Investigation of charging mechanisms in Metal-Insulator-Metal structures

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Abstract

In this paper we have investigated the temperature dependence of the charging effects in Metal-Insulator-Metal structures, aiming to obtain a better insight on the charging mechanism of RF-MEMS switch insulating layer. The accumulated charge kinetics have been monitored through the transient response of the depolarization current. The transient response is shown to follow rather a stretched exponential law. The time scale of the process is found to be thermally activated with activation energy determined by Arrhenius plot. The results have been compared to thermally stimulated depolarization current assessment.

1. Introduction

Capacitive RF MEMS switches are one of the most promising applications in micro-electromechanical systems (MEMS), but their commercialization is currently hindered by reliability problems. The most important problem is the charging of the dielectric, causing erratic device behavior \cite{1–4}. The development of reliable switches requires a good understanding of the charging mechanism, as well as, of its relation to the dielectric deposition method and conditions. This in turn will allows the contemplation of an adequate model that will describe, the way charge accumulates in the dielectric and how it influences the device behavior. In spite of the numerous efforts the knowledge on the dielectric charging mechanism is still limited. Here it must be pointed out that it is well known that the deposited insulating films, typically SiO\textsubscript{2} and Si\textsubscript{3}N\textsubscript{4}, contain large density of traps \cite{4,5} associated with dangling bonds \cite{5}. These traps are of amphoteric nature, so they can be negatively or positively charged. Under high field conditions it is possible for charges to be injected and further to be trapped in the dielectric film. In addition, due to high resistivity of the material, the recovery time can be of the order of seconds or even days.

The aim of the present work is to employ metal-insulator-metal (MIM) structures in order to investigate the charging mechanism in RF-MEMS switches. This has achieved by studying the depolarization process in MIM capacitor through the analysis of the discharge current transient (DCT). The analysis results allow the determination of the characteristic time and its dependence on temperature. Finally, thermally stimulated depolarization current experiments (TSDC) have been performed in order to be compared to the...
DTC results.

![Graph](image)

Fig. 1. Transient depolarization current obtained at 420K. Circles correspond to experimental data and continuous line the stretched exponential relaxation.

2. Theoretical analysis

In insulators, the dipolar or space charge relaxation time $\tau$ is investigated with thermally stimulated depolarization current, capacitance-frequency dependence, and other techniques [6]. In such materials, the time and temperature dependence of polarization and depolarization processes are determined by the competition, between the orienting action of the electric field and the randomizing action of thermal motion. In the fundamental theory of dielectrics [6], the buildup of polarization during a time $t$ after the application of an electric field at a given temperature is given by an exponential function of time

$$P(t) = P_S \cdot \left[1 - \exp\left(-\frac{t}{\tau}\right)\right]$$

(1)

where $P_S$ is the steady state polarization. Provided that the relaxation times for polarization and depolarization of the dielectric can be considered identical, the decay of polarization after removal of electric field is given by $P(t) = P_p \cdot \exp\left(-\frac{t}{\tau}\right)$ and the corresponding depolarization current density (DTC) $I_{dis}(t)$ is given by

$$I_{dis}(t) = -\frac{dP(t)}{dt} = \frac{P(t)}{\tau}$$

(2)

In both cases, polarization and depolarization, the current flowing through the external circuit consists of several components including, the polarization or depolarization current, the absorption current ($I_a$), and in the case of polarization the dielectric conduction current. Since there is no conduction current under zero bias the current measured in the external circuit will be determined by the sum $I_{dis}(t) + I_a(t)$. A significant point is that the absorption current decreases exponentially with a time constant of $\tau = \rho \cdot \varepsilon$, where $\rho$ and $\varepsilon$ are the resistivity and the dielectric constant of the dielectric material, respectively. Consequently, the discharging current of MIM structures can be considered that constitutes a method determining, not only the presence and distribution of traps in the band gap of insulators, but also the charging mechanisms of materials being used in RF-MEMS switches and varactors.

Finally, it must be taken into account that the insulating materials used in RF-MEMS are amorphous, and the polarization effects arising from dipole orientation or space charge polarization may not follow the ideal Debye model, thus the transient depolarization current may not follow an exponential decay relation as already mentioned above.

![Graph](image)

Fig. 2. Temperature dependence of exponential component.

3. Results and discussion

The investigation of the discharge current transients (DCT) has been monitored in MIM samples with 200nm Si$_3$N$_4$ insulating layers and in the temperature range of 200K to 440K. An electric field of ±25KV/cm was applied to polarize the dielectric and the short circuit discharge current was recorded after the removal of the electric field. As shown in Fig.1, for both electric field polarities, the discharge transient followed rather a stretched exponential relation.
\[
\Delta I(t) = \Delta I_0 \cdot \exp \left[ -\left( \frac{t}{\tau} \right)^n \right]
\]  (3)

where \( \tau \) is process time scale being thermally activated \( \tau(T) = \tau_0 \exp \left( \frac{E_A}{kT} \right) \) with activation energy \( E_A \) and \( \tau_0 \) the relaxation time at infinite temperature. Finally, \( \beta \) is the exponential component. The amphoteric nature of the involved traps and its effect on the discharge current transients, was manifested by the fact that similar but with opposite polarity transients were recorded for positive polarization bias.

