lower value with respect to any reported one. Such a low current level seems plausible if we take into account the long discharge time of heavily charged MEMS switches. On the other hand these low current levels can be easily attributed to mechanisms such as hopping, percolation etc, which can be expected to occur in amorphous and disordered dielectrics under the presence of intrinsic and gradually vanishing electric fields. Here it is essential to emphasize that the knowledge of the magnitude and time dependence of the bulk discharge current provides valuable information that can provide feedback on the further optimization and/or engineering of the MEMS dielectric films.

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