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ASSESSMENT OF DIELECTRIC CHARGING IN MICRO-ELECTRO-MECHANICAL SYSTEM CAPACITIVE SWITCHES

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Abstract. *The assessment of dielectric charging in MEMS capacitive switches is investigated. The information can be obtained only from simultaneous assessment of Metal-Insulator-Metal capacitance and MEMS capacitive switches the former allowing the determination of material properties and the latter of the device*.

Key words: *MEMS, Capacitive switches, Dielectric charging, Reliability*

1. INTRODUCTION

Radio Frequency Micro-Electro-Mechanical System (RF-MEMS) capacitive switches have emerged as promising technology for several applications due to significant advantages such as low cost, low power consumption and high linearity [1]. In spite of this, their commercialization is still hindered due to reliability issues among which the most severe one is the dielectric charging [1]-[4]. Charging may occur under different conditions. During pull-in state, charges are injected through the contacting areas under high electric fields (i.e. $\geq 10^6$ V/cm) and trapped in defects, characterized by long trapping time constants [5]-[7]. The trapped charge gives rise to shift of pull-in and pull-out voltages and finally to device failure due to stiction [4], [8]. Another charging mechanism is the induced charging that under certain conditions that can be large enough to give rise to compensation [9], [10].

The aim of the present paper is to provide a better understanding of the charging mechanisms in MEMS capacitive switches. The characteristics of dielectric charging are studied by employing Metal-Insulator-Metal (MIM) and MEMS switches and the information obtained from each device will be discussed. The importance of temperature and electric field intensity on assessing of dielectric charging will be also addressed.

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2. Assessment Methods

Up to now the assessment of the dielectric charging has been limited mainly to cycling by counting the number of cycles till stiction, due to shift of pull-in voltage beyond actuation bias or the pull-out voltage crossing zero volts. This may provide empirical information on the device lifetime but no linking is made between the device operation conditions and the dielectric material electrical properties. In order to obtain a better insight on the charging kinetics the assessment must include both MIM and MEMS. The information obtained from each device will be analyzed in the following.

2.1. MIM assessment

The assessment of dielectric charging in MIM capacitors is accomplished by recording the Discharge Current Transient (DCT) and/or the Thermally Stimulated Depolarization Current (TSDC). Both methods allow the calculation of the stored charge, the calculation of characteristic times and the determination of thermally activated mechanisms.

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 [11]. 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. [11]. The discharge current is expressed as

$$I_{dis}(t) = \frac{dP(t)}{dt} \tag{1}$$

where P(t) is macroscopic polarization. The resulting current in 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. The discharging current of MIM structures constitutes a method to determine the interaction of injected charges with the injecting electrodes since in low leakage insulators the injected charge is confined near the injecting contacts [12]. Compared to MEMS, the DCT provides a reasonable simulation of the discharge of MEMS capacitive switches after stiction and before bridge release. Finally, it is essential to notice that the time constants calculated from this method are directly determined by the experimental time window of observation.

2.1.2. Thermally Stimulated Depolarization Current (TSDC)

The TSDC technique is a DCT method in the temperature, which is energy domain. The TSDC spectrum allows the separation of the different contributing trapping, in the case of space charge polarization, or dipole randomization mechanisms and the calculation of time constants over a very wide range such as $1{:}10^6$. The charging is achieved by applying an electrostatic field at a polarization temperature (T_p) and the discharge by linear sweeping the temperature. 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 [11]:

$$J_D(T) \approx \frac{P_S(T_p)}{\tau_0} \cdot \exp\left(-\frac{E}{kT}\right) \cdot \exp\left[-\frac{1}{\gamma\tau_0} \cdot \frac{kT^2}{E} \cdot \exp\left(-\frac{E}{kT}\right)\right] \tag{2}$$

where τ_0^{-1} is the attempt escape frequency related to lattice, P_S is the steady state polarization, E the activation energy of the contributing polarization mechanism, γ the heating rate and $\tau(T) = \tau_0 \cdot \exp(E / kT)$ is the thermally activated relaxation time for each contributing mechanism with a corresponding activation energy E and τ_0. The electric charge density σ_0 collected during the depolarization scan can be estimated by the integration over the TSDC spectrum (from T_0 to T_f).