It is worth noticing that the stretched exponential relaxation is implemented in a very wide range of phenomena and materials, and it is derived assuming a distribution of parallel rates arising from a random distribution of active centers and microscopic distance-dependent interactions [7]. Regarding the dielectrics, the corresponding phenomenon is called Williams-Watts-Kohlrausch relaxation law [8]. Microscopic models such as, the estimation of survival probability of a random walking particle in the presence of a static distribution of random traps [9], the assumption of hierarchy in relaxation levels [7], and the dynamic scaling hypotheses applied for percolation clusters [10], can explain the stretched exponential decay. These possible mechanisms may occur in our case, since the investigated dielectric film is amorphous. In such a system, the dielectric film constitutes a rather disordered material with a defect concentration of \( 10^{18} \text{cm}^{-3} \) [1,5]. A figure of the uncertainty of the composition lies also on the fact that the deposited silicon-nitride film is often labeled as SiNx. Therefore it is more appropriate to assume that the stretched exponential relaxation mechanism is the one that describes better the situation. Such a hypothesis cannot overrule the case of space charge polarization, i.e. the polarization due to excess charges, which causes the material to be spatially charged [3]. In this polarization procedure, several processes can be involved simultaneously, the parameters of which are not exclusively time and space dependent. Finally, this relaxation process may also arise from, dipole-dipole interactions, variation in size and shape of the dipolar entities, anisotropy of the internal field in which the dipoles reorient, etc. These phenomena are plausible in any material with high dipole and defect concentration.

The fitting to experimental data allowed the determination of \( \tau \) and \( \beta \) as well as the transient amplitude for temperatures above 400K. Below this temperature the transients’ amplitude decreased significantly and so did exponential component \( \beta \) (see Fig.2), hence no concrete results were obtained. The process time scale was found to be thermally activated, as already mentioned above. The activation energy \( E_A \) was determined from the Arrhenius plot of \( \tau \) and presented in Fig.3. Here it is important to notice that the process time is no more thermally activated practically below 415K. The Arrhenius plot allowed the determination of the discharging mechanism activation energy \( E_A \) (1.13eV), as well as, the relaxation time \( \tau_0 \) (7x10^{-16} \text{sec}) at infinite temperature.

Finally, in order to further investigate the polarization/depolarization mechanisms, we performed thermally stimulated depolarization current (TSDC) measurements. The temperature dependence of the TSDC current is given by:

\[
J_{SD}(T) = \frac{P_S(T_p)}{\tau_0} \cdot \exp \left( \frac{E_A}{kT} \right) \cdot \exp \left[ -\frac{1}{\tau_0} \cdot \frac{kT^2}{E} \cdot \exp \left( -\frac{E_A}{kT} \right) \right]
\]  (4)

where \( P_S(T_p) \) is the equilibrium polarization at the polarizing temperature \( T_p \), the other parameters being described above. At temperatures where the ratio \( E_A/kT \) is large enough, the above equation can be simplified and used to determine the activation energy of the leading depolarization mechanism from an Arrhenius plot of \( \ln(J_{SD}) \) vs \( 1/T \).

For TSDC measurements the sample was cooled under the presence of an electric field [6] of 25KV/cm, for the data presented in Fig 4. When the starting temperature was reached, the field was removed and the short circuit current was measured vs temperature.
under a constant heating rate. The plot of TSDC short circuit current vs 1/T is shown in Fig. 4 and above 360K reveals two thermally activated mechanisms. The lower temperature one exhibits an activation energy of about 2.16eV, while the higher temperature one an activation energy of about 1.39eV. The latter lays close to the mechanism that has been determined from discharge current transients. It is important to mention that both mechanisms are detected at temperatures larger than 385K.

Fig. 4. TSDC measurements obtained for a polarization field of 25KV/cm and a heating rate of 2.5K/min.

4. Conclusions

The paper presents a consistent method, the discharge current transient (DTC), for the determination of thermally activated charging processes in insulator used in RM-MEMS switches and varactors. The results obtained from the DTC method have been compared to those obtained from thermally stimulated depolarization current experiments. The analysis of the experimental data confirms that the charging is a complicated process, which can be better, described through the stretched exponential relaxation. The proposed method allows the determination of the corresponding relaxation time and the activation energy of the discharging mechanism. Since there are several microscopic models that lead to the stretched exponential decay, all practically applicable in materials possessing a degree of disorder, a systematic investigation involving both experimental processes and material growth conditions, will lead to a better understanding of the charging mechanism in RF-MEMS switches.

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