2.2. MEMS assessment

In a MEMS switch during pull-up state the only available discharge path is through the dielectric film and all injected charges to be collected by the bottom electrode. The bulk discharge current transient in MEMS capacitive switches is determined using the Kelvin Probe Force (KPF) method, proposed in [13], [14]. This method adopts the device model proposed in [15] of a real MEMS switch with non-uniform charge and air gap distributions. According to KPF method, the up-state capacitance attains its minimum at the bias (V_m) for which the electrostatic force is minimum.

$$V_m = \frac{d_\varepsilon}{\varepsilon_r \varepsilon_0} \mu_\psi \tag{3}$$

where μ_ψ is the mean value of the equivalent surface charge distribution and the other symbols have their usual meaning. When the moving armature is released, pull-up state, the injected charges can be collected only through the bottom electrode and the resulting discharge current through the dielectric film is given by:

$$J_{dis} = -\frac{\varepsilon_r \varepsilon_0}{d_\varepsilon} \cdot \frac{dV_m(t)}{dt} \tag{4}$$

The collected charge density (σ_{disch}) during discharge process can be calculated by integrating the discharge current density within the time window of observation.

3. Experimental Results and Discussion

The most common dielectric material used in MEMS capacitive switches is silicon nitride with a thickness ranging from 100nm to 400nm. This material is deposited by PECVD method at low temperatures, ranging from 100°C to 350°C, and plasma frequencies of 13.5 MHz (HF) and 380 KHz (LF). The resulting material is disordered material and may significantly deviate from stoichiometry with controlled concentration of hydrogen.

The charging process of MEMS dielectric can be simulated with the charging in MIM capacitors under electric fields ranging from about 0.5 MV/cm to 2 MV/cm. A typical

DCT transient, after charging with 1MV/cm for 15 min, is presented in Fig. 1a for HF and LF SiN. The charging current transient is exponential and the amplitude obeys the Frenkel-Poole law (Fig. 1b).

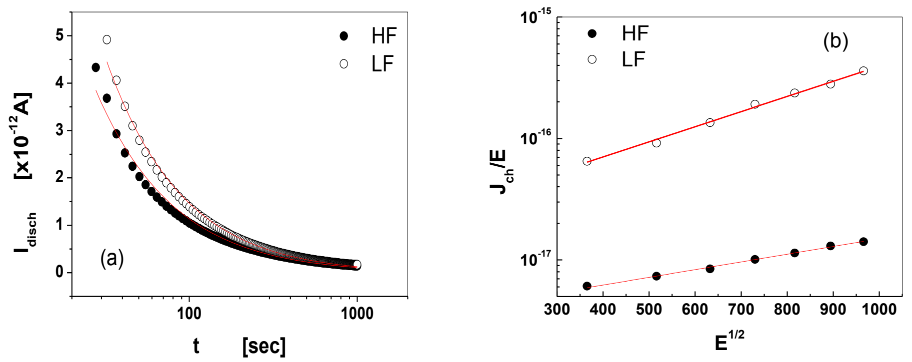

Fig. 1 (a) Discharge current transient and (b) transient amplitude following FP law with current density in A/cm2 and field intensity in V/cm

The integration of transients for the time window of observation reveals an amount of stored charge of $5x10^{-10}$C for LF material and $4.2x10^{-10}$C for the HF one with corresponding relaxation time constants of 94sec and 213sec respectively. On the other hand the differences observed in Fig.1b can be attributed to both different barrier height and impurity defect band [16], the latter being responsible for the faster charge collection. The TSDC assessment of both materials arises from a continuous distribution of discharge mechanisms (Fig. 2). Changing the temperature ramp and applying fractional peak cleaning [11] it is possible to separate or reveal the different contributing mechanisms. The relaxation times obtained from this analysis and normalized to 300K, according to Frohlich law, can be plotted in the activation energy (E_A). The results in Fig. 3 show a distribution in both time constant and energy domains forming groups that obviously arise from complex defects [6].

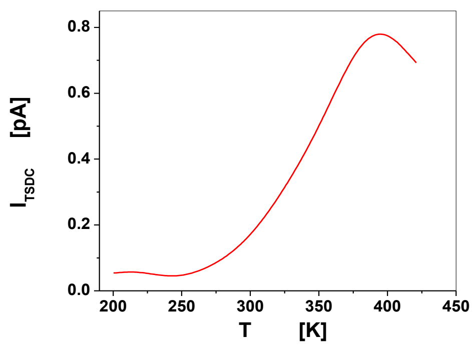

Fig. 2 TSDC spectrum of HF material

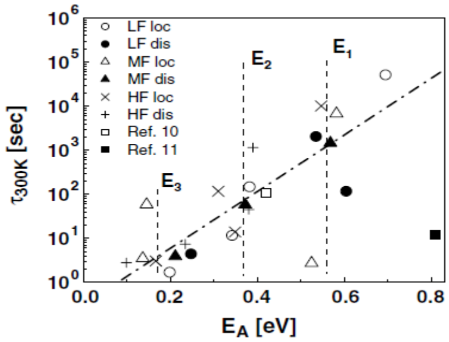

Fig. 3 Distribution of relaxation times in activation energy domain [6]

The results in Fig. 3 have been obtained from HF, LF and MF (mixed frequency) PECVD silicon nitride and indicate that the same electrical active defects are founded in all materials but the local configuration affects the parameters τ and E_A.

As already mentioned, the application of Kelvin probe method in MEMS allows the determination of the average charge density at the surface of dielectric, hence to separate the injected from induced charging and calculate the discharge current through the dielectric film. The shift of the bias for up-state minimum capacitance is presented in Fig. 4.

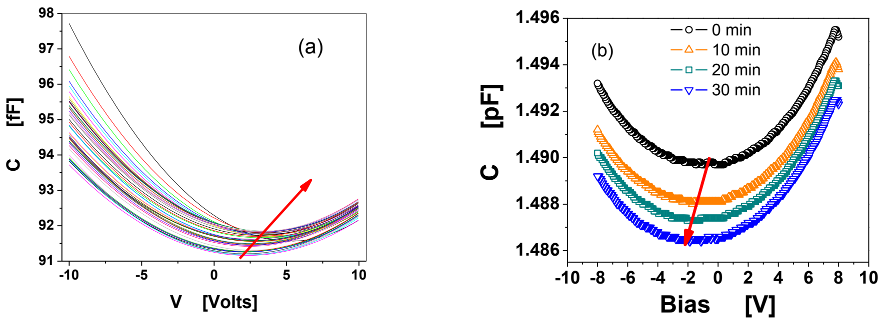

Fig. 4 Shift of bias for up state minimum capacitance (a) contacted charging at +30V and (b) during successive contact-less charging at + 8 Volt

The shift of bias for minimum capacitance is in opposite directions with respect of the applied stress bias for the contacted and contactless charging for a switch with pull-in voltage of 25 Volt. The charging current for the two processes has been calculated with Eq.4 and shown in Fig.5. As expected, the charging process in the contacted charging is much faster than in the contact-less one. Moreover, the magnitude of the charging current at t = 0 sec is much larger for the contacted charging due to charge injection through tunneling effect [12] and decreases faster due to Frenkel-Poole effect that redistributes the injected charges and gives rise to empty sited for the tunneling effect. On the other hand, the contactless charging, which arises from the displacement of intrinsic free charges and the orientation of dipoles, is much slower. It is important to notice that the calculated currents cannot be compared to the steady state leakage current, which does not contribute to charging. In contrast, the charging currents arise from transient phenomena, the charging of the dielectric material. The integral of the above transients is equal to the stored charge that leads to shift of V_m. The calculated corresponding charging time constants and density of stored charge are 50 sec and 114 nC/cm^2 in the case of contacted charging and 1000 sec and 28 nC/cm^2 in the case of contact-less charging. Here it must be pointed out that although the corresponding time constants differ by almost two orders of magnitude the stored charge differs by only one order of magnitude, a fact that may allow partial compensation since the contact-less charging is always present.

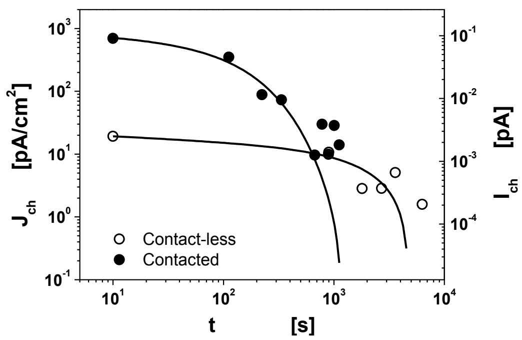

Fig. 5 Charging current under contacted and contact-less stress

In conclusion, the assessment of dielectric charging in MEMS capacitive switches has been investigated. It has been shown that the process is complex and both MIMs and MEMS are required to draw conclusions on the material electrical properties, the charge kinetics and the charge removal from the injecting electrodes in the case of MIM capacitors and the opposite electrodes in the case of MEMS switches. The material properties can be only assessed with MIM capacitors while the devices with MEMS switches.

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